An Evaluation of Bur Oak (*Quercus macrocarpa* Michx.) Decline in the Urban Forest of Winnipeg, Manitoba, Canada

BY

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A Thesis
Submitted to the Faculty of Graduate Studies
In Partial Fulfillment of the Requirements
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MASTER OF SCIENCE

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An Evaluation of Bur Oak (*Quercus macrocarpa* Michx.) Decline in the Urban Forest of Winnipeg, Manitoba, Canada

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of

Manitoba in partial fulfillment of the requirement of the degree

Of

Master of Science

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ABSTRACT

Catton, Haley A. M.Sc., The University of Manitoba, October 2005. An Evaluation of Bur Oak (*Quercus macrocarpa* Michx.) Decline in the Urban Forest of Winnipeg, Manitoba. Major Professor; W. R. Remphrey.

Winnipeg is the only city in western Canada with a large, indigenous population of bur oak (*Quercus macrocarpa* Michx.). In the 1980s, many of the city's bur oaks were showing signs of decline, a disease caused by a complex of abiotic and secondary biotic stressing agents. Potential causal factors were investigated by comparing various aspects of 180 bur oaks visually rated as healthy, medium, or declined, based on crown dieback levels. Selected trees were located away from roads where harmful deicing salt is applied in the winter. The results indicated that many selected bur oak trees predated their surrounding urban development. Declined trees were significantly older and had more severe stem wounds and competition from surrounding trees than healthy specimens. Medium trees were generally intermediate between healthy and declined trees. No statistically significant differences in present-day tree size, foliar nutrient levels, nearby visible urban disturbances, or soil characteristics appeared between healthy and declined trees, although these results were not considered conclusive evidence that these factors were not related to bur oak decline in Winnipeg because present conditions do not necessarily reflect conditions at the time of onset of decline. Average annual growth ring widths of healthy and declined trees were similar in the early part of the 20th century; however, growth

of declined trees became slower than that of healthy trees beginning sporadically in the 1940s and consistently from 1974 to the present. The divergence in growth rates coincided with a time of intense urban development in the city following World War II, and the separation between the two categories was more intense in years with high precipitation levels during the early years of decline. Based on these data, it was suggested that decline of bur oak in Winnipeg had been occurring for decades before symptoms were noticed, and may have been caused by a combination of increasing tree age, disturbances from urban development detrimental to oak root systems, and waterlogged soils from the combined effect of impeded drainage and high precipitation levels. Urbanization, however, was not always detrimental to trees, as some showed increased growth rates following development, presumably from the removal of competing trees.

1.0 INTRODUCTION

Bur oak (*Quercus macrocarpa* Michx.) is a large, slow-growing, deciduous tree species capable of bearing seeds up to the age of 400 years, longer than any other oak native to North America (Johnson, 1990). The tree is considered to be drought resistant and flooding intolerant (Johnson, 1990) and is found in a range of habitats, from high areas along riverbanks to very sandy sites, where the tree can become shrub-like and slow growing. Although bur oak tends to be versatile in terms of habitat suitability, it is reportedly sensitive to small changes in its growing environment once established on a site (Allen and Kuta, 1994).

Winnipeg, Manitoba, Canada is a city with a population of near 620,000 residents built around the junction of the Red and Assiniboine rivers, and is situated near the northwestern boundary of the native range of bur oak, the only oak species native to the Canadian prairies. As a result, Winnipeg is the only major city in western Canada to have a large, indigenous population of mature oaks in its urban forest. Many of these trees are located in the city's parks and boulevards, as well as on commercial and residential properties. The trees are reported to predate urban development as the city was effectively built around the bur oak forest (Allen and Kuta, 1994). Together, bur oak and several other native tree species comprise Winnipeg's urban forest to provide functional, aesthetic and economic benefits to the city such as shelter, shade, beautification, and increased property values that improve the urban environment.

In 1986, it was noticed that many of the city's bur oaks were showing signs of distress (Allen and Kuta, 1994). Stress symptoms reported included crown dieback, epicormic shoot growth, and susceptibility to a wood-boring beetle not known to attack healthy oaks, called the two-lined chestnut borer (*Agrilus bilineatus* Weber). A preliminary investigation indicated that no single, aggressive primary pathogen was responsible for the damage, and that the problem was in fact a disease known as oak decline (Allen and Kuta, 1994). As a result of this problem, over 1700 affected bur oaks were removed from the city from 1986-2000 (M. Allen, personal communication). Similar stress symptoms have also been reported more recently in other species of oaks in urban parks in Toronto and Oakville, Ontario (Hashemi, 2004; Ric and Bykov, 2002).

Tree decline is described as a premature, progressive loss of vigour not explained by an aggressive disease or insect, and has long been a global problem in many tree species (Ciesla and Donaubauer, 1994). It is a complex disease involving environmental, tree, and pest factors (Houston, 1974; Wargo, 1996), and may be a natural ecological response in trees growing in unsuitable conditions (Manion, 1981a). In North America, oak decline was first reported in the early 20th century (Ciesla and Donaubauer, 1994; Jensen, 1901; Kessler, 1989) , and has since been observed in all major species of oak in the United States (Wargo, 1993). Research in the 1990s revealed that, although cases of oak decline often share several common features, strong geographical differences exist and region-specific information is necessary in order to comprehend oak decline in a particular area (Luisi et al., 1993). An issue of particular importance to Winnipeg is that little knowledge exists on decline of bur oak in general (Ware, 1982; Ware and Howe, 1974), especially in the northern part of its native range.

The urban forest in particular represents a stressful environment for trees adapted to growing in a natural forest setting. When humans enter an area, nearly everything involved in the process of urbanization results in an unfavourable alteration of a tree's natural environment (Howe, 1974; Root, 1974; Sinclair et al., 1987; Ware and Howe, 1974). With the exception of sugar maple (*Acer saccharum* Marsh., Dyer and Mader, 1986; Horsley et al., 2000; Mader and Thompson, 1969; Ruark et al., 1983; Westing, 1966), decline studies on trees in the urban environment have been limited. Therefore, a local investigation of bur oak decline is necessary to characterize the decline phenomenon observed in Winnipeg.

The overall objective of this study is to uncover factors responsible for bur oak decline in Winnipeg. To accomplish this objective, the following characteristics were compared among trees in various health conditions:

1) **Present-day characteristics**, including

a) Physical tree properties such as age, size, trunk wounds and foliar nutrient levels, and

b) Environmental conditions such as amount of nearby urban development around trees, competing vegetation, and soil parameters

2) **Past characteristics**, including

a) Growth rates and patterns as represented by annual growth ring widths

b) Growth response in relation to climatic conditions and known disturbances

2.0 LITERATURE REVIEW

2.1 Study Area – Winnipeg, Manitoba, Canada

Winnipeg, Manitoba, Canada is a city with an area of 465 km^2 and a population of roughly 620,000 (Statistics Canada, 2004) found at the junction of the Red and Assiniboine rivers on the Canadian prairies (49° 54′ N 97° 14′ W) (Figure 1). Urban development began in the 1860s near the present-day centre of the city and expanded rapidly in the 1870s (Dafoe, 1998). Many of the city's neighbourhoods were built in the 1940s as a response to the post-war housing shortage (Dafoe, 1998) and further suburban development continued at a rapid pace until approximately 1980 when rapid construction moved beyond the city limits to surrounding municipalities. In 1945, Winnipeg contained approximately 50,000 dwellings, and by 1960 that number had more than doubled (City of Winnipeg, 2004). By 1980, nearly 200,000 dwellings existed, and in 2001, Winnipeg contained 252,810 dwellings (Statistics Canada, 2004).

Winnipeg has a subhumid, continental climate that is characterized by high summer and low winter temperatures (Michalyna et al., 1975). From 1938-1990 Winnipeg's mean monthly temperatures ranged from -18.3°C in January to +19.8°C in July (Environment Canada, 2003). The mean annual precipitation was 504.4 mm, with over 80% occurring as rainfall (Environment Canada, 2003). The hydroclimate of the area has been relatively stable over the past 200 years, with

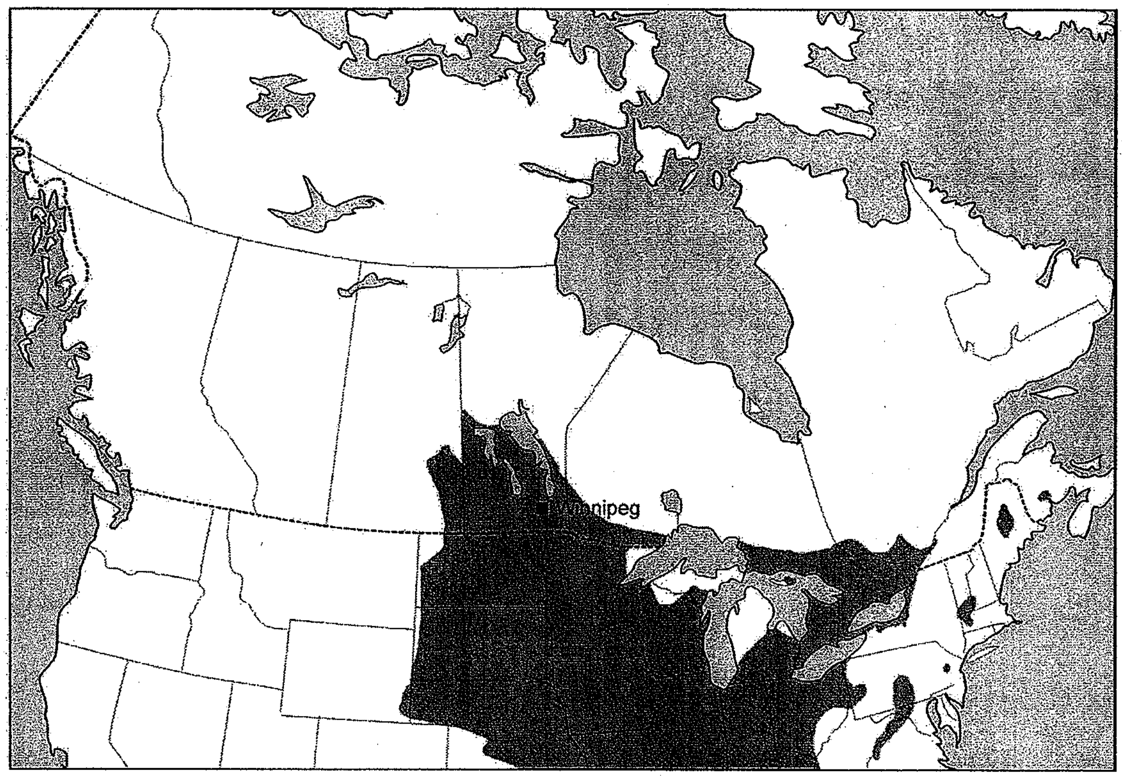

Figure 1. A map showing the location of Winnipeg, Manitoba, Canada, within the northern portion of the native range of bur oak (shaded region). Used with permission by W. R. Remphrey.

several wet periods occurring in the late 1820s and 1850s, and exceptionally dry years occurring periodically, according to inferences from tree ring records (St.George and Nielsen, 2002).

As part of the Red River valley, Winnipeg's soil tends to be black heavy clay, with high fertility and poor drainage. The natural vegetation prior to European settlement was a mix of forest near the waterways shifting to grassland further away as moisture became less available. The arrival of European immigrants meant that almost all trees were harvested for firewood and construction materials in the mid-1800s, leaving a barren landscape (Dafoe, 1998; Ross, 1856; St.George and Nielsen, 2002). As a result, many of Winnipeg's present-day trees germinated during the regenerative time period of the mid to late 1800s when there was little competition for light or water from established, dominant specimens.

2.1.1 Winnipeg's Urban Forest

Winnipeg is located near the northwest boundary of the native range of the bur oak (*Quercus macrocarpa* Michx.) (Figure 1). As a result, it is the only major city in western Canada to have a large, indigenous population of mature bur oaks in its urban forest. Many of the bur oaks in the city's parks and boulevards, as well as commercial and residential properties predate urban development in their areas, as the city was effectively built around the bur oak forest (Allen & Kuta 1994). These trees, along with other species that comprise

Winnipeg's urban forest provide functional, aesthetic and economic benefits such as shelter, shade, beautification, and increased property values that improve the city environment.

Not all the trees in Winnipeg's early urban forest were naturally-occurring. With a future vision of a lush urban forest, citizens transplanted thousands of American elm (*Ulmus americana* L.) saplings from riverbanks to boulevards beginning in the late 1800s (Dafoe, 1998). Presumably because of their poor ability to adapt to transplantation (Allen and Kuta, 1994), bur oaks were not successfully included in the plantation program. Bur oaks were left to disperse naturally and became part of the urban environment as development occurred around and among them (Allen and Kuta, 1994). Today, Winnipeg contains many trees, some naturally dispersed and some planted, including bur oak, American elm, green ash (*Fraxinus pennsylvanica* Marsh.), American basswood (*Tilia americana* L.), Manitoba maple (*Acer negundo* L.), cottonwood (*Populus deltoides* Bartr. ex Marsh.), trembling aspen (*Populus tremuloides* Michx.), and spruce (*Picea*) and pine (*Pinus*) species.

2.2 *Quercus macrocarpa* Michx.

2.2.1 *Quercus*

Oaks are popular trees both in forest plantations and urban settings in North America, Europe and Asia, as they are recognized for their long life spans and high quality wood. Taxonomically, *Quercus* (oak) is one of eight genera along with *Fagus* (beech) and *Castanea* (chestnut) that comprise the family Fagaceae, part of the order Fagales, subclass Hamamelidae of the Magnoliopsida (dicot) class of plants (Cronquist, 1988). Approximately 500-600 species make up the *Quercus* genus, with many being native to the northern temperate regions of the world (Farrar, 1995). Roughly 60 species occur in the USA and 11 in Canada (Farrar, 1995).

Quercus species found in Canada can be classified into two main groups: the red oaks (*Erythrobalanus*), and the white oak group (*Lepidobalanus*) (Farrar, 1995). Species in the red oak group include red oak (*Q. rubra* L.), black oak (*Q. velutina* Lam.), pin oak (*Q. palustris* Muenchh.), and scarlet oak (*Q. coccinea* Muenchh.), and are easily recognizable by the bristle-tipped lobes on their leaves, although they are often difficult to distinguish from one another (Farrar, 1995). Trees in the white oak group have rounded leaf lobes and are distinguishable from one another by twig and leaf characteristics. Species found in Canada in the white oak group include bur oak, white oak (*Q. alba* L.), swamp white oak (*Q. bicolor* Willd.), and English oak (Q. *robur* L.). Species in the red oak group have been observed to be more susceptible to the harmful effects of drought and defoliation than those in the white oak group (LeBlanc, 1998; Sinclair et al., 1987; Starkey and Oak, 1989).

2.2.2 Biology of *Q. macrocarpa*

Bur oak is a slow-growing, moderately shade-tolerant tree (Farrar, 1995), and can bear seed between the ages of 35 to 400 years (Johnson, 1990). Under favourable growing conditions, bur oak is a long-lived species, and specimens of 300 years old (Wolfe, 2001) and even 500 years old (Hildahl and Benum, 1987) have been reported in Manitoba. It is considered to be drought-resistant, relatively flood-intolerant and is often found on sandy and loamy prairie soils and well-drained bottomlands. Bur oak can tolerate a range of soil conditions and depths, and is common on riverbanks but only above the frequently flooded zone, as well as near the forest-prairie boundary (Johnson, 1990; St.George and Nielsen, 2003; Weaver and Kramer, 1932). Its native range is roughly triangular in shape, extending from southeastern Saskatchewan to south Texas to southern Quebec (Johnson, 1990) (Figure 1).

Bur oak is monoecious and dichogamous, and female flowers are frequently fertilized by cross-pollination over long distances, thus promoting genetic variability within and among stands (Dow and Ashley, 1998). Acorns, the bur oak fruits, ripen within the growing season and are produced in variable numbers from year to year (Dow and Ashley, 1998; Farrar, 1995; Johnson, 1990). Acorns are dispersed by gravity, squirrels (Johnson, 1990), and birds (Darley-Hill and Johnson, 1981), over distances greater than 90 m (Dow and Ashley, 1996).

Measurements on bark thickness on mature bur oak vary between 4-6 cm (Szafoni et al., 1994). This thick, corky bark is fire-resistant, allowing bur oak to survive periodic prairie fires that eliminate competing species (Farrar, 1995). Prior to European settlement, oaks in North America grew in uneven-aged stands (Abrams, 1995, 1996; Loewenstein et al., 2000) and depended on fire to create conditions favourable for regeneration.

The growth rate of bur oak is variable depending on tree characteristics and environmental conditions. In a forest plantation of bur oak in Iowa ranging from 10 to over 56 cm in trunk diameter at breast height (DBH), Johnson (1990) reported typical radial growth rates, including bark, of between 1.5-2.8 mm/year. Szafoni et al. (1994) reported that four open-grown specimens with large canopies and short trunks in Illinois increased in radius at a rate of 5-7 mm per year, excluding bark. The sturdy structure required for support against wind forces in open-grown trees allows for their deposition of wider annual rings than taller forest-grown bur oaks, which can be double the age of open-grown oaks of the same size (Szafoni et al., 1994). Typical radial growth in bur oak in Manitoba is between approximately 0.7-2.0 mm/year (Boone, 2003; St.George and Nielsen, 2002; Wolfe, 2001).

The root system of bur oak is known to be a deep and wide-spread anchoring and absorption structure that allows for survival in dry environments. Weaver and Kramer (1932) studied a 65-year-old bur oak in eastern Nebraska, 11.43 m in height, and 35.6 cm in basal diameter and found it had a rooting depth of up to 4.3 m, and a lateral spread of up to 18 m. The main vertical root (the taproot) gave rise to at least thirty main lateral branches within the first 0.6 m of soil, and most extended widely (6-18 m) before turning downwards and forming other taproot-like structures. The entire A horizon within 3.7 m of the trunk was occupied with fine, absorbing roots, the bulk which were found near the surface of the soil, an observation also noted by McVickar (1949). At increasing distances many metres from the trunk, soil still contained numerous absorbing roots, but in less concentration as roots from other trees provided competition. The mass of the entire root system was estimated to be greater than that of the above-ground portion of the tree, including leaves, but only 90% of the volume (Weaver and Kramer, 1932).

2.3 Tree Decline

On a broad scale, tree decline is a sign of poor forest health. Healthy forests are by definition sustainable (Ciesla and Donaubauer, 1994), and their condition is governed by many factors, including climate, site conditions, effects of fire and pests, and management practices.

Tree decline is a complex phenomenon that threatens forest sustainability, and can be described as "an episodic event characterized by premature, progressive loss of tree and stand vigour and health over a given period without obvious evidence of a single clearly identifiable causal factor such as physical disturbance or attack by an aggressive disease or insect" (Ciesla & Donaubauer 1994). Rather than originating from a single causal agent, decline is a result of a complex of factors acting on trees resulting in a loss of vigour (Houston, 1992; Luisi et al., 1993; Manion, 1981a; Wargo, 1981).

The noticeable damage caused by decline and questions about its causes have warranted ambitious global study in many tree species since approximately 1975. Nevertheless, in many cases the factors responsible for specific declines remain unknown (Ciesla and Donaubauer, 1994).

2.3.1 Tree Death

Tree death is natural and normal and plays an important ecological role as it allows resources contained in tree structures to be returned to the ecosystem (Franklin et al., 1987). In general, trees die when they are unable to acquire or mobilize adequate amounts of resources to heal injuries or perform other operations necessary to sustain life (Waring, 1987). Despite the ecological importance of tree death, its complex patterns and causes are not well understood (Bigler and Bugmann, 2003; Franklin et al., 1987). Attempting to explain a tree's death based solely on its current environment and recent condition will most often lead to incorrect conclusions (Pedersen, 1998). Factors that affected trees for decades prior to death must be considered if the true reasons for mortality are to be understood.

The effect of age on tree death and vigour is also not well understood. Molisch (1938) proposed that trees growing in favourable environments have the potential to be immortal, and must be killed by an external agent. However, it appears that age alone can cause a decrease in vigour that allows trees to be more vulnerable to pathogens (Franklin et al., 1987), with the critical age depending on the species of the tree and its growing conditions (Hyink and Zedaker, 1987).

Evidence exists that in some species, tree size, specifically DBH, is a more reliable predictor of tree death than age (Harcombe, 1987). Kramer and Kozlowski (1979) concluded that large trees with complex crowns exhibit a decrease in metabolism and growth and are more susceptible to pests and unfavourable environmental conditions. Although large trees tend to be older than small trees, this is not always the case (Szafoni et al., 1994) and therefore the effects of age and size can be confounded (Harcombe, 1987).

2.3.2 Decline Symptoms

In most species, healthy trees generally have fairly symmetric crowns with branches occurring in a predictable manner along the main stem (Waring, 1987). Therefore, abnormalities in crown structure can be indicators of stress (Waring, 1987). By definition, symptoms of decline appear progressively, and may include decreased radial growth, shortened internodes, root necrosis, premature fall colouring, sprouting from adventitious buds (epicormic shoot production), dieback of branches in the upper crown, and increased infection from root rotting organisms such as *Armillaria* species (Kessler, 1989; Manion, 1981a; Wargo et al., 1983). Foliage may be undersized, distorted, chlorotic, and marginally necrotic. Abnormally large crops of fruits, termed “distress crops” are often produced (Sinclair and Hudler, 1988), and mycorrhizal associations may be reduced (Causin et al., 1996; Kessler, 1989).

Dieback and epicormic shoot growth are often the most conspicuous symptoms of decline. As a survival response to stress, declining trees produce as much leaf tissue as possible on a minimum of stem tissue (Houston, 1973). Stems can also die back because they are girdled by wood-boring insects or wounds.

Root necrosis is common in declining trees, and may occur before crown symptoms are visible in oaks (Jacobs et al., 1993; Thomas and Hartmann, 1996; Vincent, 1991). Staley (1965) found that 77% of fine roots were necrotic in declined oaks, 37% were dead in oaks showing early signs of decline, and only 5% were necrotic in healthy oaks. Thomas and Hartmann (1996) found necrotic fine roots only in severely declined oaks. Root decay was observed in declining urban sugar maples (*Acer saccharum* Marsh.), even in favourable rooting environments (Ruark et al., 1983).

2.3.3 Decline as a Disease

Manion (1981a) defined plant disease as "any deviation in the normal functioning of a plant caused by some type of persistent agent". Agents can be biotic or abiotic, but must be "persistent" to differentiate disease from injury.

Most forest pathologists consider tree decline to be a distinct class of disease brought about by a combination of stressful factors, and often the term "decline" is associated with progressive disorders that are at least partially unexplained (Sinclair & Hudler 1988). A common characteristic in cases of tree decline is a link with different forms of environmental stress that leave the trees vulnerable to attack by organisms they normally could resist (Houston 1974).

Manion (1981a) created a widely accepted model for tree decline by classifying damaging elements into three groups: predisposing, inciting, and contributing factors. **Predisposing factors** are long term, chronic or slow-changing environmental factors including climate, air pollution, site conditions such as soil compaction or fertility, and tree characteristics such as genetic potential and age that weaken plants growing in suboptimum sites (Manion, 1981a). **Inciting factors** are those that are more acute or short term in duration such as defoliation, drought, frost, and mechanical injury. These events often cause drastic injuries and trigger further weakness and vulnerability in trees. Trees may attempt recovery after inciting factors have occurred but are often prevented because of the effects of predisposing stresses (Manion, 1981a). The recovery effort depletes the tree's energy reserves and compromises its defence systems, creating vulnerability to agents that ultimately may cause more damage than the inciting factors, known as the **contributing factors** (Sinclair and Hudler, 1988). These factors are conspicuous, biotic, and often the final cause of death. However, they are frequently falsely blamed as being solely responsible for tree death instead of indicators of more prolonged stresses (Manion, 1981a). Wood-boring beetles, canker fungi and root-decay fungi are all examples of contributing factors. The combined effects of sequential predisposing, inciting, and contributing factors can be described as a conceptual downward "spiral" of interactions leading to tree death (Manion, 1981a).

Manion (1981a) stated that at least one factor from each of the three categories of predisposing, inciting and contributing stresses must be present for decline to occur. However, Houston (1992) hypothesized that inciting factors are not always necessary to trigger decline, as predisposing factors alone may cause sufficient physiological changes in trees, leaving them open to attack by contributing factors. Sinclair and Hudler (1988) proposed that decline could occur from chronic irritation from a single component in the environment, such as a toxin or nutrient deficiency. Factors causing tree decline may vary with each occurrence, and site-specific research is needed to understand individual cases of decline.

2.4 Oak Decline

Oak decline was reported in the literature as early as 1739 in Germany (Hartmann and Blank, 1992) and 1901 in North America (Jensen, 1901). Since then, oak decline has been reported in all major North American, and some European, *Quercus* species in their native ranges (Wargo, 1993), although there are strong regional differences in causal factors (Luisi et al., 1993). Oak decline has been reported both in forest environments (Boone, 2003; LeBlanc, 1998; Nichols, 1968; Oak et al., 1991; Pedersen, 1998; Phipps and Whiton, 1988; Standovar and Somogyi, 1998; Starkey and Oak, 1989) and in urban settings (Allen and Kuta, 1994; Houston, 1974; Ware, 1970; Ware, 1982; Ware and Howe, 1974). Similar to the general model for tree decline, the causes of oak decline can be classified into predisposing, inciting, and contributing factors.

2.4.1 Predisposing Factors

2.4.1.1 Site Factors

Shigo (1985) stated that "trees either grow on suitable sites, adapt to unsuitable sites, or die". Decline tends to affect trees growing in environments on the periphery of their specific site tolerances (Manion, 1981a), a common scenario in forestry operations and urban landscapes where oaks are desirable and often planted despite unsuitable growing conditions. Alternatively, environmental stress can occur when growing areas are modified around existing oaks. Site factors are especially important in oak decline because they drastically influence the effects of climate (Fritts, 1960; Siwecki and Ufnalski, 1998); for example drainage varies with soil texture, slope, and other factors. Site quality has been linked to oak decline in previous studies (Boone, 2003; Kegg, 1973; Oak et al., 1996; Phipps and Whiton, 1988; Standovar and Somogyi, 1998; Starkey and Oak, 1989) as well as decline in other species (Hager et al., 1993; Horsley et al., 2000; McClenahen and McCarthy, 1990).

2.4.1.1.1 Soil

Successful uptake of water and nutrients by trees depends on their availability in the soil and the tree's ability to absorb them (Dyer and Mader, 1986; Kozlowski et al., 1991). Absorption potential is determined by the size, architecture, and vitality of the root system, which are largely influenced by the soil environment (Weaver and Kramer, 1932). Increasingly unfavourable soil conditions can have an exponential negative effect on tree health after damage to the fine root system has already begun, as a tree's dependence on each remaining live root rises with increasing damage to the root system. In suppressed trees it is inevitable that root growth will be inhibited. This in turn decreases uptake of water and minerals resulting in further growth retardation (Kozlowski and Peterson, 1962).

Tree roots near the soil surface are more vulnerable to physical damage, soil compaction, temperature stress and competition from aggressive root systems of plants such as turf grasses, which can predispose the trees to decline

(Houston, 1974; Jensen, 1901; Pomerleau and Lortie, 1962; Staley, 1962; Staley, 1965). Soil depth and texture can determine root depth, as heavy clay or shallow soil forces trees to concentrate their root systems near the soil surface to accommodate limitations in space and aeration (Houston, 1974). Shallow, clay-panned soils were a predisposing factor in the decline of scarlet, red, and white oak, but not bur oak in southeastern Wisconsin (Jensen, 1901). Low soil sand content was associated with sugar maple decline in Massachussets (Dyer and Mader, 1986; Ruark et al., 1983). Oak mortality was found to be greater on sites with shallow, gravelly soil because its low water retention forced trees to be dependent on rainfall for water supply, and thus more vulnerable to drought (Oak et al., 1996; Starkey and Oak, 1989).

Clay soil may also be detrimental to oaks because it shrinks and expands depending on its moisture content. This causes cracks in the soil that expose and (or) damage fine absorbing roots (Allen, 1993). Soils in the urban environment often have a higher clay content than normal, as surface and deeper materials are mixed during urban development, bringing very dense C-horizon clay into the rooting zone (Evans et al., 2000; Ware, 1980).

Compaction of soil around trees can cause major physical damage to the existing fine root system, and slow growth of new roots because of mechanical impedance, reduced aeration and decreased water infiltration (Craul, 1994; Gerard et al., 1972; Glinski and Stepniewski, 1985; Hopkins and Patrick Jr., 1969; Ruark et al., 1983; Sinclair et al., 1987; Vepraskas, 1994). Soil compaction, which was suggested as the cause of reduced starch levels in roots of oaks in heavily used campsites compared to those in undisturbed sites (Kalisz and Brown Jr., 1976), has been linked with decline of bur oak (Chapman, 1915) and other oak species in Europe (Amorini et al., 1996). Compaction is a common occurrence in the urban environment from the effects of construction and vehicular and foot traffic (Randrup and Lichter, 2001; Ruark et al., 1983; Ware and Howe, 1974), as these and other urban factors disrupt the renewing process in which a favourable rooting environment is maintained. Decline of urban sugar maple was associated with high soil bulk density (Dyer and Mader, 1986).

Poor soil aeration may be a factor causing decline in species of oak (Gaertig et al., 2002) and maple (Dyer and Mader, 1986). Besides compaction, poor aeration can occur from inadequate drainage, raising the soil grade, and covering the soil with construction materials such as piles of soil or gravel (Ware and Howe, 1974). Concrete and asphalt soil coverings may also reduce soil aeration, and have been linked with decline in maple (Hubbard and Morton, 1977; Mycek, 1978). Poor aeration often prevents tree roots from occupying soil under paved roads (Van Camp, 1961), and this can severely limit the available soil space for trees in the urban environment.

The absence of natural soil covering around city trees is also a predisposing factor in decline, as removal of natural forest mulch leaves soil exposed to high temperatures from the sun, which can limit root growth or injure existing roots (Kozlowski, 1955). Fluctuations in soil temperature and moisture may be the most detrimental factors to the development of oak fine root systems in the urban environment (Johnson, 1977). Applying artificial mulch can be helpful in preventing or reducing this problem, as bur oak has responded positively to such mulching (Truax and Gagnon, 1993). In the urban environment, healthy white oaks in lawn situations and those disturbed by construction activities showed significant improvements in radial growth and depth of fine roots when woodchip and forest litter mulches were applied on the soil surface and in feeder holes (Struss, 1981). However, these changes were not effective in improving declined oaks, which seemed unable to capitalize on the amended soil conditions, possibly due to low carbohydrate reserves (Struss, 1981).

Soil fertility may be important in tree decline, as it can affect overall tree health. Foliar nutrient levels are thought to be fairly indicative of the nutrient availability in the soil and the absorbing power of the tree's root system (Mitchell, 1936); thus, foliar analysis is often used to detect potential soil problems (Dyer and Mader, 1986; Kozlowski et al., 1991). Mader and Thompson (1969) found that declined sugar maples had lower foliar N levels than their healthy counterparts, and fertilizing the trees led to more drought tolerance, perhaps because of an increase in root system development (Houston, 1973; Mader and Thompson, 1969). However, a comparison of foliar and soil nutrient levels in white oak revealed that foliar levels were very similar on a range of different soils, indicating that white oaks are efficient at foraging for essential nutrients, even on poor soils (McVickar, 1949). Jacobs et al. (1993) found no significant difference in foliar nutrient content between healthy and declined cork oak (*Q. suber* L.) trees in Europe.

2.4.1.1.2 Pollution

Several studies have linked the presence of industrial pollutants such as ozone and sulphur dioxide with decreased growth in oaks (Carlson, 1979; McClenahen, 1983; McClenahen and Dochinger, 1985; Reich et al., 1986), although they are not considered to be conclusive evidence for the harmful effects of air pollutants on oak forests (Kessler, 1989; Siwecki and Ufnalski, 1998; Smith, 1987). In Europe, the concentrations of toxic metals in leaves and roots, along with soil acidity were significantly higher in declining oaks than in healthy trees (Siwecki and Ufnalski, 1998), and a relationship between high copper content and poor wood and tree vitality was found in oaks in Poland (Opydo, 1994).

Bur oak is considered to be fairly tolerant of pollutants such as sulphur dioxide and nitrous oxide (Johnson, 1990); therefore, exhaust fumes in the urban environment are unlikely to be a predisposing factor in bur oak decline. This is supported by a recent study in southeastern Manitoba where emissions from a coal-fired generating station were found not to be responsible for regional bur oak decline (Boone, 2003).

Application of deicing salt to roads in the winter may be a predisposing factor in oak decline (Kessler, 1989), and has also been linked to urban maple decline (Dyer and Mader, 1986; Ruark et al., 1983; Westing, 1966). Salt is damaging because not only is it toxic in high concentrations in plant tissue (Kozlowski et al., 1991), it prevents uptake of essential nutrients such as Ca, Mg, and K (Westing, 1966) and has a negative effect on soil structure resulting in higher bulk density (Bohn et al., 1979).

In the urban environment, application of lawn herbicides is harmful to oak roots (Ware, 1970; Ware and Howe, 1974). The main chemicals used in lawn care are 2,4-D, dicamba and mecaprop, which are all group 4 herbicides that attack broadleaved plants, including trees (Manitoba Agriculture and Food, 2001). Therefore, bur oak may be predisposed to decline when exposed to lawn herbicides.

2.4.1.1.3 Competing Vegetation

Turfgrass is the main kind of vegetative ground cover found in the urban environment and is considered detrimental to oaks for several reasons. Firstly, it has a very competitive root system that can outcompete those of oaks (Ware, 1970), and secondly it is unable to insulate the oak roots from temperature fluctuations as effectively as forest litter (Ware, 1970). Thirdly, turfgrass is also related to other unfavourable factors, such as increased soil compaction from mowing and traffic, and harmful lawn herbicides (Ware, 1970).

Competing trees may also affect tree health, as they were shown to account for 50% of the variability in annual radial growth of Norway spruce (*Picea abies* L., Bigler and Bugmann, 2003). Even surrounding trees of the same species can be stressful, as oak decline in the southeastern USA was more severe in stands with a high percentage of oak trees (Oak et al., 1996). When groups of trees of the same species grow together, they all compete for the same resources; therefore, species self-thinning occurs as the weakest specimens die off with the increasing resource demands of dominant trees (Spurr and Barnes, 1980). Removing nearby trees in an oak forest may not be a simple solution to this problem because the remaining oaks are not physically adapted to withstand the forces of wind, and the remaining soil will be unsheltered (Ware and Howe, 1974).

Vigorous competing vegetation has been a stress for oaks in North America. Fire exclusion by European immigrants has allowed competitive shade-tolerant understory species to survive and suppress growth of oak seedlings, causing oak recruitment to suffer in the 20th century in eastern USA (Abrams 1995, 1996). Shade-tolerant vegetation can eventually replace the oaks if burning does not occur (Lorimer, 1984; Lorimer et al., 1994; McCune and Cottam, 1985).

2.4.1.2 Tree Characteristics

As was the case with tree death, decline generally occurs in trees in their mature, reproductive growth stages, as opposed to the juvenile stage where there is more recuperative ability (Manion, 1981a; Ware, 1982). Increased age and/or size may cause a decrease in vigour depending on a tree's growing conditions (Franklin et al., 1987; Hyink and Zedaker, 1987; Kramer and Kozlowski, 1979; Sinclair et al., 1987; Westing, 1964). For example, digging ditches to improve soil drainage around mature English and sessile oaks on waterlogged soils in France led to a decrease in annual growth ring widths of oaks over 110 years in age, but increased the growth of younger trees (Becker et al., 1996). Tainter et al. (1988, 1990) found that oaks in the southern USA classified as "declined" were slightly older than their healthy counterparts. Sonesson (1999) and Oak et al. (1991, 1996) reported that frequency of decline increased with tree age in Sweden, and the southeastern USA, respectively. In Winnipeg, it has been noted that older oaks seemed to be more affected by decline than younger specimens (Allen, 2000). In other studies, however, age could not be linked with oak decline (Dujesiefken and Balder, 1991; McClenahen, 1983; Phipps and Whiton, 1988).

There is a natural decrease of annual growth ring width in bur oak with age, commonly due to changes in the competitive dynamic between trees (Phipps and Whiton, 1988), but also because the incremental volume of wood produced each year must be distributed over a larger surface area as the tree's circumference grows (Hyink and Zedaker, 1987). Szafoni et al. (1994) found that ring widths of seven open-grown bur oaks in an Illinois prairie grove had been gradually decreasing within the past three decades for no known reason except for increasing tree age. St. George and Nielson (2002) also found a gradual decrease in ring width in bur oak, and attributed it to natural age-related growth change.

Resistance or susceptibility to oak decline is also at least partly under genetic control, although it is likely a complex trait (Hertel and Zaspel, 1996; Steiner, 1995). Nevertheless, some oaks seem to be more genetically suited to withstand adversity, and poor genetic potential is a predisposing stress in oak decline. Improper management practices, such as having low genetic diversity in a population may have unintended consequences that could favour the development of oak decline (Steiner, 1995).

2.4.2 Inciting Factors

2.4.2.1 Drought and Flooding

Moisture deficits or excesses can both be considered as either predisposing or inciting stresses, depending on their severity and frequency. However they are most often classified as inciting factors. Drought has a negative effect on trees, causing problems such as a reduction in photosynthesis, depleted carbohydrate reserves and secondary metabolites (i.e. defence compounds), eventually resulting in a loss in canopy volume (Landsberg and Wylie, 1983). Biochemical changes caused by drought and defoliation may make trees vulnerable to attack by contributing factors (Houston, 1973). Moisture excess is harmful to trees as it decreases soil aeration and smothers root systems (Ware and Howe, 1974). Moisture deficits and excesses may be caused by precipitation levels, site factors, root disturbances, or a combination of these factors (Griffin et al., 1993).

Many studies have linked oak decline with preceding periods of dryness (European and Mediterranean Plant Protection Organization, 1990; Fergus and Ibberson, 1956; Hursh and Haasis, 1931; Jensen, 1901; LeBlanc, 1998; Oosterbaan and Nabuurs, 1991; Pedersen, 1998; Siwecki and Ufnalski, 1998; Staley, 1965; Starkey and Oak, 1989; Tainter et al., 1988; Tainter et al., 1990; Tainter et al., 1983; Vannini et al., 1993). For example, Jensen (1901) blamed decline in several oak species in southeastern Wisconsin on a severe drought from 1893 to 1895, and an especially cold and dry winter in 1898-1899. However, reports of the effects of drought do not always agree, as Nichols (1968) concluded that drought was not a major factor in oak decline in Pennsylvania, and that its effect was approximately equal to that of a moderate defoliation, causing no more than a 30% reduction in growth from normal in dry years.

Drought has also been a major inciting factor in oak decline in Europe, with reports from France, Germany, Romania, and Poland (Siwecki and Ufnalski, 1998). In one study, declined oaks in Europe were shown to have lower leaf water contents even when precipitation was not limiting, suggesting that the declined oaks had damaged root systems and were more vulnerable to drought than healthy trees (Thomas and Hartmann, 1996).

Tainter et al. (1990) provided an example of oaks attempting to recover from inciting stress in the southern USA. Tree basal area increment (BAI) patterns were compared in red oaks classified as either “healthy” or “declined” based on crown dieback levels, and it was concluded that declined trees were actually a part of a population of oaks that were weakened by a series of short-term droughts in the 1950s. Because of this, the oaks were more susceptible to the damaging effects of short-term droughts in the years post-1950 and thus appeared declined in the 1980s. Both health categories showed decreased post-drought BAI values but it was not clear why certain trees were more damaged by the droughts than others.

Trees in the urban environment may be more susceptible to drought because compacted urban soils lead to poor water infiltration and shallow root systems. In addition, urban trees may have higher transpiration demands as they are exposed to additional sunlight reflected from buildings and high albedo ground coverings such as pavement, as well as increased heat from city life (Craul, 1999).

Moisture excess was reported to incite decline in thousands of mature oaks in Illinois after two years of unusual springtime precipitation (Ware, 1982), and also in Romania, where oaks were surrounded by standing water from melting snow (Siwecki and Ufnalski, 1998). Flooding was implicated in the decline of an oak stand north of Winnipeg after the construction of a nearby road impeded natural drainage patterns (Boone, 2003). Water excess was also blamed for decline of English oaks in the Netherlands, as decline was more severe in areas where water tables were high in the spring, leading to an overload of moisture during the growing period (Nabuurs, 1991; Oosterbaan, 1991). Standing water is especially detrimental on clay soils, which generally have poor internal drainage (Kight, 1988; Wargo et al., 1983).

2.4.2.2 Defoliation

Defoliation, particularly from insect damage has been a major inciting factor in oak decline (European and Mediterranean Plant Protection Organization, 1990; Sinclair et al., 1987) and maple decline (Horsley et al., 2000). Nichols (1968) described that mortality of oak in Pennsylvania was most often preceded by defoliation by either insects or late spring frost, which can also damage expanding leaves (Balch, 1927; Beal, 1926).

Defoliation early in the season just after shoots have finished expanding has more of an impact on tree health than late-season damage, as it can initiate a second flush in growth before the original crown can become photosynthetically active and able to replenish depleted energy reserves (Sinclair and Hudler, 1988; Waring, 1987). For example, McLaughlin et al. (1980) found that white oak uses 30% of its stored carbohydrate reserves to grow its canopy in the spring, and levels are replenished through photosynthetic activity by the end of June. Therefore if defoliation was to occur before carbohydrate reserves were recovered, the energy necessary to produce a second flush of growth would cause a severe depletion in stored carbohydrate reserves and thus leave the trees vulnerable to other stresses.

The gypsy moth (*Lymantria dispar* L.), is a defoliating insect that was accidentally introduced from Europe and became a major pest on oaks in the northeastern USA in the early 20th century (Baker, 1941). Defoliation by the gypsy moth has been implicated as an inciting factor in many cases of oak decline (Dunbar and Stephens, 1975; Kegg, 1973; Wargo, 1977). Consistent with the properties of an inciting factor, it was observed that while a single, complete defoliation event would cause a reduction in the annual radial growth for that year, it was rarely solely responsible for killing oaks (Baker, 1941). The gypsy moth is presently established in some eastern regions of Canada, but not in Manitoba (Canadian Food Inspection Agency, 2003).

2.4.2.3 Disturbance

When humans enter a forested area, most activities involved in the process of urbanization result in an unfavourable alteration of a tree's natural environment (Howe, 1974; Root, 1974; Sinclair et al., 1987; Wargo et al., 1983). Oaks do not "domesticate" well, especially if environmental changes are sudden (Ware, 1970), possibly from slow root growth and regeneration following disturbance (Struss, 1981). Disturbances from urban development may be predisposing or inciting factors depending on their severity, and they include excavation, soil compaction, soil covering, alteration of drainage patterns (Ware and Howe, 1974), changes in soil grade or composition and microflora, disruption of surrounding vegetation including turfgrasses and other trees, and the removal of forest groundcover (Rockwell, 1976; Shigo, 1985; Sinclair et al., 1987). Excavation and soil tilling or mixing may be powerful inciting factors as they not only sever roots, but also expose those remaining to atmospheric conditions, which can quickly be fatal to delicate absorbing oak roots (Struss, 1981). Regeneration of damaged oak roots can be stimulated by applying auxin sprays to freshly cut root tissue (Lumis, 1982). Raising the soil grade has been reported as having a smothering effect on tree roots (Ware and Howe, 1974). However, a 20 cm compacted raise in soil grade had no effect on white oak growth or physiology over three years (Day et al., 2001).

2.4.2.4 Wounding

Trees respond to wounds by compartmentalizing healthy wood from dead and damaged tissue to prevent the spread of infection (Shigo, 1985). However, this process renders the compartmentalized tissue no longer functional, girdling a portion of the tree's xylem and phloem, and if severe enough can be fatal within one year (MacKinney and Korstian, 1932). Trunk wounds can reduce tree longevity, and wounded trees can "starve" even if environmental factors are not limiting, simply due to a lack in conduction ability (Shigo, 1985). Even minor surface wounds can be very damaging to oaks as nutrient transport occurs in a layer of phloem tissue 0.2 mm thick just beneath the bark surface (Holdeheide, 1951), adjacent to the outermost 1-2 annual rings that handle the water conduction in bur oak (Kozlowski and Winget, 1963).

Trees in the urban environment are more likely to sustain wounds than undisturbed forest trees simply from increased human activity, particularly lawn mower damage. A series of minor trunk wounds can be severe enough to incite oak decline and make trees vulnerable to contributing factors by triggering the release of volatile compounds attractive to damaging insects (Haack and Benjamin, 1982).

2.4.3 Contributing Factors

In North America there are two main contributing factors to oak decline: a wood-boring insect named the two-lined chesnut borer (*Agrilus bilineatus* Weber) and *Armillaria* root-rotting fungi (Haack and Benjamin, 1982; Nichols, 1968; Wargo, 1996; Wargo et al., 1983). The relationship between these two damaging agents is well-documented, as they are often found together in high levels on weakened oaks, but are absent or found separately causing only mild damage on healthy oaks (Chapman, 1915; Dunbar and Stephens, 1975; Haack and Benjamin, 1982; Houston, 1973; Sinclair et al., 1987; Ware, 1982; Wargo, 1977; Wargo et al., 1983). They are natural, ever-present organisms in the ecosystem, serving the purpose of roguing out weak trees and decomposing dead trees (Wargo, 1996). They are difficult to control because trees dying from normal competitive forces provide a constant supply of substrate that allows sufficiently high pest population levels to be maintained so that vigorous trees can be attacked when stressed (Wargo, 1996). These organisms are typically the direct cause of death in declining trees, and attempting to eliminate them in visibly-declined specimens is generally futile in preventing tree death because major damage to the trees has often occurred past the point of recovery (Manion, 1981a). Contributing factors may be more important in the decline of urban trees than forest trees, as urban trees are generally more stressed by their environments (Houston, 1985).

2.4.3.1 The Two-Lined Chestnut Borer

The two-lined chestnut borer (*Agrilus bilineatus* Weber, Coleoptera: Buprestidae), is a beetle that attacks oaks by consuming foliage in its adult stage and boring through xylem and phloem tissue in its larval stage, preventing transportation of water and nutrients in the trees. The larvae thrive best in living oak tissue, therefore infestation begins in the upper crown and proceeds downward as tree tissue is killed by girdling. This girdling effect is generally linked to the eventual mortality of declining oaks (McClenahen, 1995; Nichols, 1968) and normally leads to tree death after two to three years of infestation, a time frame consistent with the effects of mechanical girdling in oaks (MacKinney and Korstian, 1932). However, in the case of a severe attack, an oak may die within a single growing season (Haack and Benjamin, 1982). Trees with reduced radial growth may be especially vulnerable to major damage by the two-lined chestnut borer, as thinner growth rings are more likely to be completely girdled by borer galleries (Cote, 1976).

The two-lined chestnut borer prefers oaks as host trees, although it may attack other hardwood species when oaks are not available. Adults are naturally attracted to feed and oviposit on stressed oaks over their healthy counterparts, based on root starch measurements (Haack and Benjamin, 1982). When offered foliage of eight hardwood species in a bioassay, adult beetles consumed significantly more bur oak foliage than that of white oak, black oak, red oak, and four other non-oak species (Haack and Benjamin, 1982), and the beetle has been observed in declining bur oaks in Winnipeg (Allen and Kuta, 1994). The two-lined chestnut borer was identified as a major causal factor in oak decline in

Pennsylvania (Dunbar and Stephens, 1975). It was also found in 89% of recently dead oaks, but less than 10% of living oaks, in the Ohio River Valley (LeBlanc, 1998), and over 60% of dead oaks in the Midwestern USA (Pedersen, 1998).

There is currently no viable chemical control available for the two-lined chestnut borer (Allen and Kuta, 1994; Hashemi, 2004). Feasible population management lies in minimizing the amount of substrate available to the beetles by removing weakened or dying oaks (Allen and Kuta, 1994). They are the most effective hosts for the borer because larvae generally require living tissue to survive (Chapman, 1915). Many slowly-dying trees remain in the urban environment because homeowners do not want to cut down specimens that show any signs of life, as they are hopeful for recovery, however unlikely it may be in severely declined oaks (Chapman, 1915). The optimum time for removing infested oaks is in the summer (mid to late July), as this promotes rapid drying of wood tissue, thus killing larvae and preventing adults from emerging (Haack and Acciavatti, 1992). To a lesser extent, oak firewood, if not properly dried, has a capacity to host the two-lined chestnut borer (Allen and Kuta, 1994), and should be debarked, or covered before storage.

2.4.3.2 *Armillaria* Root Rot

Armillaria root rot, caused by fungi in the genus *Armillaria*, is one of the most damaging diseases of forest and ornamental woody plants in the world

(Sinclair et al., 1987), with over 600 host species, mainly woody angiosperms and gymnosperms (Raabe, 1962). *Armillaria*'s ecological role is to provide selection pressure against weak trees and decompose woody material after tissues or whole plants have died (Kile et al., 1991; Wargo, 1996). The disease is common in the Canadian prairies, and Manitoba contains at least three *Armillaria* species (Mallett, 1992).

Armillaria root rot kills trees by invading and consuming their root systems and lower boles, disrupting the transport of water and nutrients from the soil to the crown (Sinclair et al., 1987). Both defoliation and drought cause a depletion in tree root starch and an increase in reducing sugars, favouring *Armillaria* growth (Houston, 1973; Wargo, 1981; Wargo, 1996). Wargo (1977) found that in Pennsylvania, the roots of most dead and dying oaks were colonized by *Armillaria* after defoliation by the gypsy moth. Since then, there have been reports of oak decline both with (Bruhn et al., 2000) and without *Armillaria* (Stringer et al., 1987) in the USA. The only available control method available for *Armillaria* is to keep trees in a vigorous condition (Manion, 1981a).

2.5 Statistical Analyses Used in Decline Studies

Depending on experimental design and data structure, several statistical methods can be used in decline studies to compare conditions surrounding healthy and declined oaks. These range from simple univariate methods like analysis of variance (ANOVA) to more complex multivariate methods.

2.5.1 Multivariate Methods

Multivariate statistical methods enable multiple variables for a set a objects to be analyzed simultaneously, and can be used to find groups of similar objects or variables (Manly, 1994). In other words, multivariate analysis is an examination into the structure of interrelationships among more than one variable (Huberty, 1994). This interactive form of analysis is especially valuable in environmental studies where variables, by nature, tend to be interrelated.

2.5.1.1 Multiple Regression

When decline symptoms are rated on a quantitative scale, associated factors can be identified by performing correlation analysis or multiple regression among symptom severity, site factors, and/or climatic variables. Using this approach, Oak et al. (1996) found that site and stand factors explained 22-65% of the occurrence of oak decline in various sites in the southeastern USA. These R^2 values were relatively low, but that is not surprising, as tree decline is caused by a complex of factors (Ciesla and Donaubauer, 1994).

2.5.1.2 Multiple Discriminant Analysis

Multiple discriminant analysis (MDA) is a multivariate method used to examine variables in data sets where objects are classified into predefined groups. The objective of MDA is to interpret variable combinations associated with group differences (Huberty, 1994) and identify important discriminating variables (Manly, 1994).

Oak et al. (1996) used MDA to find site and stand factors linked with oak decline in the southeastern USA and develop a decline risk-rating system for the area. MDA was used as a supplement to ANOVA in a study on declining sugar maple in urban areas of Massachusetts (Dyer and Mader, 1986). Variables studied included average 20-year tree growth rate, soil properties, and foliar nutrient status data for four groups of trees grouped according to their decline status and proximity to roadways. ANOVA found significant differences in nine variables among the groups; however MDA revealed that only high soil Na and low sand content were important group discriminators when all variables were considered together. This demonstrated the potential limitations of using univariate analysis techniques that rely on a single variable at a time in a data set where variables are interactive, and the problem was multivariate (Orloci, 1978). There are also other studies that have used multivariate methods to assess the importance of predisposing site factors for tree decline (McClenahen and McCarthy, 1990; McCracken et al., 1990; Oak et al., 1996; Ruark et al., 1983).

2.6 Dendrochronology

Ring-porous woody species such as those belonging to the genera *Ulmus*, *Fraxinus*, and *Quercus*, produce vessel cells of decreasing size during the growing season as available moisture becomes limiting (Fritts, 1976). This phenomenon creates a visual boundary between wood cells produced from year to year and forms the appearance of annual growth rings when viewed in cross section. As a *Quercus* species, bur oak is ring-porous and forms distinct annual rings (St.George and Nielsen, 2000).

Dendrochronology is a science that recognizes trees as "biological legacies" of their environments (Lewis, 1995) by using ring width patterns (Fritts, 1976), chemical compositions (Levy et al., 1996), and anatomical features (St. George and Nielsen, 2000; St. George and Nielsen, 2003; St. George et al., 2002; Woodcock, 1989) to study past growing conditions such as climate, environmental disturbances, and soil properties. There is some evidence that dendrochronology may even be used to predict future environmental conditions and crop yields (Kairiukstis et al., 1990).

Annual ring width is a function of many factors, including available moisture, temperature, and disturbance. Cook (1990) described a tree's observed ring pattern as an aggregate of several unobserved series: (1) the age-size related trend in ring width, (2) the climatically related environmental signal, (3) disturbance on a localized scale, (4) standwide disturbance, and (5) the unexplained year-to-year variability not related to other signals. Depending on the objective of the research, different series are considered desirable signals relevant to the problem being studied, while others become "noise" that interfere with deducing the desired information. In dendroclimatic studies, all series but the climatic signal are noise. In decline studies, the climatic and age-related series are often noise, while the others, particularly disturbance, may or may not be considered signals. Different statistical techniques are available to minimize the effects of noise in tree ring series and highlight the signals in the data (Cook et al., 1990; Fritts, 1976).

2.6.1 Climate Reconstruction

Tree ring series have been widely used to reconstruct past climate histories, including those in western Canada, by focusing on climatic signals and removing noise from tree ring data. In Alberta, ring widths were used to reconstruct and extend streamflow records by over 350 years past the instrumental records in the South Saskatchewan River Basin (Bonin, 2002). In Manitoba, bur oak ring widths series and anatomical features have been used to reconstruct the hydroclimate and flooding history of the Red River Valley back to the year A.D. 1409 (St.George and Nielsen, 2002; St.George and Nielsen, 2003; St.George et al., 2002).

Anatomical characteristics of tree rings can also be used to identify years in which severe, late spring frost occurred (Fritts, 1976). In such cases, severe frost after cambial activity has been initiated in the spring causes damage to newly formed vessels under the bark, which can easily be identified microscopically as rings with cresent-shaped vessels or discolouration (Fritts, 1976).

2.6.2 Trees Rings, Environmental Change, and Decline

In general, dendrochronology alone cannot prove cause and effect. However, when combined with experimental results and observations, it can provide evidence for environmental change and/or tree decline by demonstrating that the observed growth is less than what would occur with no disturbance (Hyink and Zedaker, 1987; Nash III and Kincaid, 1990).

A common way to detect change through dendrochronology is to compare average ring width patterns (chronologies) between affected and unaffected trees (Nash III and Kincaid, 1990). Unaffected chronologies can either be from trees found in an area unaffected by the environmental change in question (control sites), or from years prior to the disturbance. Differences in ring width values and variability between the two chronologies may be important indicators of change. Peterson et al. (1987) used a control-site approach to study the effects of ozone pollution on growth of Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) in two national parks in California. Chronologies from symptomatic and asymptomatic trees were compared and shown to be identical prior to 1965, after which time symptomatic trees were exposed to ozone pollution, and exhibited a growth reduction of 11% compared to asymptomatic trees. This approach was also used to characterize the effects of spruce budworm infestations in trees in the central Rocky Mountains (Swetnam, 1987; Swetnam et al., 1985). Based on the dendrochronological data, pest outbreaks were determined to have a typical duration of 14 years, with an average interval of 35 years between them, and the mean maximum growth reduction was estimated to be 50.0% of potential growth.

A change in tree health or growing environment can also be deduced by examining the climate-growth relationship under the assumption that it can be influenced by changes in the non-climatic environment (Innes, 1990; Nash III and Kincaid, 1990). In other words, sufficiently stressed trees may be unable to respond with increased growth in favourable conditions as a result of damaged growing environments and/or poor tree health (Innes, 1990; McClenahen and Dochinger, 1985). Such comparisons of chronology statistics to climate data have revealed deviations from normal growth resulting from air pollution effects in western larch (*Larix occidentalis* Nutt.,Fox et al., 1986), singleleaf pinyon (*Pinus monophylla* Torr. & Frém., Thompson, 1981) and white oak (McClenahen and Dochinger, 1985). It has also been reported that ring width response of declined trees can be more sensitive to climatic fluctuations than healthy trees (Tainter et al., 1990). This may be because in some cases, declined trees are less able than healthy trees to handle slightly unfavourable climatic conditions such as mild drought, and thus have narrower growth rings in slightly dry years.

Dendrochronology can make a valuable contribution to the understanding of recent forest decline, especially when the causes are not known (Innes, 1990). In that case, chronologies must be examined for any changes that would indicate the onset of decline, an often feasible but difficult task (Innes, 1990). Decline can be reflected in a tree ring series as either a pulse (non-persistent shock), or a downward shift in ring width compared to the rest of the chronology and especially compared to a chronology of a healthy subpopulation (McClenahen, 1995). Specific statistical methods involving univariate and multivariate models have been developed to detect changes in growth pattern and tree decline (McClenahen, 1995). For example, tree ring analysis was used to determine that red spruce (*Picea rubens* Sarg.) in the Appalachian Mountains have been declining since the 1960s, but the decline is only partially related to climatic factors such as drought (Adams et al., 1985; Cook et al., 1987; Hornbeck and Smith, 1985), and may be somewhat attributed to pollution.

Numerous tree-ring studies imply that trees in both Europe and North America have been declining for much longer than is apparent from visible symptoms (Greve et al., 1986; Hornbeck and Smith, 1985; Kairiukstis and Dubinskaite, 1986; Kenk, 1983). This is important in understanding the causes of tree decline because it undermines the validity of attributing it to factors that coincide with the onset of visible symptoms, and encourages investigation of factors affecting the trees at the onset of growth reductions (Innes, 1990). Possible methods of immediately detecting changes in tree vigour where decline is suspected include measuring biochemical aspects of the trees that are altered under stress, such as carbohydrate reserves, and conducting chemical analysis of tree rings to detect pollutants or other changes when trees are in decline (Innes, 1990).

Predisposing or inciting factors in decline can be reflected in a tree's ring width series as a decrease in annual growth over time (McClenahen, 1995). A gradual decrease in ring widths could result from alterations in the microenvironment of the tree, such as soil changes, nutrient imbalance, and pest development, while sudden decreased growth shocks could indicate the tree has suffered from physical damage (root damage, defoliation, frost damage), or physiological stress (drought, flooding) (McClenahen, 1995). These factors can also occur together to form a more complex set of signals in the chronology. It is important to realize that dendrochronology can be useful in interpreting decline in terms of its timing and the type of stresses that may be responsible, but to be most valuable, tree ring information must also be considered along with past and present-day information about the sample tree's environment (McClenahen, 1995).

2.6.3 Tree Rings and Oak Decline

A reduction in ring width in oak may be indicative of decline (Skelly, 1974; Staley, 1965). Pedersen (1998) successfully used dendrochronological and statistical techniques to detect ring width patterns in oaks that support the decline theory proposed by Manion (1981a) regarding predisposing, inciting and contributing factors. A comparison among chronologies of healthy and dead oaks in the midwestern USA revealed that trees dead at the time of study were growing an average of 18% slower prior to any inciting stresses than presently healthy trees during the same period of time, suggesting that declined oaks were negatively affected by predisposing stresses (Pedersen, 1998). It is also possible that even prior to inciting stresses, oaks that were declined at the time of study were simply naturally less vigorous than oaks that were healthy at the time of study, concepts supported by other studies (Amorini et al., 1996; LeBlanc, 1998). Pedersen (1998) also demonstrated that 75% of dead oaks had declining growth patterns indicative of inciting stresses (mostly droughts), and gradual tree death an average of 20 years later. This study demonstrated that oak decline cannot be fully explained by a tree's current environment or condition. Factors that affected the oak tree for decades prior to death must be considered when studying the aetiology of oak decline (Pedersen, 1998).

A dendrochronologial investigation of declining English oak in Poland determined that oak decline was likely incited by several years with low precipitation in May and June (Wazny et al., 1991). The largest part of annual wood increment in oaks is laid down during the early spring and summer; therefore climatic events during this time are crucial in determining annual radial growth (Amorini et al., 1996). Tainter et al. (1988) compared ring widths of oaks categorized as "healthy" or "declined" based on crown symptoms in the southern USA. Separation between the growth curves of the two health categories became evident in the mid-1930s in some areas and mid-1950s in others, coinciding with local droughts. The gap between the growth curves widened with time, indicating that the declined trees did not recover from the effects of drought, the inciting factor. A similar study revealed that decline in red oaks was also incited by droughts in the 1950s (Tainter et al., 1990).

In some cases, decline in oaks has been detected using dendrochronology, although the causes remained unexplained. For example, Phipps and Whiton (1988) found a long-term growth decline beginning abruptly in the 1950s in 40 of 60 white oaks with no visible crown damage in eastern and midwestern regions of the USA. Factors involved in the decline were unknown but were apparently unique to the 1950s and the authors concluded it did not involve tree age, geographic location, site quality, climatic trends, or air pollution (Phipps and Whiton, 1988). McClenahen (1995) used ring width ratios to determine that the onset of decline in an even-aged oak stand began in 1960s, but was not able to find an inciting factor, except for a lightning strike in one tree in the stand.

Dendrochronology has also been used with oaks to assess a tree's response to decline treatments. As an example, Struss (1981) reported that applying mulch around white oaks in the urban environment increased ring width growth to pre-disturbance levels.

3.0 MATERIALS AND METHODS

3.1 Sample Tree Selection

3.1.1 Selection Area

For this study, only bur oak trees growing within the city limits of Winnipeg, Manitoba were selected (Figure 1). The exception was the inadvertent inclusion of three trees that were located less than 0.5 km west of the city limits.

3.1.2 Tree Health Classification

The study was based on a comparison of a number of characteristics among trees in various states of health. To accomplish this, three categories of tree health (healthy, medium, and declined) were predetermined and clearly defined for visual assessment based on two main criteria: 1) crown dieback, or the amount of dead branches in the crown, and 2) epicormic shoot production, the sprouting of lateral buds on the lower tree trunk. Both are symptoms of tree stress (Kessler, 1989; Manion, 1981a; Siwecki and Ufnalski, 1998), with the former resulting from an insufficient root system, and the latter considered a way for stressed trees to recover photosynthetic area lost through crown dieback. Each health category had specific requirements for the two factors. Bur oaks in the category named "healthy" had less than 5% dieback in their crown volumes, and were required to show no evidence of epicormic shoot growth (Figure 2a). Trees in the "medium" category had 5-25% crown dieback and were allowed to

Figure 2. Photographs of examples of (a) healthy, (b) medium, and (c) declined bur oak trees included in the study. The healthy tree had less than 5% crown dieback, the medium specimen had between 5-25% crown dieback, and the declined tree had more than 25% crown dieback.

have epicormic shoots (Figure 2b). To be classified as "declined", bur oaks were required to have more than 25% crown dieback, and were allowed to show epicormic shoot growth (Figure 2c). Trees that did not meet the specifications of any of these three categories were considered ineligible to be included in the study. Trees were assessed visually, and the study was designed to include approximately equal numbers of trees of each category. Similar classification methods have been used in other studies (Dunbar and Stephens, 1975; Dyer and Mader, 1986; European and Mediterranean Plant Protection Organization, 1990; Jacobs et al., 1993; LeBlanc, 1998; Mader and Thompson, 1969; McClenahen, 1995; McClenahen and McCarthy, 1990; Sonesson, 1999; Standovar and Somogyi, 1998; Tainter et al., 1988; Tainter et al., 1990; Vannini et al., 1993; Wargo, 1977).

3.1.3 Proximity to Roadways

The study was designed to include trees in parks and those along roadways in approximately equal numbers. Trees within 15 metres of roads were termed "roadside", and those beyond that distance were designated as "non-roadside", similar to the system of Dyer and Mader (1986).

3.1.4 Sample Tree Requirements

Besides having to fit into one of the health categories, sample trees had to meet several other requirements to eliminate factors that could potentially confound proper tree health assessment. Therefore, trees eligible for selection were located at least 100 metres away from roadways where road salt is normally applied during the winter, because road salt is widely known to be harmful to trees (Dyer and Mader, 1986; Manion, 1981a). As well, trees near obvious recent major disturbances, or with severe trunk wounds (over 25% of trunk circumference affected) were excluded because those disturbances may in themselves cause dieback. In an effort to focus on mature individuals, a minimum tree size of 15 cm diameter at breast height (DBH) was required (see Section 3.2.1.1). Trees with multiple stems needed to have at least one stem with a DBH of 15 cm or more to be included.

3.1.5 The Selection Process

In order to get a sample pool of trees representing all parts of Winnipeg equally, the city was divided into three areas of similar sizes henceforth designated as northeast, southeast, and west. The goal was to select, at random, 66 trees dispersed within each area, with 22 from each health category for a total of 198 sample trees. Of the 22 trees in each health category, there were to be 11 roadside, and 11 non-roadside trees.

Sampling was randomized by dividing each city area into "cells" consisting of land 0.5 km^2 in area, and visiting them in a random order to search for sample trees. A maximum of 6 trees, consisting of a roadside and non-roadside specimen from each health category, was selected in each cell. Eligible trees were selected in the order that they became visible while sampling in each cell, and new cells were visited until all the required trees were selected. In some cases, it was not possible to find enough qualifying trees in each category and this contributed to unequal sample sizes.

3.1.6 Ethics, Consent Forms, and Questionnaires

Many of the trees selected were privately-owned, and the tree owners were considered human subjects by the University of Manitoba Joint-Faculty Research Ethics Board. To receive approval for the project from the committee, a consent form, explaining the small risk (from tree coring) involved in including the tree in the study, was created for distribution to owners of selected sample trees (Appendix A). Trees were only included in the study once the signed forms were returned. Negative answers and non-responses contributed to uneven sample sizes, as there was no opportunity to select replacement trees. As well, a questionnaire regarding site histories around trees was distributed to tree-owners.

The City of Winnipeg gave permission in advance for any trees on city-owned property to be included in the study. Therefore, no consent forms or questionnaires exist for publicly-owned trees.

3.2 Data Collection

3.2.1 Present-Day Tree Information

3.2.1.1 Tree Size

DBH, a standard gauge of tree size, was measured on tree stems 1.4 m above the ground using a DBH measuring tape. If a tree had multiple stems, the DBH of the largest stem only was collected.

Tree height was measured using a clinometer. This instrument uses trigonometry to calculate tree height to a precision of 0.5 m by measuring the angle from the ground to the top of the crown when standing at a known distance from the tree. For trees with dieback at the top, the highest point of the crown, dead or alive, was considered the height of the tree.

3.2.1.2 Wounds

Although it was intended to select trees with no evidence of major wounding, in some cases such trees were inadvertently included because wounding was missed during the first visit to the tree. Therefore, all sample trees were later given a wound rating from 0 to 3 based on visual estimation of the percentage of the trunk base circumference affected by wounding or scarring in the lowest 1.5 metres of the trunk, including buttress roots. The rating scale was as follows:

- 0 = Virtually no wounding, less than 5% affected tissue
- 1 = Small nicks, including vertical wounds or scars, 5-10% affected

tissue.

- 2 = Medium nicks, 10-25% affected tissue
- 3 = Severe wounding, more than 25% affected tissue.

Selected trees with a wound rating of 3 were subsequently disqualified from the study.

3.2.1.3 Buttresses

Trees growing in an undisturbed environment tend to have tapered bases near the ground level (Johnson, 1999), known as buttresses. Assuming that all or most bur oaks naturally have buttresses, the absence of a buttress suggests that the soil grade around the tree base may have been raised from its original level, causing major disturbance to the underlying root system (Johnson, 1999). Sample trees were visually examined, and any tapering visible at ground level was judged to be presence of a buttress.

3.2.1.4 Foliar Nutrients

Foliar nutrient levels may be an indicator of nutrient availability in the soil and the ability of a tree's root system to absorb them (Mitchell, 1936). In order to compare the foliar nutrient status of trees among health categories and city areas, leaf samples for all trees were collected for laboratory analysis from the three city areas from August 29 to September 13, 2002. The collection procedure for each tree involved using pole pruners to cut branch ends exposed to full sunlight around the crown, as recommended by Benton Jones Jr. (1998).

Five cuts of approximately 30 cm in length from the mid-third height region of the crown were made, and 10 mature randomly-chosen leaves from each were collected for a total of 50 leaves per tree. In some cases, trees had experienced a second flush of shoot growth in the year, and a mixture of new and old leaves was included in the sample.

The leaf samples were submitted to Norwest Labs in Winnipeg, Manitoba for analysis. The laboratory method used to determine %N and %S was the LECO combustion method, while %Ca, %Mg, %P, %K, and %Na were determined using inductively coupled plasma spectroscopy (Watson, 1998).

3.2.2 Present-Day Environmental Information

3.2.2.1 Distance to Nearest Disturbance

The distance to the closest visible urban disturbance was recorded for each tree. These disturbances were often concrete roads or sidewalks, gravesites, dirt paths, or buildings.

3.2.2.2 Description of Growing Area

For the purposes of this study, the space considered as a tree's "growing area" was defined as the circular area centred at the tree's trunk with a radius of the tree's height. In this way the area studied was standardized to tree size.

The growing area was described in terms of percentages of its space occupied by the following pre-described categories: concrete, turf, forest (trees with naturally-occurring understory), unavailable soil space (basements, excavated pools, rivers, abbreviated as USS), covered space (sheds, garages), and "other" which included all types of space not described by the previous categories. This process was carried out by visual estimation to a precision level of 5%.

In order to account for the effect of potential root disturbances in the growing environment, turf or forest that occurred distal to a perceived barrier was categorized separately. Root barriers were pre-determined to be anything that would impede root growth or survival such as concrete, unavailable soil space, excavated areas (ditches), covered spaces, cobblestone, asphalt, gravel, and compacted dirt paths.

3.2.2.3 Competing Trees

For each sample tree, the quantity of, and distance to, other trees with crowns overlapping the growing area were recorded. Competing trees were identified to the species or genus level, and for the sake of simplicity, either considered small (DBH of 15-40 cm) or large (DBH of over 40 cm). Trees with a DBH smaller than 15 cm were not specifically tallied but were usually accounted for in the category percentages because they tended to occur in space that would be categorized as forest. Trees distal to root barriers were scored as such.

3.2.2.4 Soil Parameters

A subsample of 24 trees from the original sample was selected to examine the chemical and physical properties of soil around healthy and declining bur oaks and among the three city areas. The selection criteria for the subgroup of trees for soil sampling were very specific. Medium trees were excluded to free resources to study the extreme cases (healthy and declined trees). In order to focus on the effects of the soil, roadside trees and those with major disturbances in their growing areas were not considered eligible for selection. For logistical reasons, trees on residential property were also not included because they were more likely to be near dangerous underground utility lines. Therefore, only non-roadside park or golf course trees with vegetation only (and no barriers) in their growing areas were included in the soil study.

To ensure even representation from both health categories and all three city areas, the subsample consisted of 12 healthy and 12 declined trees, each with 4 trees from the northeast, southeast and west. Under the assumption that trees in different environments receive different kinds of cultural management (i.e. fertilizing, mulching, foot traffic), each city area within the two health categories contained (when possible), two trees from urban environments (surrounded by mowed park turf), one from a forest environment and one from a golf course. By having equal numbers of these trees in both health categories and areas, the confounding effects of these factors could be reduced. It should be noted that several trees with wound ratings of 3 were removed from the soil study after sampling but prior to data analysis.

3.2.2.4.1 Soil Sample Collection

Before collecting soil samples, the area around each selected tree was scanned for the presence of electric and gas lines by Manitoba Hydro. After the soil around each tree was deemed safe for digging, 4 holes of 6 cm wide and 35 cm deep to the north, south, east and west of each tree were dug with a soil auger at the edge of the crown. The top 10 cm of soil were discarded because it consisted of roots and plant material. For each sample, 2 to 4 undisturbed soil clods were collected, and the rest of the soil bagged and stored for laboratory analysis. It was not possible to collect clods from any specific soil depth because compaction from the edges of the auger made undisturbed clods difficult to obtain. Holes were refilled with topsoil, and the top 10 cm of soil, including the grass divots, were replaced whenever possible.

3.2.2.4.2 Soil Fertility and Texture

Each tree had four separate soil samples. Because of limited resources for laboratory testing, north and east samples were combined, as were south and west samples. The soil was mixed, and approximately 500 g each were sent for laboratory analysis at Norwest Labs in Winnipeg. Percent organic matter (by mass of dry tissue) was determined using the modified Walkley-Black digestion followed by colorimetric analysis. The value for total extractable cations (TEC) approximates the cation exchange capacity of the soil and was measured by base saturation. Electrical conductivity (EC) was measured with an electrode, and pH was determined with a pH probe in a solution of 2 parts soil to 1 part distilled, deionized water. Soil texture analysis was done using the hydrometer method.

The concentrations of NO_3^- and PO_4^{3-} in parts per million were determined by the modified Kelowna extraction solution (Qian et al., 1994) and colorimetric analysis method. The modified Kelowna extraction solution was also used for K^+, but was followed by an automated flame photometry method. A calcium chloride extraction followed by colorimetric analysis was used to measure the amount of SO_4^{2-}. Concentrations of Ca^{2+}, Mg^{2+}, and Na^+ were determined by inductively coupled plasma spectroscopy (Watson, 1998).

3.2.2.4.3 Soil Bulk Density

Soil bulk density is the most direct quantitative measure of compaction (Vepraskas, 1994) and was determined by dividing the oven-dried mass of the clods by their volumes. For each of the four soil samples collected per tree, 20-70 g of oven-dried clods were weighed to a precision of 0.01 g. Clod volumes were determined by measuring the amount of net buoyant force applied to wax-coated, waterproof clods when submerged in water.

3.2.3 Data of the Past: Annual Growth Ring Widths

Each sample tree was cored to obtain a record of its annual ring history. A core sample is a cylindrical sample of wood radially extracted from the trunk, approximately 0.5 cm in diameter and the length of the tree's radius. A perfectly extracted core contains a portion of every annual tree ring of the trunk at the height of sampling so the rings can be counted and measured for analysis.

3.2.3.1 Core Sampling

One core from each sample tree was obtained between July and September of 2002 using a 40.6 cm or 45.7 cm long Hagloff tree corer that extracted cores 5.5 mm in diameter. To facilitate the extraction, the outer parts of the corers were sprayed with WD-40 lubricant. The holes created in the trees were plugged with oak wood dowels (9.5 mm in diameter) to reduce chance of pathogen entry. Cores were prepared for analysis by standard procedure (Stokes and Smiley, 1996), details of which are described in Appendix B.

3.2.3.2 Ring Counting and Measuring

On each prepared core, annual growth rings were counted under a microscope beginning with the outermost complete ring (year 2001) to the oldest visible ring near the centre of the tree. Years corresponding to decades were marked on the cores.

After counting was complete, the width of each annual ring was measured to a precision of 0.001 mm using a Velmex, Inc. measuring system. This procedure consisted of immobilizing cores on a movable microscope stage that electronically measured the distance required to manually move the stage the radial width of one ring to the next, as visible through the microscope. In total, over 18,000 annual rings were counted and measured.

To ensure the rings in each core were counted correctly (and that there were no missing or extra rings), each core was “crossdated” with a large, established bur oak tree ring database from southern Manitoba (St.George and Nielsen, 2002). Crossdating is a standard dendrochronological technique used to verify the years assigned to tree rings by counting. It is based on the concept that trees in the same general area share a certain amount of year-to-year ring width variation due to wide-ranging environmental influences such as climate (Fritts, 1976). Common shared signals among trees include increased ring widths from wet years, or decreased widths from dry periods. All cores were crossdated in the program COFECHA (Holmes, 1982; Grissino-Mayer, 2001).

In some cases where ring width crossdating was inconclusive, cores were visually crossdated using a distinct, wide-ranging morphological irregularity in the year 1946. Earlywood vessels in many trees in 1946 were incompletely formed, characteristic of the effects of a late-spring severe frost (Fritts, 1976). This marker was useful in dating several problematic cores in the study. Because spring frost injury can be an inciting factor in oak decline (McClenahen, 1995), trees with “frost rings” in 1946 were tallied as such.

The next step in dendrochronological studies would normally be ring “standardizing”. It is common practice to convert raw ring width values to index values (no units) when comparing growth patterns among trees by dividing each year’s ring width by the tree’s overall mean ring width (Fritts, 1976). This is normally done in studies focusing on climate reconstruction through tree ring patterns where the year-to-year variation among ring widths is the signal and differences in average growth rates are considered noise. However in this study, the overall growth rates, long-term growth trends and year-to-year variation of groups of trees relative to each other were all important signals. Therefore, because standardizing would mask key information for this study, leaving the ring width values in raw form for analysis was deemed appropriate.

3.2.3.3 Tree Age

The crossdated number of rings counted per core yielded an approximate age value for each tree. The true age values could not be found for several reasons. Firstly, trees were cored at breast height (1.4 m above the ground); and the number of years it took for each tree to reach that height was unknown. Secondly, cores did not always go through the pith of the tree, but nevertheless were near the pith judging by the curvature of the rings in the cores. Because these factors caused the ring counts to be underestimations of the true tree age, a method was developed to increase the accuracy of the estimated tree age. This involved grouping each tree into the particular decade when its pith reached breast height (if visible in the core); or if not visible, was estimated to be at breast height based on the curvature of the rings in the core. An index for the approximate number of years since achieving breast height (henceforth referred to as "age") was thus obtained by subtracting the year of coring (2002) from the middle year of the decade in which the pith was found, or estimated. For example, a tree with a pith in the 1920s was calculated as being 2002 – 1925 = 77 years in age. Therefore, all age values in the analysis end with a 7.

A total of 10 trees had hollow trunks at breast height, or had cores that did not approach the pith. They were deemed "hollow" and no age values were calculated for these trees.

3.3 Data Analysis

In general, variables were compared among categories within three main sample tree groupings: (1) health category (healthy, medium, declined); (2) city area (northeast, southeast, west); and (3) proximity to roadways (roadside, non-roadside). Comparisons between all pairs of categories were performed using univariate statistical analysis including Student's t-tests for continuous data, chi-square analysis for ordinal and nominal data, as well as Pearson Product-Moment correlations and regressions among some variables. Foliar nutrient data and some environmental data were also analyzed with the multivariate statistical methods, multiple discriminant analysis and principal component analysis, respectively. All statistical tests were performed at a significance level of 0.05.

Where possible, all sample trees were used for variable analyses, but the numbers in some analyses were lower depending on the details of the comparisons. In addition, because tree age potentially influenced other variables such as ring widths (see Section 3.3.2), a second comparison was made for most variables using only trees of similar ages determined as such by Student's t-test.

3.3.1 Present-Day Information with Different Analyses

3.3.1.1 Foliar Nutrients

Multiple discriminant analysis (MDA) – also known as canonical variate analysis – is a multivariate statistical method that combines variables (in this case foliar nutrient percentages) to maximally distinguish predefined groups of objects (tree categories) in a minimum number of dimensions (Gittins, 1985). The method creates linear combinations that best separate the groups and indicates which variables are most responsible for the separations. A visual representation of the results is produced in a biplot where objects are plotted along the linear combinations so that their relative similarity is reflected in their Euclidean distance from one another (Gittins, 1985). In other words, objects close to one another are similar in terms of the variables considered, and objects far apart are dissimilar. Information on how the variables separate the groups is reflected in the direction and length of their vectors. Longer vectors indicate more important variables, while the direction of each vector indicates its plane of highest variability. Also produced on an MDA biplot are 95% confidence circles for each group, meaning that objects that fall within a group's circle are 95% likely to belong to that group. MDA was performed on trees grouped by health category, city area, and health categories within city areas using the program ORDIN in the statistical package SYN-TAX 2000 (Podani, 2001). The variable %Na was not included because it contained low variability and negligible values.

3.3.1.2 Environmental Information

Preliminary analysis of the types of space occupying the sample trees' growing areas consisted of principal components analysis in the program ORDIN in SYN-TAX 2000 (Podani, 2001). These ordinations, however, did not reveal differences among categories within the groupings, and they are not presented in the results section. Instead, the data were simplified into categories of trees that either contained or did not contain urban space (concrete, unavailable soil space, covered space) in their growing areas, and were analyzed with chi-square analysis.

Tree competition data were also manipulated for analysis. The number of competing trees around each sample tree was converted into an estimate of competing tree basal area per unit growing area by the following formula:

$$\frac{[\text{\# of small trees} \bullet \pi/4 \bullet (31.0\ \text{cm})^2] + [\text{\# of big trees} \bullet \pi/4 \bullet (52.0\ \text{cm})^2]}{\text{Sample tree growing areas (m}^2\text{)}} = \frac{\text{cm}^2\ \text{competing tree basal area}}{\text{m}^2\ \text{growing area}}$$

The numbers 31.0 cm and 52.0 cm were derived from sample tree DBH data and represent average DBH values for competing trees that fall within the definitions of small (DBH of 15-40 cm) and large (DBH of over 40 cm) competing trees used during data collection.

3.3.2 Data of the Past: Annual Growth Ring Widths

Individual tree ring series are typically pooled for comparison with other groups of trees (i.e. comparing growth patterns among sites) into "chronologies" (Fritts, 1976). Although chronologies normally use standardized tree ring series (Fritts, 1976), ring width values in this study were left in raw form (See Section 3.2.3.2). Ring width values from each year from every tree were averaged within all categories to create a set of chronologies for all three of the main tree groupings.

Ring widths and their variability tend to decrease gradually as trees age, mainly because as a tree's diameter increases, more wood must be created to make a ring of equal width (Fritts, 1976). In order to ensure that trees in the health category chronologies had similar ages, any trees that did not have rings from prior to 1930 were excluded. This left 143 trees (47 healthy, 48 medium, and 48 declined), whose ages were not significantly different according to Student's t-test. Using annual ring widths of similarly-aged trees in evenly-sized health category chronologies reduced the direct influence of age in the comparisons.

For each grouping, overall ring width values from all years, and values from each year from 1900-2001 were compared among categories with Student's t-test. Although the earliest ring widths of some trees date back to the 1820s, only the years from 1900 onward were reported due to low sample sizes in earlier years (Appendix B).

Tree ring series were also plotted individually and their patterns were compared to local disturbance data of limited availability such as house construction dates. This was done in an effort to visually link changes in ring width patterns to known disturbances (Appendix C).

3.3.2.1 Ring Widths and Climate

Climate data from Winnipeg International Airport (49°55′ N 97°14′ W, elevation 239 m) were obtained for the period of 1938-2002 (Environment Canada, 2002). Regressions were performed for healthy trees on average annual ring width versus both total monthly precipitation and average monthly temperatures for each year from 1938-2001, as both temperature and precipitation can influence annual growth ring widths (Fritts, 1976). For each year, months from the previous October to the current year's September were considered separately, and in groups, to determine the most influential period of climate on growth. These months were chosen because similar time periods were used in other studies involving the investigation of oak growth in the USA (Estes, 1970; Friesner and Friesner, 1941; Kleine et al., 1936; Kozlowski et al., 1962; Miller, 1950; Tryon and True, 1958; Zasada and Zahner, 1969). Although winter months were not considered in most of those studies, they were included in this study because of the possibility of snowfall influencing spring melt water levels and flooding (Siwecki and Ufnalski, 1998).

3.3.2.1.1 The Critical Period

It was determined over the course of the study that annual growth ring widths of healthy and declined trees became dissimilar as the 20th century progressed. The time period beginning when healthy and declined ring widths were first significantly different and ending when the two categories began to be consistently different was chosen for more detailed analysis. This period of 31 years, from 1944-1974, was named the Critical Period for the purposes of this study. The Critical Period was examined because it encompassed the beginning of decline, when climatic factors (predisposing and inciting factors) were more likely to have an effect on ring widths in declined trees as opposed to later years when secondary pathogens (contributing factors) were likely to have much greater effect on their vigour.

To compare growth patterns between healthy and declined trees during the Critical Period, the mean ring width of declined trees was subtracted from that of healthy trees for each year. The differences were compared with total precipitation and mean temperature data for individual months and groups of months to examine possible factors that promoted a separation in the ring widths between the two groups. Finally, extreme levels of precipitation during the Critical Period were noted and visually compared with the chronologies.

3.3.2.2 Reclassifying Health Categories Using Ring Widths

In order to compare tree ring width patterns to visual health assessment, trees were reclassified as healthy, medium or declined based on their ring width patterns. To reclassify the trees, a ratio was calculated for each of 141 sample trees of similar ages (47 healthy, 48 medium, 46 declined) according to the following formula:

$$\text{Recent Radial Growth Ratio (RRGR)} = \frac{\text{Mean ring width from 1990 - 2001}}{\text{Total mean ring width}}$$

A similar ratio has been used to assess recent relative growth rates in urban sugar maples (Dyer and Mader, 1986; Mader and Thompson, 1969). Corresponding with the number of trees in the visual health categories, the 47 trees with the highest RRGR values were assigned a ring-based rating of healthy, the 46 trees with the lowest RRGR values were given a ring-based rating of declined, and those in the middle were given ring-based ratings of medium. To test the agreement between visual and ring-based health ratings, the proportions of trees with each ring-rated health category within the visually-rated health categories were tested using chi-square analysis.

3.3.2.2.1 A Comparison of Extremes: Vigorous and Ailing Trees

The 30 trees each with the highest and lowest RRGR values were labelled "vigorous", and "ailing", respectively, regardless of their previously-assigned visual health ratings. These new terms were introduced to avoid confusion with the "healthy" and "declined" labels. The proportions of trees of each visually-rated health category were calculated within both the vigorous and ailing categories and compared with chi-square analysis. To truly compare the "best" and “worst” trees, all variables were reanalyzed between the two new categories, using the same univariate methods as for the larger sets of sample trees.

4.0 RESULTS

4.1 General Descriptions and Locations of Selected Bur Oaks

The selection process resulted in 68 healthy, 60 medium, and 52 declined bur oaks being chosen for inclusion in the study (after the disqualification of 9 wounded sample trees), for a total of 180 sample trees (Figure 3). Sixty-five trees were selected in the northeast city area, 55 from the southeast, and 60 from the west. There were 85 roadside trees, and 95 non-roadside trees, while 86 trees were privately-owned, and 94 were publicly-owned.

Selected bur oaks were located mainly in parks, private yards, boulevards, cemeteries, golf courses, and along riverbanks. Nearly all selected trees were located within 3 kilometres of either the Red, Assiniboine, Seine, or LaSalle Rivers. Few bur oaks were found farther than that distance from waterways.

Qualitative observations of the areas surveyed suggested that the southeast city area contained the highest number of declined bur oaks, while the northeast had an intermediate amount and the west had a much lower frequency of distressed bur oaks. General observation indicated that the northeast region also seemed to have larger specimens than the other two areas. Interestingly, no bur oaks were found at the junction of the Red and Assiniboine rivers (known as "The Forks"), although other riverbank species such as elm, ash, and cottonwood were abundant.

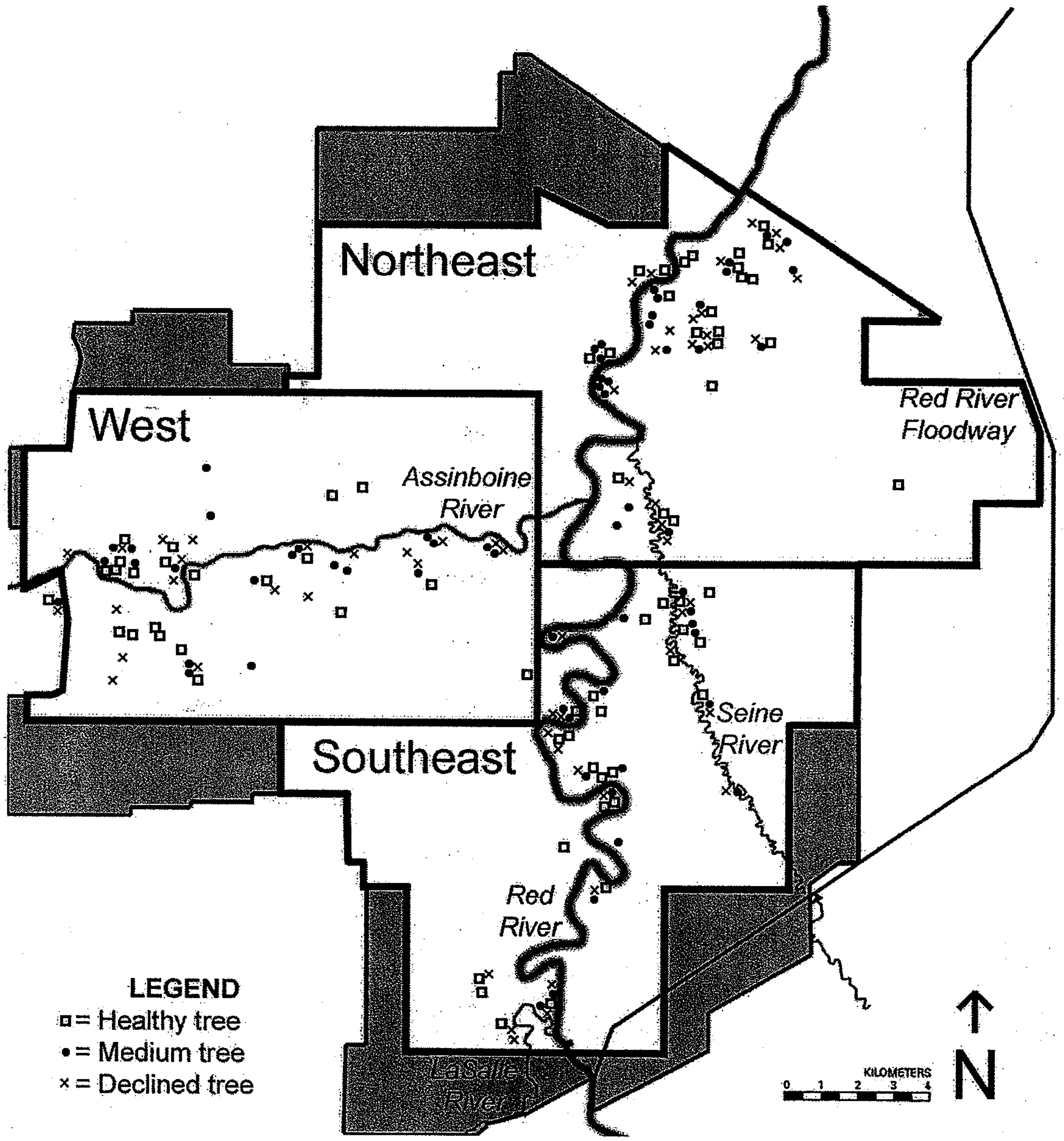

Figure 3. A map of Winnipeg, Manitoba showing the northeast, southeast, and west designated city areas, and locations of healthy (n=68), medium (n=60), and declined (n=52) bur oaks for a total of 180 sample trees. Shaded areas were not sampled.

4.2 Present-Day Tree Information

4.2.1 Age and Size

Tree ages ranged from 47 to 177 years, with an overall mean and standard deviation of 104.1 ± 32.3 years for all trees excluding hollow specimens, where age data were not available (Table 1). When trees were grouped according to health category, it was found that healthy trees were significantly younger (94.6 ± 30.9 years) than medium and declined trees (107.7 ± 33.9 and 111.2 ± 29.4 years, respectively). Mean ages were not significantly different among city areas or between roadside and non-roadside trees.

The stem diameter at breast height (DBH) values of all 180 trees ranged from 15.0 to 77.0 cm and had a mean and standard deviation of 42.0 ± 13.1 cm (Table 2). There was a trend for increasing stem girth from declined to medium to healthy trees, but no significant difference. Trees in the northeast had significantly larger DBH values than those in the southeast or west areas of the city, which substantiated the qualitative observations made during the selection process. There was no significant difference in stem girth between roadside and non-roadside trees.

When only trees of similar ages were compared (n=142), declined trees had significantly smaller stem girths than healthy trees (42.3 ± 13.0 and 47.4 ± 12.4 cm, respectively), while medium trees were intermediate between the two

Table 1. Age values for 170 bur oaks (hollow trees not included) in Winnipeg, Manitoba, grouped according to health categories, city areas, and proximity to roadways. Mean (± standard deviation) values for categories within each grouping with no letters in common were statistically different ($P<0.05$).

Categories	Number of Trees	Tree age (years since trees were breast height) Mean	Minimum	Maximum
Healthy	63	94.6 ± 30.9 *a*	47	167
Medium	58	107.7 ± 33.9 *b*	67	177
Declined	49	112.1 ± 29.4 *b*	57	177
Northeast	60	107.3 ± 36.9 *a*	47	177
Southeast	52	104.7 ± 32.9 *a*	47	167
West	58	100.3 ± 26.1 *a*	47	157
Roadside	82	100.9 ± 32.9 *a*	47	177
Non-Roadside	88	107.1 ± 31.6 *a*	47	177
Total	170	104.1 ± 32.3	47	177

Table 2. Tree stem diameter at breast height (DBH) comparisons for 180 bur oak trees in Winnipeg, Manitoba, in relation to their health categories, city areas, and proximity to roadways. Mean (± standard deviation) values for categories within each grouping with no letters in common were statistically different ($P<0.05$).

Categories	Number of Trees	DBH (cm) Mean	Minimum	Maximum
Healthy	68	43.1 ± 13.7 *a*	15.0	72.5
Medium	60	41.9 ± 12.1 *a*	20.5	77.0
Declined	52	40.6 ± 13.5 *a*	17.0	75.0
Northeast	65	46.9 ± 13.0 *a*	16.0	77.0
Southeast	55	40.3 ± 12.6 *b*	15.0	70.5
West	60	38.2 ± 12.3 *b*	17.0	72.5
Roadside	85	42.8 ± 13.3 *a*	15.0	75.0
Non-Roadside	95	41.2 ± 13.0 *a*	16.0	77.0
Total	180	42.0 ± 13.1	15.0	77.0

categories (data not shown). Unlike the analysis of all 180 trees, the difference among the three city areas was more pronounced in trees of similar ages, as DBH increased significantly from trees in the west to the southeast to the northeast (39.2 ± 12.8, 44.4 ± 10.9, and 49.9 ± 11.3 cm, respectively). Finally, similar to the analysis of all trees, trunk diameter of roadside and non-roadside trees did not differ in the 142 trees of similar age.

Tree heights ranged from 4.8 to 24.9 m with a mean and standard deviation of 13.1 ± 3.6 m (Table 3). Medium trees were significantly taller than both healthy and declined trees. Trees in the west were significantly shorter than those in the northeast and southeast city areas, and there was no difference in height between roadside and non-roadside trees.

When only trees of similar ages were compared (n=142), there were no significant differences from the results of the complete data set (n=180).

Regressions of tree DBH and height with age indicated that tree size increased linearly with age. Although there was considerable variation, stem girth in healthy trees increased significantly with age, with an R^2 value of 0.43 and a mean annual increase of 0.29 cm (Figure 4). This growth rate was very similar in declined trees, except that the declined trees had a smaller DBH at the same age as healthy trees. Tree height and age of healthy trees were also significantly related, with an overall R^2 value of 0.34 and a mean annual increase of 0.06 m (Figure 5).

Table 3. Tree height comparisons for 180 bur oak trees in Winnipeg, Manitoba, in relation to their health categories, city areas, and proximity to roadways. Mean (± standard deviation) values for categories within each grouping with no letters in common were statistically different ($P<0.05$).

Categories	Number of Trees	Height (m) Mean	Minimum	Maximum
Healthy	68	12.6 ± 2.9 *a*	7.2	22.2
Medium	60	14.0 ± 4.1 *b*	8.1	24.9
Declined	52	12.6 ± 3.5 *a*	4.8	23.4
Northeast	65	13.6 ± 3.6 *a*	7.2	24.2
Southeast	55	13.8 ± 3.7 *a*	7.5	24.9
West	60	11.8 ± 3.1 *b*	4.8	20.4
Roadside	85	13.3 ± 3.8 *a*	7.3	24.9
Non-Roadside	95	12.9 ± 3.4 *a*	4.8	24.2
Total	180	13.1 ± 3.6	4.8	24.9

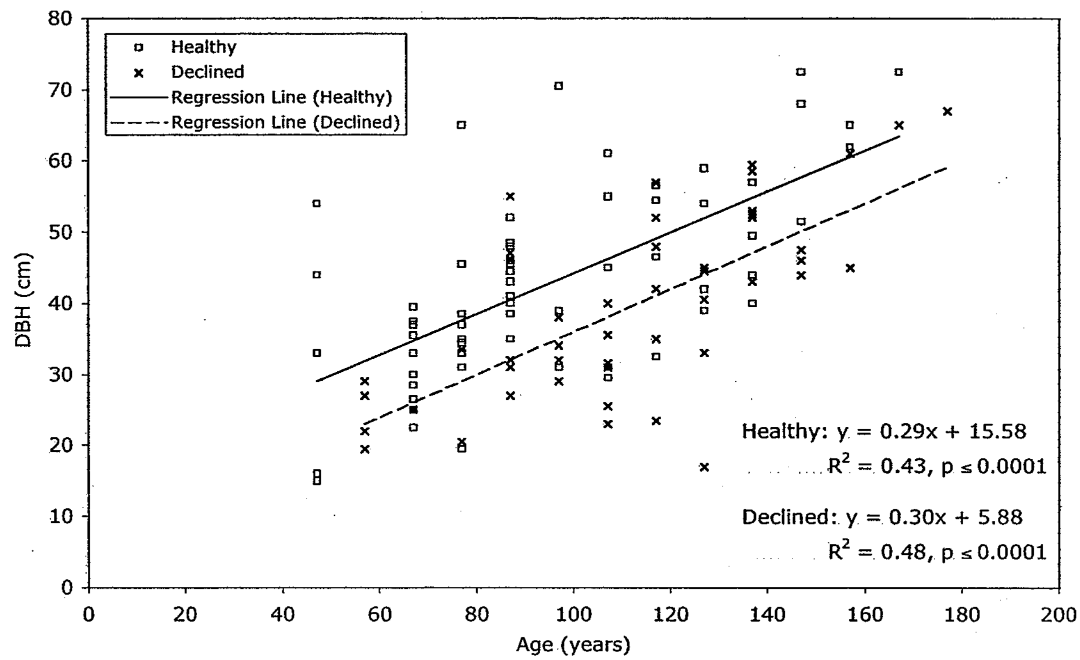

Figure 4. Regressions of stem diameter at breast height (DBH) and tree age for 63 healthy and 49 declined bur oaks in Winnipeg, Manitoba.

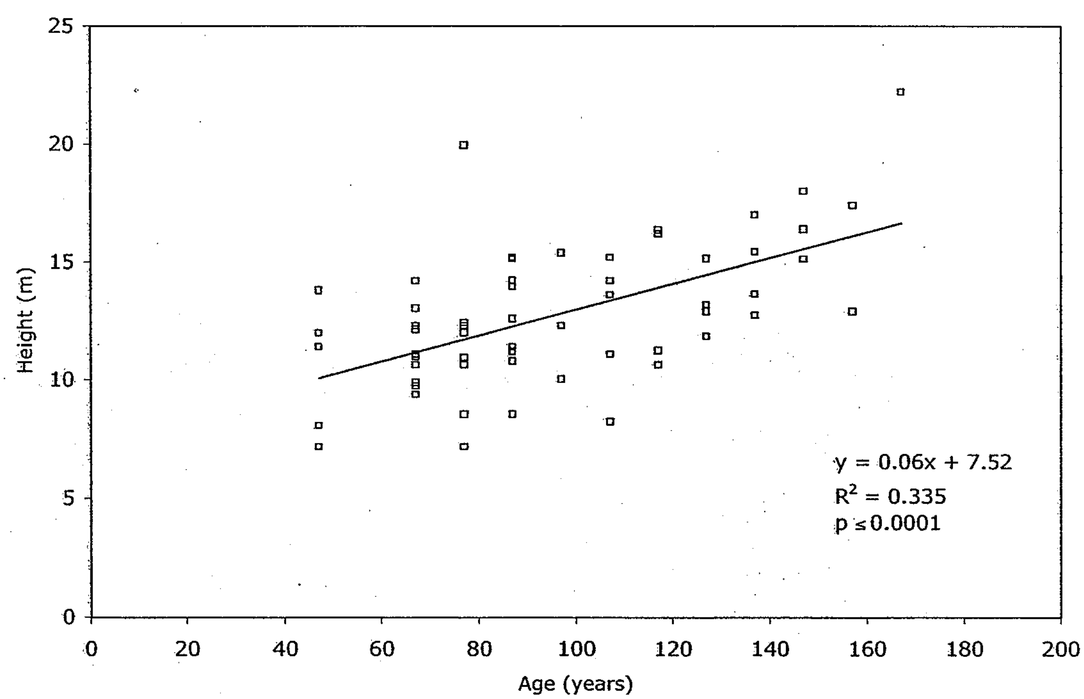

Figure 5. Regression of tree height and age for 63 healthy bur oaks in Winnipeg, Manitoba.

4.2.2 Wounding

A total of 9 trees with wound ratings of 3 were removed from the study. A comparison of wound ratings for the remaining180 trees showed no significant difference in the relative percentage of wound ratings within health categories or city areas. However somewhat surprisingly, the roadside category had a higher percentage of trees with ratings of 0 and a smaller percentage with ratings of 2 than non-roadside trees (Figure 6).

Perhaps more telling was the comparison among the 142 trees of similar ages, because those trees had similar amounts of time to be exposed to disturbances. That comparison showed there was a significant difference in the relative amounts of trees with different wound ratings among the health categories (Figure 7). The healthy category was dominated by trees with wound ratings of 1, and had few with ratings of 2. The medium category was similar, except it had more trees with no wounds. The declined category had a nearly identical percentage of wound-free trees to the medium category, but had approximately double the number of trees with ratings of 2. In short, the declined category had more trees with more severe wounding than the medium and healthy categories.

When the 142 trees were grouped according to their city areas and proximity to roadways, the results were very similar to those for all 180 trees.

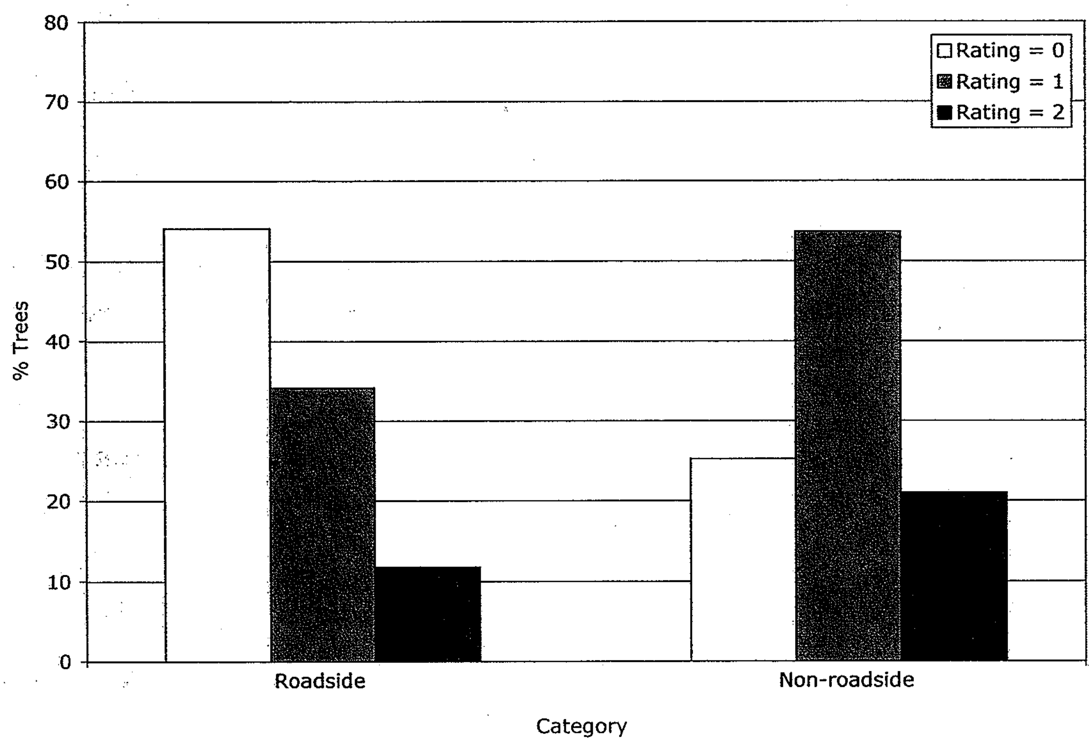

Figure 6. Percentages of 62 roadside and 80 non-roadside bur oaks in Winnipeg, Manitoba, with different wound ratings. Ratings corresponded to the amount of trunk circumference within the lowest 1.5 m of the ground that showed visual evidence of damage or scar tissue: 0= <5%, 1= 5-10%, 2= 10-25%. The difference in proportions was statistically different between roadside and non-roadside trees (P<0.05).

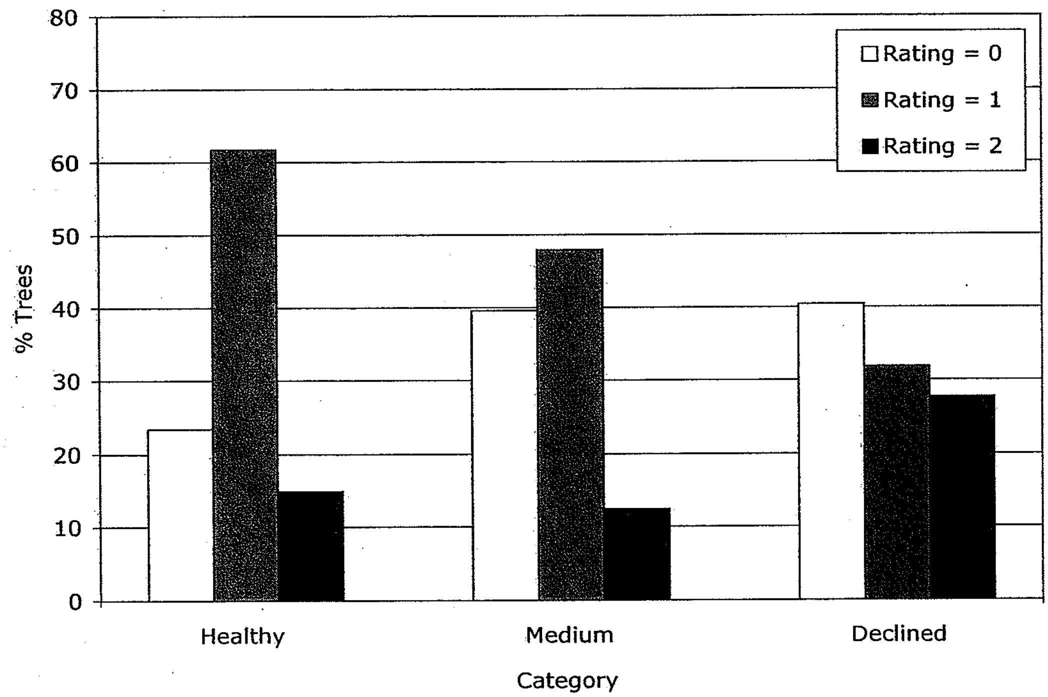

Figure 7. Percentages of 47 healthy, 48 medium, and 47 declined bur oaks all of similar age, in Winnipeg, Manitoba, with different wound ratings. Ratings corresponded to the amount of trunk circumference within the lowest 1.5 m of the ground that showed visual evidence of damage or scar tissue: 0= <5%, 1= 5-10%, 2= 10-25%. The difference in proportions was significantly different among the health categories ($P<0.05$).

4.2.3 Buttresses

A total of 68% of the 180 sample trees had visible buttresses. No significant differences in proportions of trees with visible buttresses were found among health categories or city areas (Figure 8). However, significantly more non-roadside trees had buttresses (81%) compared to roadside trees (53%).

When only trees of similar ages were compared (n=142), results were very similar to the complete data set, except that trees in the southeast appeared to have a higher percentage of trees with buttresses than the northeast or west (88%, 62%, and 69%, respectively).

4.2.4 Foliar Nutrition

When considered together in multivariate analysis, the values for 6 leaf nutrients measured did not discriminate among the tree health categories (Figure 9). There appeared to be a relatively large amount of variation of %N, %Ca, %K, and %P among the categories, but very little in %S or %Mg.

When health categories were ignored and trees were grouped according to their location in the city, there was a significant difference among the combined nutrient variables in the northeast, southeast, and west, with sizeable variation in all the variables (Figure 10). In general, trees in the northeast had above average levels of %S, %Mg, %N, but lower values of %P and %Ca. Trees in the southeast were distinguished by high levels of %P and %Ca, and low levels of %S and %N. Trees in the west were notably below average in almost

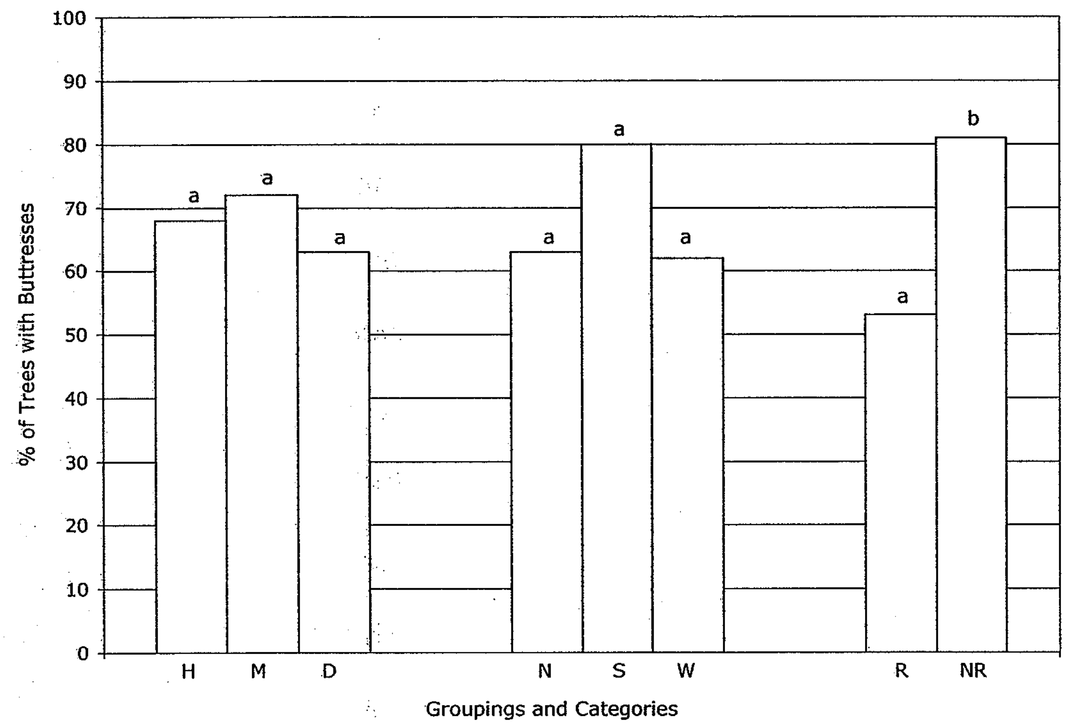

Figure 8. Percentages of 180 bur oaks with visible buttresses in Winnipeg, Manitoba, grouped by three criteria. The first grouping was by health category into 68 healthy (H), 60 medium (M), and 52 declined (D) trees. The second grouping was by city area into 65 northeastern (N), 55 southeastern (S), and 60 western (W) trees. The final grouping was into 85 roadside (R), and 95 non-roadside (NR) trees. Category values within the three groupings with no letters in common were statistically different ($P<0.05$).

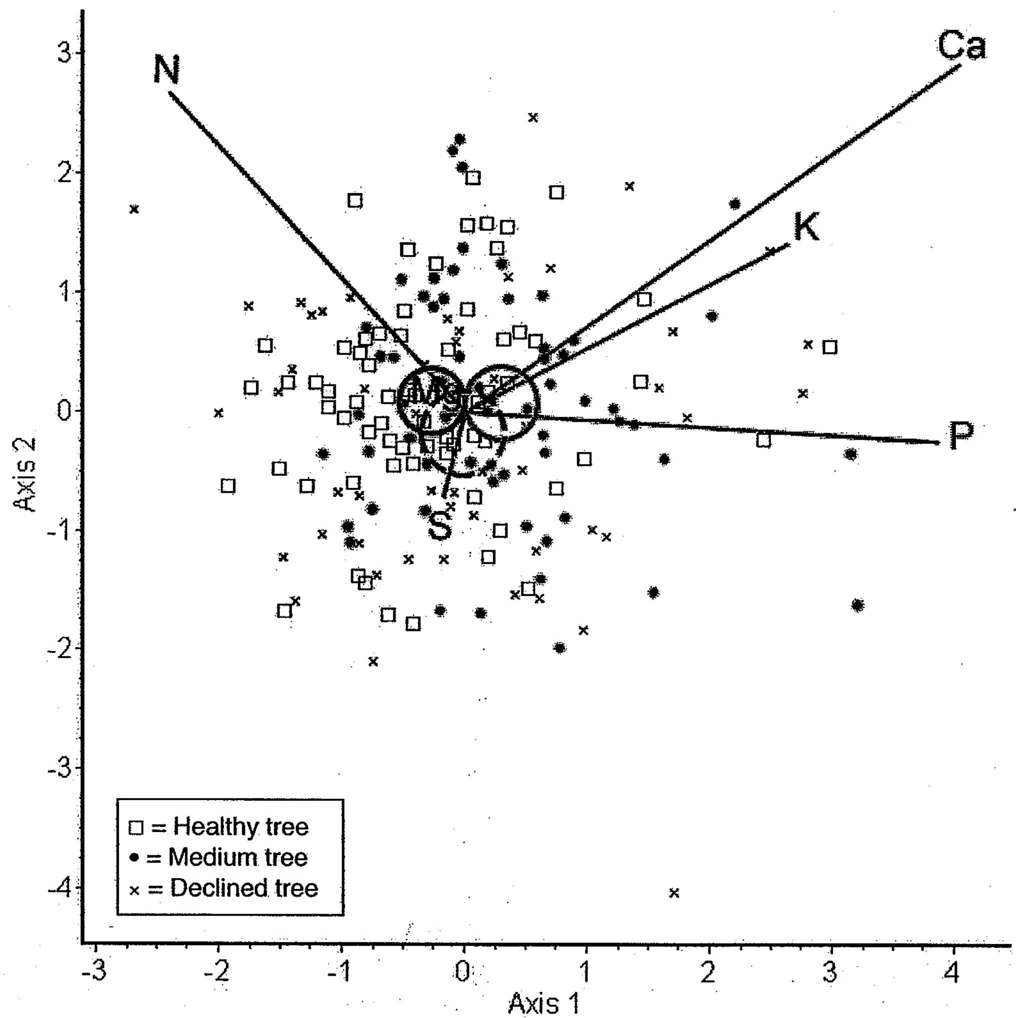

Figure 9. A multiple discriminant analysis biplot of foliar percentages of N, P, K, S, Ca, and Mg for 180 bur oaks in Winnipeg, Manitoba. Trees were grouped into healthy (n=68), medium (n=60), and declined (n=52) trees. The 95% confidence circles for the three groups are the circles with the solid black line, grey line, and dotted line, respectively. The variables do not significantly discriminate the categories (P>>0.25). Eigenvalues: λ_1= 0.06 (84%), λ_2= 0.01 (16%).

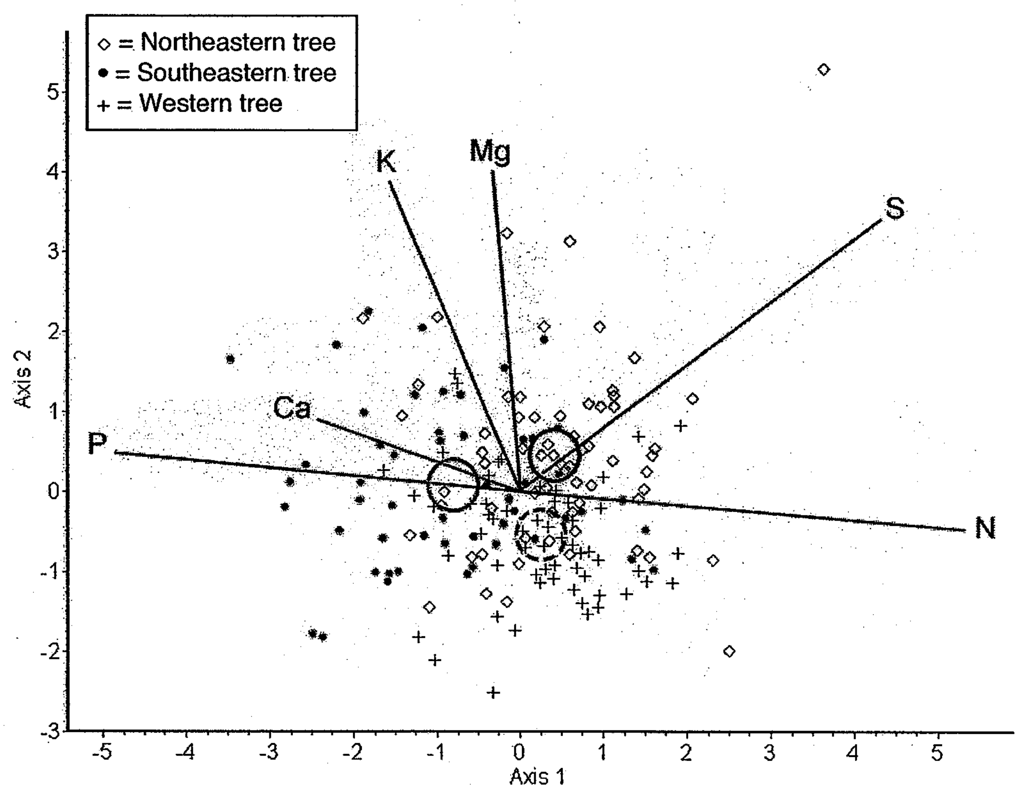

Figure 10. A multiple discriminant analysis biplot of foliar percentages of N, S, Ca, K, P, and Mg in 180 bur oaks in Winnipeg, Manitoba. Trees were grouped into northeastern (n=65), southeastern (n=55), and western (n=60) trees. The 95% confidence circles for the three groups are the circles with black, grey, and dotted lines, respectively. The variables significantly discriminated the categories ($P<0.05$). Eigenvalues: $\lambda_1= 0.28$ (68%), $\lambda_2= 0.13$ (32%).

all nutrients except %N.

Analysis of variance performed on each variable separately revealed results consistent with the multivariate analysis. Significant differences were not found among health categories but were apparent among city areas. Trees in the southeast had significantly lower levels of %N and higher levels of %P than trees in the northeast and west (Table 4). Percent Ca levels in western trees were lower than southeastern trees, but neither was significantly different from northeastern trees. Western trees also had significantly lower levels of %K and %Mg than trees in the other two areas, while northeastern trees had higher %S levels than trees in the other areas. These individual results confirm those expressed visually in the MDA output for the city areas (Figure 10).

Because of the differences in foliar nutrient content in relation to geography, health categories within each city area were analyzed separately using MDA, and foliar nutrient variables still did not discriminate among the health categories (data not shown).

When trees were grouped according to proximity to roadways, there were no significant differences among the leaf nutrients, except for nitrogen, which was significantly higher in roadside trees (2.69% ± 0.38), than non-roadside trees (2.57% ± 0.26). Values for %Na were generally negligible (data not shown).

When only trees of similar ages were compared (n=142), results for foliar analysis were very similar to those for all trees (data not shown).

Table 4. Mean (± standard deviation) values of foliar nutrients in leaf samples collected from 180 bur oaks in three areas of Winnipeg, Manitoba between August 29 and September 13, 2002. Values with no letters in common were statistically different ($P<0.05$).

Categories	Number of Trees	% N	% Ca	% P	% K	% Mg	% S
Northeast	65	2.71 ± 0.26 *a*	1.05 ± 0.21 *ab*	0.22 ± 0.05 *a*	0.93 ± 0.20 *a*	0.39 ± 0.09 *a*	0.17 ± 0.04 *a*
Southeast	55	2.46 ± 0.32 *b*	1.12 ±0.21 *a*	0.26 ± 0.05 *b*	0.94 ± 0.21 *a*	0.38 ± 0.08 *a*	0.15 ± 0.02 *b*
West	60	2.69 ± 0.34 *a*	1.04 ± 0.21 *b*	0.22 ± 0.05 *a*	0.84 ± 0.16 *b*	0.35 ± 0.08 *b*	0.16 ± 0.02 *b*
Total	180	2.63 ± 0.33	1.07 ± 0.21	0.23 ± 0.05	0.90 ± 0.19	0.37 ± 0.09	0.16 ± 0.03

4.3 Present-Day Environmental Information

4.3.1 Distance to Nearest Disturbances

The mean distance of each tree from a disturbance was 6.7 ± 10.2 m (Table 5). There were no differences among the groups of health categories or city areas. However, roadside trees had a significantly smaller distance to disturbance than non-roadside trees. Results were nearly identical when only trees of similar ages were compared (n=142).

4.3.2 Description of Growing Area

Preliminary ordinations indicated no differences or major trends in the types of space surrounding trees of different health categories or city areas (data not shown). Non-roadside trees tended to have more turf before barriers than roadside trees, as would be expected by their definitions.

The ordinations, however, did reveal that several types of space were highly correlated with each other when all trees were considered, specifically concrete, unavailable soil space, covered space, and turf after a barrier. The other main types of space around the trees were forest before a barrier, and turf before a barrier, which were both negatively correlated with the above-mentioned spaces.

Because of their high tendency to occur together, concrete, unavailable soil space and covered space were subsequently grouped together and called "urban space" for the purposes of this study. Overall, 49% of the 180 sample

Table 5. A comparison of the distance from the main stem to the nearest urban disturbance (mean ± standard deviation) for 180 bur oak trees in Winnipeg, Manitoba, in relation to their health category, city area, and proximity to roadways. Category values within each grouping with no letters in common were statistically different (P<0.05).

Categories	Number of Trees	Distance to Urban Disturbance (m)
Healthy	68	7.7 ± 10.5 *a*
Medium	60	6.6 ± 11.4 *a*
Declined	52	5.4 ± 8.2 *a*
Northeast	65	5.9 ± 10.0 *a*
Southeast	55	7.9 ± 9.9 *a*
West	60	6.4 ± 10.7 *a*
Roadside	85	2.8 ± 2.9 *a*
Non-Roadside	95	10.2 ± 12.8 *b*
Total	180	6.7 ± 10.2

trees contained urban space in their growing environments. There appeared to be no difference in the proportion of trees with urban space in their growing area among healthy, medium and declined trees (Figure 11). Trees in the southeast had a slightly lower percentage of trees surrounded by urban space, but the difference was not significant.

When differences in urban space were examined among health categories separately within each city area, no significant differences were found. In fact, the trends in the northeast and west were the opposite of what would be expected, with slightly more healthy trees having urban space than declined trees.

When trees were grouped by proximity to roadways, a much larger proportion of roadside trees was found to be near urban space than non-roadside trees, as would be expected by the definitions of the categories (Figure 11). When only those trees of similar age were compared (n=142), results were nearly identical to those from the complete data set (data not shown).

4.3.3 Competing Trees

The overall level of competition to the sample tree from surrounding trees was expressed as the mean basal area of competing trees of any species per unit area of the sample tree's defined "growing area" (see Section 3.2.2.2). Based on this criterion, the mean amount of competition for all 180 sample trees

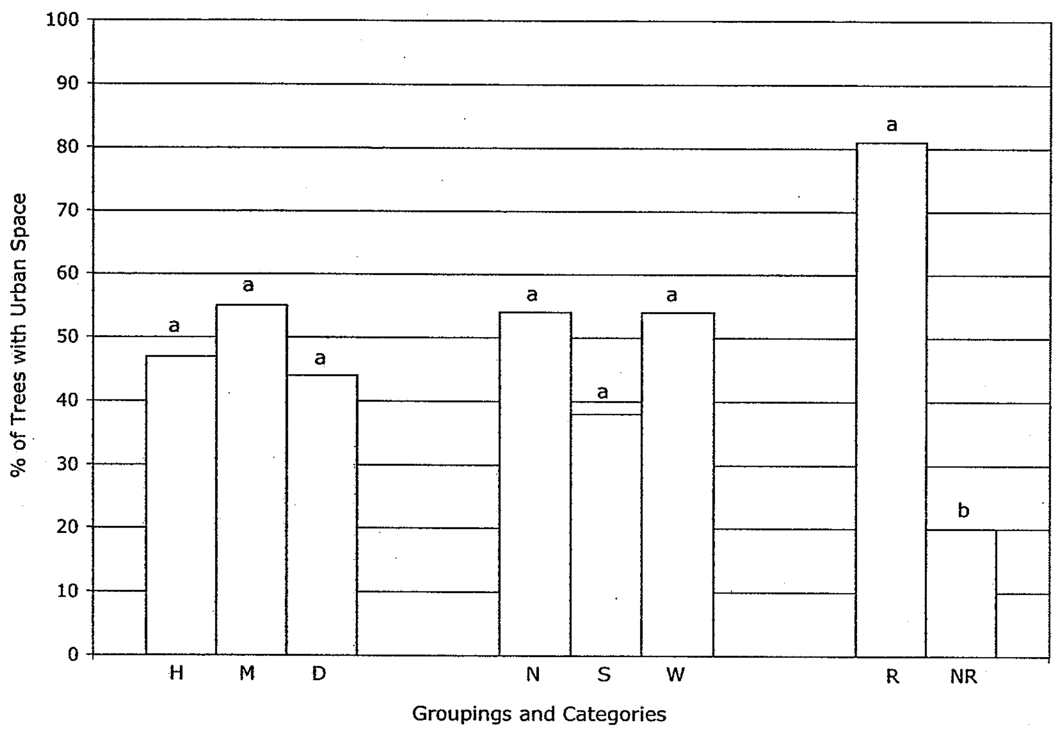

Figure 11. Percentages of 180 bur oaks in Winnipeg, Manitoba, with urban space within a radius of their height, grouped by three criteria. The first grouping was by health category into 68 healthy (H), 60 medium (M), and 52 declined (D) trees. The second grouping was by city area into 65 northeastern (N), 55 southeastern (S), and 60 western (W) trees. The final grouping was into 85 roadside (R), and 95 non-roadside (NR) trees. Category values within the three groupings with no letters in common were statistically different ($P<0.05$).

was 23.4 ± 13.7 cm^2/m^2. Healthy trees had a significantly lower level of overall competition than medium or declined trees (Figure 12). No difference was evident among the three city areas, and roadside bur oaks had significantly less competition than non-roadside specimens. Results were similar when only trees of similar ages (n=142) were compared.

Bur oak was by far the most abundant competing tree species surrounding sample trees with a mean of 14.6 ±13.8 cm^2/m^2 (Table 6), and appeared to drive the differences in total competition among the health categories (Figure 12). It was followed in order of decreasing abundance by elm, ash, maple, basswood, poplar, and spruce species (Table 6). There was also a category of "other" trees, which included in very small amounts willow, chokecherry, mountain ash, apple, cedar, lilac, birch, and larch. No species besides bur oak differed among health categories. Only subtle differences were observed when only those trees of similar age were compared (data not shown).

Many species in the growing areas of sample bur oaks differed in abundance among the city areas (Table 6). Most notable, because of their abundance, were bur oak, American elm, and ash species, which were highest in the west, northeast, and southeast, respectively. Results were similar when only sample trees of similar ages were compared (data not shown).

Non-roadside trees had significantly more competition from bur oak, and less from spruce and "other" species than roadside trees (Table 6). Otherwise,

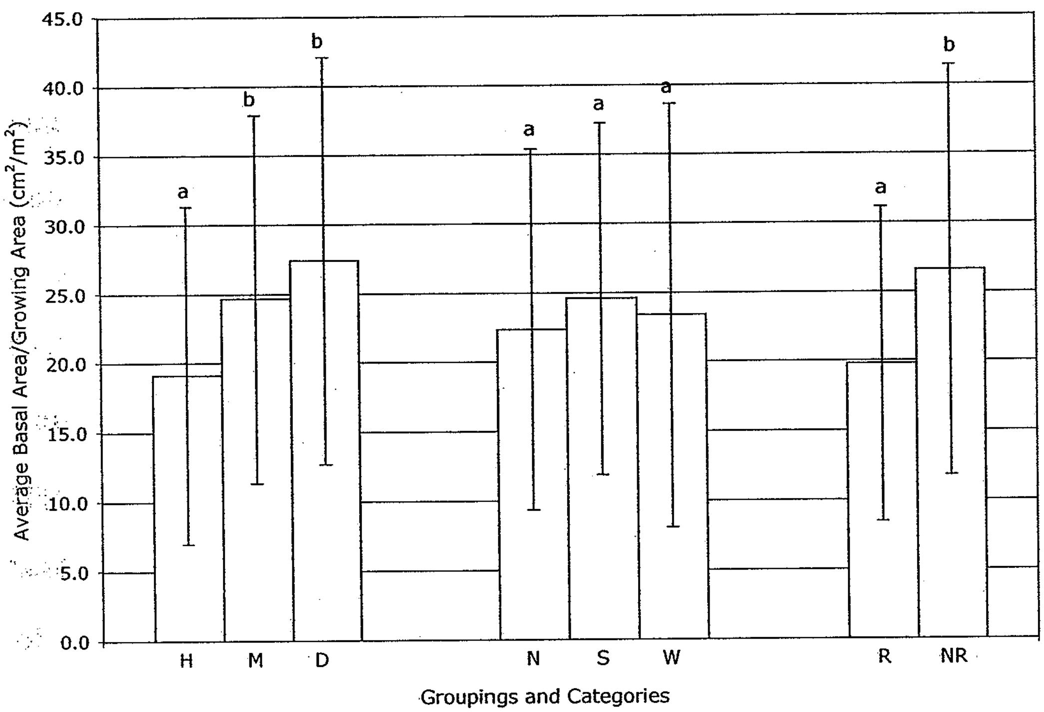

Figure 12. Mean and standard deviations (error bars) of competing tree basal area per unit ground space of a designated growing area for 180 bur oak trees in Winnipeg, Manitoba, grouped by three criteria. The first grouping was by health category into 68 healthy (H), 60 medium (M), and 52 declined (D) trees. The second grouping was by city area into 65 northeastern (N), 55 southeastern (S), and 60 western (W) trees. The final grouping was into 85 roadside (R), and 95 non-roadside (NR) trees. Category values within the three groupings with no letters in common were statistically different ($P<0.05$).

Table 6. Estimated ratio of basal area of competing trees of different species per unit growing area surrounding 180 bur oak trees in Winnipeg, Manitoba. Sample trees were grouped according to their health categories, city areas, and proximity to roadways. Mean (± standard deviation) category values within the three groupings with no letters in common were statistically different (P<0.05) under a Log (y+1) transformation.

		Estimated cm^2 Basal Area / m^2 Growing Area							
Categories	Number of Sample Trees	Bur Oak	American Elm	Ash species[1]	Maple species[1]	American Basswood	Poplar species[1]	Spruce species[1]	Others[1,2]
Healthy	68	9.9 ± 9.9 *a*	2.0 ± 4.4 *a*	2.1 ± 3.9 *a*	1.2± 2.9*a*	0.9 ± 3.0 *a*	1.4 ± 5.1 *a*	0.7 ± 1.4 *a*	1.0 ± 3.0 *a*
Medium	60	15.3 ± 14.2 *b*	3.2 ± 5.2 *a*	2.2 ± 5.4 *a*	1.4± 3.9*a*	1.1 ± 3.6 *a*	0.2 ± 1.0 *a*	0.4 ± 1.7 *a*	0.8 ± 3.1 *a*
Declined	52	19.8 ± 15.7 *b*	2.0 ± 3.9 *a*	2.2 ± 5.1 *a*	1.1± 2.7*a*	0.9 ± 3.1 *a*	0.5 ± 1.8 *a*	0.5 ± 2.0 *a*	0.4 ± 1.1 *a*
Northeast	65	12.2 ± 12.7 *a*	4.0 ± 5.8 *a*	1.9 ± 5.0 *a*	2.0 ± 4.4 *a*	0.2 ± 1.0 *a*	0.6 ± 3.8 *a*	0.8 ± 2.4 *a*	0.6 ± 1.8 *ab*
Southeast	55	14.6 ± 11.6 *ab*	1.9 ± 3.9 *b*	4.0 ± 5.8 *b*	0.7 ± 2.0 *b*	1.7 ± 4.3 *b*	1.1 ± 3.8 *a*	0.4 ± 1.3 *a*	0.3 ± 1.0 *a*
West	60	17.2 ± 16.3 *b*	1.2 ± 3.0 *b*	0.8 ± 2.4 *a*	0.9 ± 2.4 *ab*	1.0 ± 3.5 *ab*	0.6 ± 2.4 *a*	0.4 ± 0.8 *a*	1.4 ± 4.0 *b*
Roadside	85	10.7 ± 10.4 *a*	2.4 ± 4.0 *a*	2.1 ± 4.8 *a*	1.6 ± 4.0 *a*	0.7 ± 2.4 *a*	0.7 ± 3.2 *a*	0.8 ± 1.8 *a*	0.8 ± 1.8 *a*
Non-Roadside	95	18.1 ± 15.4 *b*	2.4 ± 5.0 *a*	2.2 ± 4.7 *a*	0.9 ± 2.3 *a*	1.1 ± 3.8 *a*	0.8 ± 3.5 *a*	0.3 ± 1.6 *b*	0.7 ± 3.2 *b*
Total	180	14.6 ± 13.8	2.4 ± 4.6	2.2 ± 4.7	1.2 ± 3.2	0.9 ± 3.2	0.8 ± 3.4	0.5 ± 1.7	0.7 ± 2.6

[1] Note that these trees were identified only to the genus level

[2] Trees in this category include willow, chokecherry, mountain ash, apple, cedar, lilac, birch, and larch.

there were no significant differences between the two categories. Results were nearly identical when only trees of similar ages were compared (data not shown).

Data on the size of competing trees revealed that declined trees had more small competing trees (DBH between 15 and 39.5 cm) than healthy or medium trees (Table 7). Healthy trees were also surrounded by smaller numbers of large trees (DBH of 40 cm or more) than medium or declined trees.

Healthy, medium, and declined bur oaks had similar numbers of competing trees that occurred after barriers (Table 7). The difference in abundance of competing trees was in those that were located before barriers, with declined trees having a significantly higher number than healthy trees. When only sample trees of similar ages were compared, results were very similar (data not shown).

Although there was no difference in the overall competition level among the city areas (Figure 12), there was a difference in the sizes of the trees (Table 7). Significantly increasing numbers of small trees and decreasing numbers of large trees occurred from the northeast to the west, with the southeast being intermediate. No significant difference existed in the number of competing trees before or after barriers among the three city areas. When only those trees of similar age were compared, the results were similar to the analysis of all 180 trees except there was no significant difference in the number of smaller

Table 7. Abundance information on competing trees of any species surrounding 180 bur oak trees in Winnipeg, Manitoba. Sample trees were grouped according to their health categories, city areas, and proximity to roadways. Mean (± standard deviation) values for categories within each grouping with no letters in common were statistically different ($P<0.05$).

Categories	Number of Sample Trees	Number of Competing Trees/100m² within Growing Area			
		DBH between 15-39.5 cm	DBH 40 cm or greater	Before Barrier	After Barrier
Healthy	68	1.8 ± 1.4 *a*	0.3 ± 0.3 *a*	1.6 ± 1.5 *a*	0.5 ± 0.6 *a*
Medium	60	1.8 ± 1.8 *a*	0.5 ± 0.5 *b*	1.8 ± 1.6 *ab*	0.5 ± 0.9 *a*
Declined	52	2.5 ± 1.8 *b*	0.4 ± 0.4 *b*	2.3 ± 1.7 *b*	0.6 ± 0.8 *a*
Northeast	65	1.7 ± 1.5 *a*	0.5 ± 0.5 *a*	1.6 ± 1.4 *a*	0.5 ± 0.7 *a*
Southeast	55	2.2 ± 1.5 *ab*	0.4 ± 0.4 *ab*	2.0 ± 1.3 *a*	0.6 ± 1.0 *a*
West	60	2.3 ± 1.9 *b*	0.3 ± 0.3 *b*	2.1 ± 2.0 *a*	0.5 ± 0.6 *a*
Roadside	85	1.6 ± 1.3 *a*	0.4 ± 0.4 *a*	1.3 ± 1.3 *a*	0.7 ± 0.7 *a*
Non-Roadside	95	2.4 ± 1.9 *b*	0.4 ± 0.4 *a*	2.4 ± 1.7 *b*	0.4 ± 0.9 *b*
Total	180	2.0 ± 1.7	0.4 ± 0.4	1.9 ± 1.6	0.5 ± 0.8

competing trees among the city areas.

When the competition around roadside and non-roadside trees was compared, differences between the size of the surrounding trees and their position relative to barriers were evident. Non-roadside trees had significantly more competing trees from the smaller size category than roadside trees, but there was no difference in the numbers of larger competing trees. Non-roadside trees also had significantly more competing trees that occurred before barriers, and significantly fewer that occur after barriers, compared to roadside trees. Results were nearly identical when only trees of similar ages were compared.

4.3.4 Soil Parameters

4.3.4.1 Basic Soil Characteristics

Analysis of soil variables demonstrated no significant difference between soil sampled around healthy and declined trees for bulk density, percent organic matter, electrical conductivity (EC), pH, and percentages of silt, clay and sand (Table 8). The only soil variable that varied significantly was total exchangeable cations, which was higher in soil surrounding healthy trees. Soil bulk density was slightly higher around healthy trees, but the difference was not significant.

When trees were grouped according to their geographical areas, there was a significant increase in the silt content from soil around trees in the northeast to the southeast (the west was intermediate). No other significant differences in soil characteristics existed among trees in the three city areas,

Table 8. Values (mean ± standard deviation) of variables for soil surrounding 22 bur oak trees in Winnipeg, Manitoba. Trees were grouped by health category, city area, and their surroundings. Category values within the three groupings with no letters in common were statistically different ($P<0.05$).

Categories	Number of Trees	Bulk Density (g/cm^3)	Organic Matter (% by weight)	Total Exchangeable Cations (cmol(+)/kg)	Electrical Conductivity (dS/m at 25° C)	pH	% Silt	% Clay	% Sand
Healthy	12	1.75 ± 0.09 *a*	7.1 ± 1.8 *a*	48.2 ± 5.6 *a*	1.04± 0.40 *a*	7.7 ± 0.1 *a*	31.5 ± 4.7 *a*	45.6 ± 8.5 *a*	22.9 ± 9.8 *a*
Declined	10	1.70 ± 0.18 *a*	7.0 ± 2.3 *a*	40.5 ± 7.3 *b*	0.89± 0.28 *a*	7.6 ± 0.2 *a*	34.0 ± 3.6 *a*	44.2 ± 10.8 *a*	21.8 ± 10.5 *a*
Northeast	8	1.76 ± 0.11 *a*	8.3 ± 2.5 *a*	47.6 ± 7.9 *a*	1.02 ± 0.35 *a*	7.5 ± 0.2 *a*	29.3 ± 3.1 *a*	46.9 ± 11.8 *a*	23.8 ± 11.6 *a*
Southeast	7	1.63 ± 0.16 *a*	6.7 ± 0.7 *a*	44.1 ± 4.1 *a*	0.87 ± 0.21 *a*	7.7 ± 0.2 *a*	36.2 ± 4.6 *b*	45.5 ± 6.9 *a*	18.2 ± 9.6 *a*
West	7	1.77 ± 0.12 *a*	6.1 ± 1.6 *a*	42.0 ± 8.9 *a*	1.02 ± 0.49 *a*	7.7 ± 0.1 *a*	32.8 ± 1.6 *ab*	42.2 ± 9.1 *a*	25.0 ± 8.0 *a*
Urban	10	1.73 ± 0.15 *a*	6.9 ± 2.0 *a*	44.8 ± 8.0 *a*	0.89 ± 0.26 *a*	7.7 ± 0.1 *a*	32.4 ± 4.6 *a*	41.7 ± 10.2 *a*	25.9 ± 10.6 *a*
Forest	6	1.67 ± 0.13 *a*	6.6 ± 1.6 *a*	42.8 ± 8.0 *a*	0.79 ± 0.12 *a*	7.6 ± 0.1 *a*	33.4 ± 5.4 *a*	45.6 ± 9.5 *a*	21.0 ± 11.0 *a*
Golf Course	6	1.78 ± 0.12 *a*	7.7 ± 2.4 *a*	46.4 ± 6.5 *a*	1.29 ± 0.47*b*	7.6 ± 0.2 *a*	32.2 ± 3.3 *a*	49.9 ± 6.6 *a*	17.9 ± 5.9 *a*
Total	22	1.73 ± 0.14	7.1 ± 2.0	44.7 ± 7.4	0.97 ± 0.35	7.6 ± 0.2	32.6 ± 4.3	45.0 ± 9.4	22.4 ± 9.9

including in the other textural classes, clay and sand. Bulk density in the southeast was slightly lower than in the other areas, but not significantly.

When trees were grouped according to their specific environments (urban, forest, golf course), the only variable significantly different among the groups was EC, which was higher in soil surrounding golf course trees than that from around trees in urban or forest environments. There was a weak but non-significant trend for bulk density to increase from the forest, to the urban environment and to the golf courses.

4.3.4.2 Individual Soil Nutrients

Of the extractable soil ions NO_3^-, PO_4^{3-}, K^+, SO_4^{2-}, Ca^{2+}, Mg^{2+}, and Na^+, the only significant difference between trees in the two health classes investigated was that Mg^{2+} was higher around healthy trees than declined trees (Table 9). Levels of all elements were highly variable, especially Na.

There were no significant differences in soil nutrients among trees in the three city areas. However, when trees were grouped according to their environments, golf course trees had significantly higher levels of NO_3^- and Na^+ than either urban or forest trees. Other nutrients did not vary significantly among the three categories.

4.3.4.2.1 Soil and Foliar Nutrients

Foliar nutrient compositions for the 22 trees where soil samples were collected are summarized in Appendix D. The patterns in the soil and foliar data

Table 9. Nutrient levels in soil surrounding 22 bur oak trees in Winnipeg, Manitoba. Values (mean ± standard deviation) were in units of parts per million. Trees were grouped by health category, city area, and their surroundings. Category values within the three groupings with no letters in common were statistically different ($P<0.05$).

Categories	Number of Trees	NO_3^- (±1)	PO_4^{3-} (±5)	K^+ (±10)	SO_4^{2-} (±1)	Ca^{2+} (±1)	Mg^{2+} (±1)	Na^+ (±6)
Healthy	12	4 ± 2 *a*	10 ± 8 *a*	483 ± 104 *a*	6 ± 2 *a*	5839 ± 663 *a*	2103 ± 423 *a*	110 ± 127 *a*
Declined	10	4 ± 3 *a*	18 ± 14 *a*	477 ± 103 *a*	5 ± 2 *a*	5268 ± 943 *a*	1539 ± 562 *b*	85 ± 66 *a*
Northeast	8	5 ± 2 *a*	19 ± 14 *a*	477 ± 111 *a*	6 ± 2 *a*	5913 ± 788 *a*	1996 ± 670 *a*	117 ± 116 *a*
Southeast	7	3 ± 1 *a*	16 ± 9 *a*	490 ± 56 *a*	6 ± 2 *a*	5610 ± 391 *a*	1768 ± 495 *a*	58 ± 43 *a*
West	7	5 ± 3 *a*	6 ± 9 *a*	475 ± 134 *a*	5 ± 1 *a*	5169 ± 1102 *a*	1755 ± 525 *a*	118 ± 127 *a*
Urban	10	3 ± 1 *a*	16 ± 13 *a*	477 ± 126 *a*	6 ± 1 *a*	5772 ± 814 *a*	1768 ± 624 *a*	60 ± 52 *a*
Forest	6	4 ± 2 *a*	16 ± 14 *a*	442 ± 63 *a*	5 ± 1 *a*	5661 ± 872 *a*	1609 ± 468 *a*	42 ± 11 *a*
Golf Course	6	7 ± 3 *b*	9 ± 6 *a*	524 ± 78 *a*	5 ± 2 *a*	5178 ± 834 *a*	2217 ± 382 *a*	220 ± 122 *b*
Total	22	4 ± 2	14 ± 12	480 ± 101	6 ± 2	5580 ± 834	1847 ± 558	99 ± 102

sets shared many similarities, especially in comparisons where categories among the groupings were not significantly different (Table 9, Table D.1). However, not a single significant difference among the categories in any grouping in either data set was reflected in the other.

Patterns in soil and foliar variables were very similar between healthy and declined trees. The exception was Mg, which was higher in soil around healthy trees than declined trees, but did not differ in foliar content among the health categories.

While soil nutrients did not vary significantly among city areas, foliar %N and %S increased significantly from the southeast to the northeast (with the west being intermediate).

In golf course trees, soil NO_3^- was significantly higher than in urban or forest trees, but this was not reflected in the foliar data, where %N did not differ significantly among the categories. All other variables were in agreement between foliar and soil nutrients except for K, which was uniform in the soil but was significantly lower in foliar content in forest trees when compared to urban and golf course trees.

There was little correlation between foliar and soil values for N, P, K, and S, and none of those relationships was significant (Table 10). Foliar and soil values for Ca and Mg were significantly positively related but the relationships were relatively weak.

Table 10. Pearson Product-Moment correlation coefficients (r) and coefficients of determination (R^2) between foliar nutrients (in %) and soil nutrients (in ppm) from 22 bur oak trees in Winnipeg, Manitoba. Note that soil values of N, P, and S were measured as ppm of NO_3^-, PO_4^{3-}, and SO_4^{2-}, respectively.

Nutrient	r	R^2	P value
N	-0.007	0.000	0.97
P	0.188	0.035	0.40
K	0.247	0.061	0.27
S	-0.029	0.001	0.90
Ca	0.441	0.194	0.04
Mg	0.434	0.189	0.04

4.3.5 Survey Results

A survey of private tree owners was conducted to assess residential lawn cultural practices and to determine if they were linked with tree health. The results indicated that a majority of surveyed homeowners did apply chemicals to manage the lawns surrounding the trees in their yards (Table 11). Of 43 trees on residential property (owned by 42 residents who returned completed surveys), 72% were in yards with fertilized lawns and 44% occurred where herbicide was applied to lawns. Only 23% of trees were located in yards where periodic soil aeration was performed, and 37% of trees were in irrigated yards.

When trees were grouped by health category, it was found that significantly more healthy trees were located in yards with herbicide-treated lawns compared with medium or declined trees. No other significant differences existed among health categories and city areas.

It should be pointed out that nearly all the trees in the survey were roadside specimens (often near driveways or close to the street), and therefore a fair comparison between roadside and non-roadside trees was not possible.

Table 11. Percentages of 43 bur oak trees in Winnipeg, Manitoba (owned by 42 residents) in yards where lawns were provided fertilizer, herbicide, aeration holes, and irrigation. Trees were grouped by health category and city area. Values within the three groupings with no letters in common were statistically different ($P<0.05$).

Categories	Number of Trees	Cultural Treatment			
		Fertilizer	Herbicide	Aeration	Irrigation
Healthy	18	83% a	67% *a*	17% a	39% a
Medium	16	69% a	31% *b*	31% a	31% a
Declined	9	56% a	22% *b*	22% a	44% a
Northeast	11	64% a	55% *a*	27% a	27% a
Southeast	10	73% a	45% *a*	9% a	27% a
West	21	76% a	38% *a*	29% a	48% a
Total	43	72%	44%	23%	37%

4.4 Data of the Past: Annual Growth Rings

A total of 15540 annual growth rings from 143 trees of similar ages (115.0 ± 27.5 years old) were included in the chronology, with widths ranging from 0.057 mm to 6.626 mm, and a mean and standard deviation of 1.480 ± 0.765 mm (Table 12). When data from all years were grouped together, ring widths decreased significantly from healthy to medium to declined trees. As well, all three city areas had significantly different ring widths, increasing from the west to the southeast to the northeast.

A comparison of the mean ring widths of healthy and declined trees for each year from 1900-2001 demonstrated that the radial growth patterns in these categories were very similar in terms of short-term peaks and valleys even as their mean widths diverged (Figure 13). Ring widths between the two categories were generally similar from 1900 to the early 1940s. Although they appeared to be dissimilar from 1900 to 1915, sample sizes were low during this period (Appendix B), and the differences were not significant. Statistically significant differences among ring widths of healthy and declined trees began in 1944, when the trees were an average of 56 years old, marking the beginning of a progressive decrease in annual ring widths of declined trees compared to those of healthy trees. Ring widths from healthy and declined trees were significantly different again in 1945-47, 1950, 1953-57, 1962, 1965-70, 1972, and 1974-2001.

Ring widths of medium trees followed the same general pattern of peaks

Table 12. A summary of the data used in the tree ring chronology seen in Figures 13-15, which included 143 bur oak trees of similar ages (115.0 ± 27.5 years) in Winnipeg, Manitoba. Trees were grouped by health category, city area, and proximity to roadways. Mean (± standard deviation) values for categories within each grouping with no letters in common were statistically different (P<0.05).

Categories	Number of Trees	Number of Rings	Ring Widths (mm) Mean	Minimum	Maximum
Healthy	47	4758	1.668 ± 0.760 *a*	0.109	6.626
Medium	48	5307	1.477 ± 0.787 *b*	0.057	6.610
Declined	48	5475	1.319 ± 0.707 *c*	0.059	5.958
Northeast	52	5757	1.585 ± 0.760 *a*	0.057	5.958
Southeast	43	4755	1.516 ± 0.730 *b*	0.157	4.652
West	48	5028	1.326 ± 0.777 *c*	0.059	6.626
Roadside	63	6930	1.537 ± 0.775 *a*	0.059	6.610
Non-Roadside	80	8610	1.434 ± 0.753 *b*	0.057	6.626
Total	143	15540	1.480 ± 0.765	0.057	6.626

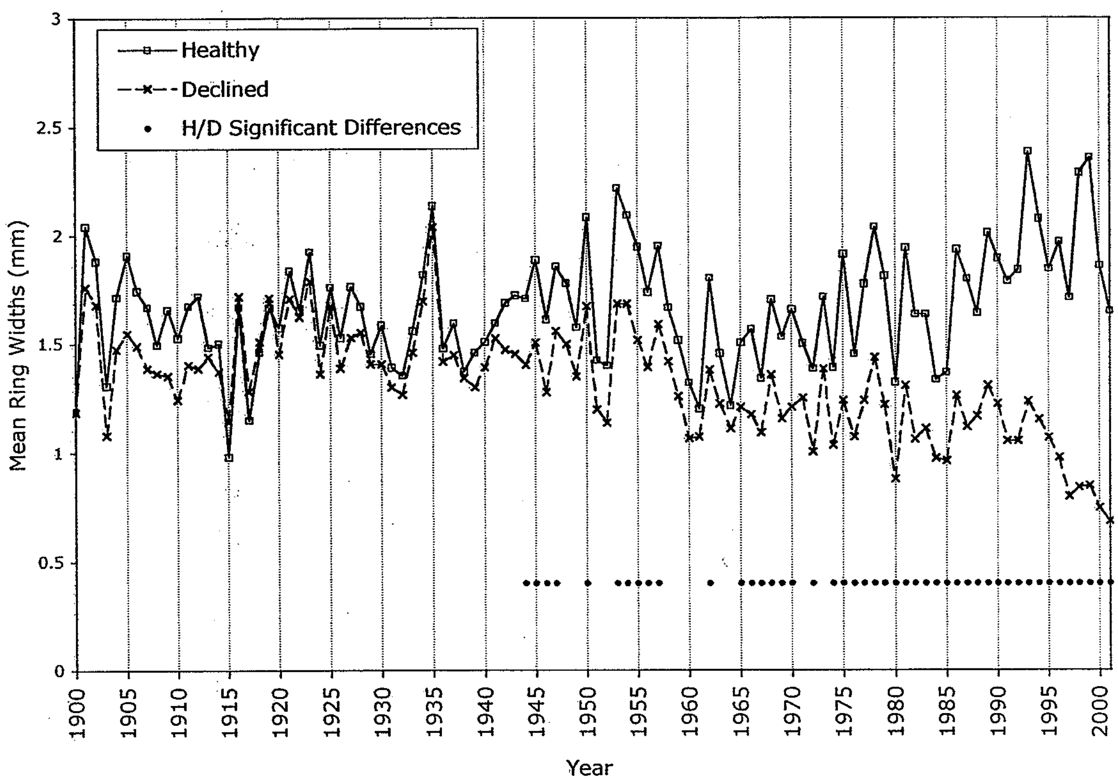

Figure 13. Mean annual tree ring widths for 47 healthy (H) and 48 declined (D) bur oak trees of similar ages (113.7 ± 25.6 years) in Winnipeg, Manitoba, from 1900-2001. Circles signify years where ring widths were significantly different between the two categories ($P<0.05$).

and valleys of the healthy and declined trees, but tended to fall between the two categories in width, especially in the 1980s and 1990s (Figure 14). Up until 1944, ring widths of all health categories were not significantly different, and this occurred again for several 2-year periods between the late 1940s and early 1960s. The exception was in 1910, where rings of healthy trees were significantly larger than rings of medium trees but not declined trees, when all three categories had low samples sizes (Appendix B).

At the time when the ring widths of healthy and declined trees began to diverge, ring widths of medium trees initially remained at an intermediate level, not significantly different from either health category. This was the case for eight years between 1944 and 1957, as well as two years in the 1960s and in 1988. Nevertheless, in several of the years where ring widths of healthy and declined trees were not significantly different (1960-61, 1971, and 1973), ring widths of medium trees were slightly larger than those of healthy trees and were significantly larger than those of declined trees. In three other years (1945, 1947, and 1986), ring widths of medium trees behaved similarly to those of declined trees, as both categories had significantly smaller ring widths compared to healthy trees. However, the opposite was much more common, when ring widths of medium and healthy trees behaved similarly, and both were significantly larger than declined rings. This was the case for 20 years between 1962 and 1995. Ring widths of all three categories were significantly different in 1987, 1990-93,

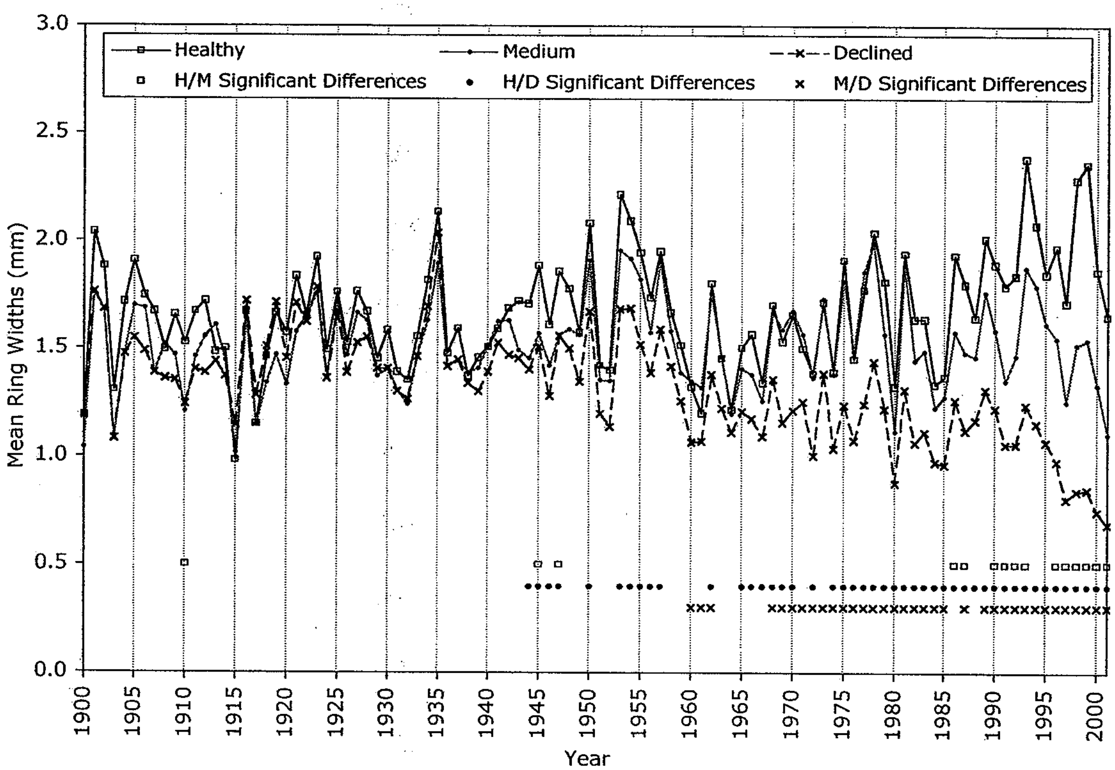

Figure 14. Mean annual tree ring widths for 47 healthy (H), 48 medium (M), and 48 declined (D) bur oak trees of similar ages (115.0 ± 27.5 years) in Winnipeg, Manitoba, from 1900-2001. Symbols near the bottom signify years where ring widths were significantly different between specified categories ($P<0.05$). This figure represents the same data as Figure 13, with the addition of the medium category.

and 1996-2001.

A comparison of mean annual ring widths for each year from 1900-2001 among trees in the three city areas demonstrated that these categories also shared a similar pattern of short-term peaks and valleys, but had different mean widths (Figure 15). Unlike the health categories, there was no consistent divergence among the ring widths of the city areas, although differences between the areas were evident in certain years scattered across the time period. In general, rings from western trees were smaller than those from the other two areas, especially the northeast (consistent with the results for tree DBH and general observations made during the sample tree selection process). Except for 6 years, rings from trees in the northeast and southeast were similar. For 46 years scattered through the time period, there were no significant differences among ring widths of the trees in the three areas. Unlike the health categories, in no years were tree rings in the three city areas all significantly different.

When ring widths of roadside and non-roadside trees were compared for each year, the two series again shared the same pattern in year-to-year variation, and did not diverge (data not shown). However, significant differences between the two categories appeared in 1974, 1976-77, 1981-84, 1988-89, 1992, and 1995, when roadside trees had larger ring widths than non-roadside trees. Ring widths between the two categories were not significantly different from 1996-2001.

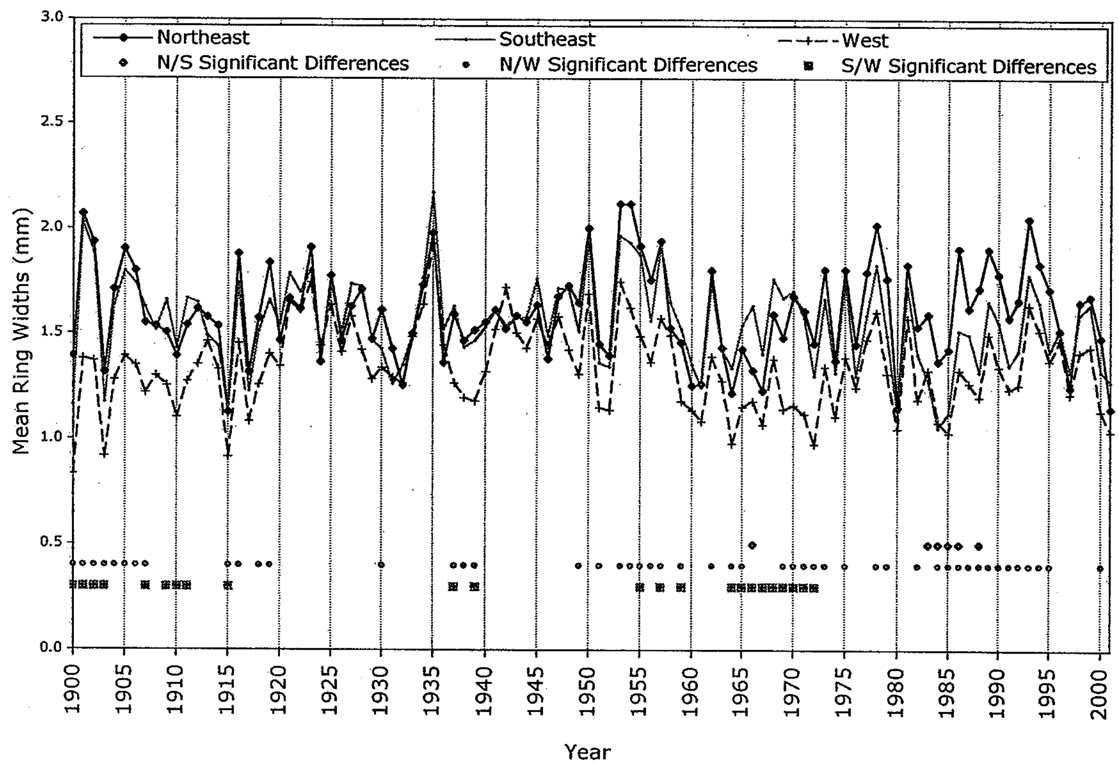

Figure 15. Mean annual tree ring widths for 52 northeastern (N), 43 southeastern (S), and 48 western (W) bur oak trees of similar ages (115.0 ± 27.5 years) in Winnipeg, Manitoba, from 1900-2001. Symbols near the bottom signify years where ring widths were significantly different between specified categories ($P<0.05$).

4.4.1 Ring Widths and Climate

Regressions performed between mean annual ring widths for healthy trees and monthly precipitation and temperature data from 1938-2001 indicated that precipitation had a significant influence on variability in annual mean ring widths, while temperature did not.

Individually, total precipitation in the months of January, May, and July of the current growing year explained only 6.3%, 8.6%, and 7.0% of the variation in healthy mean ring widths, respectively. None of the other months (including the previous year's October, November, and December) had a significant influence on ring widths in terms of precipitation levels. Of the groupings tested, the best was the combined averages of May, June, and July precipitations, which had a small but significant R^2 value of 0.147, followed closely by January-September with an R^2 value of 0.142.

When precipitation levels were compared to variability in mean annual ring widths in declined trees, there was only one significant relationship and it was fairly weak. Surprisingly, January precipitation levels explained 8.3% of the variation in ring widths in declined trees.

Mean monthly temperatures were not significantly related to healthy or declined mean annual ring widths.

4.4.1.1 The Critical Period

A comparison of climate data and the differences between healthy and declined ring widths during the Critical Period (1944-1974) suggested that the beginning of bur oak decline in Winnipeg was associated with high precipitation levels. Regressions indicated that the difference in precipitation levels each in January, May, and September explained 21.7%, 24.7%, and 13.1%, respectively, of the variation in difference between ring widths of healthy and declined trees during the Critical Period. These relationships were all positive, meaning that higher amounts of precipitation were associated with larger differences between ring widths of healthy and declined trees. None of the other months of the year had significant relationships.

The grouping that explained the most variation in growth differences between the two health categories during the Critical Period was the precipitation level from January to September, which had an R^2 value of 0.414 (Figure 16). Predictably, years with significant differences between healthy and declined trees tended to have higher values for distances between the two means during this period.

There were several extreme precipitation values of interest during the Critical Period that were record highs or lows from 1938-2002 (Environment Canada, 2002). March of 1945 received over three times the normal precipitation level. July of 1953 received over 2.5 times its normal rainfall, and

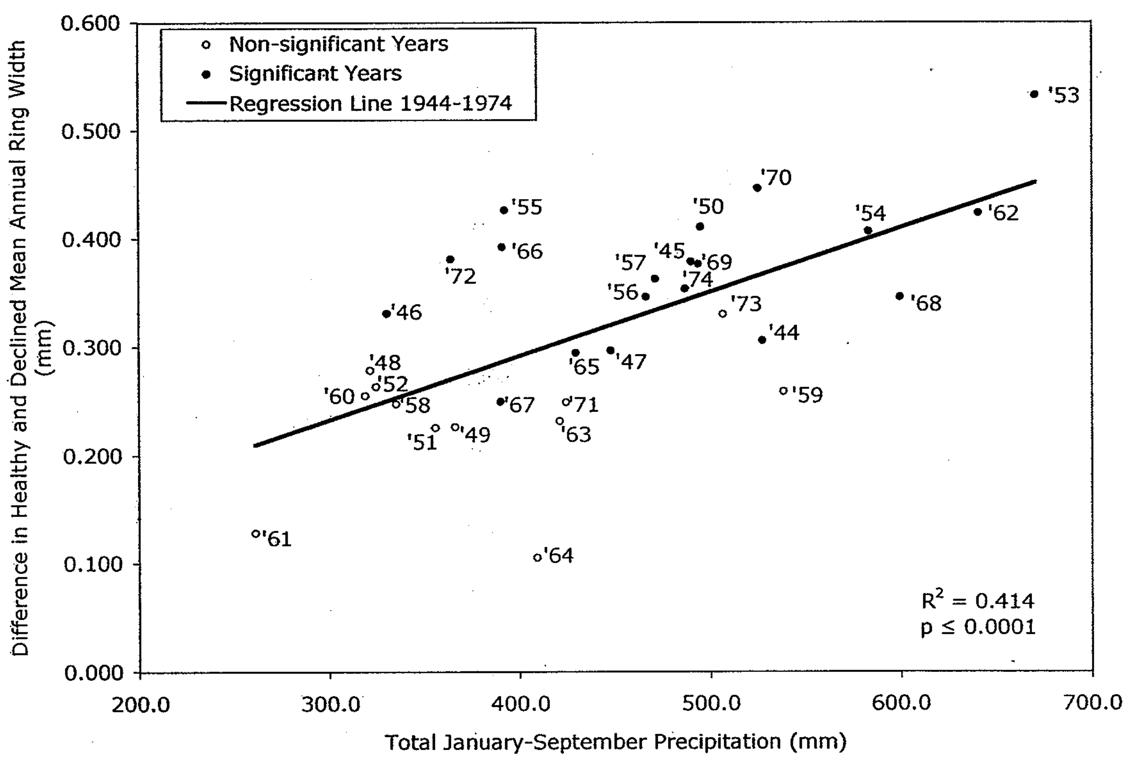

Figure 16. A regression of the difference in annual mean tree ring width between 47 healthy and 48 declined bur oak trees in Winnipeg, Manitoba, versus the combined precipitation levels from January to September in each year from 1944 to 1974. Circles are labelled by their corresponding years. Solid circles indicate years where rings from healthy trees were significantly larger than those from declined trees ($P<0.05$), while hollow circles indicate years where the two categories were not significantly different. Trees in both categories were of similar ages (113.7 ± 25.6 years old in 2002).

October of 1949 had over four times its normal precipitation. In 1955, both November (3.57 times the normal) and December (2.51 times the normal) had record highs for precipitation. Record lows occurred in January in 1973, June 1961, July 1960, September 1948, and December 1954 (Environment Canada, 2002). The highest and lowest precipitation totals for January to September were 1953 and 1961, respectively. These values both corresponded with relatively high and low ring widths for both healthy and declined trees (Figure 13).

No significant relationship was found between the difference in ring widths in healthy and declined trees and temperature during the Critical Period. However, it should be noted that during that time period, each year where the May-June temperature varied from its 1938-2001 mean by more than its standard deviation was a year with a significant difference between healthy and declined ring widths. This occurred seven times, and the temperature was below normal six of those times.

4.4.1.2 Frost Rings

A total of 18% of the 172 sample trees containing growth rings from 1946 showed anatomical evidence of frost damage that year (data not shown). No statistically significant differences among categories were seen when the trees were grouped by health category or proximity to roadways. However, significantly more trees in the northeast area were affected by frost in 1946 (36%), than in the southeast (12%) or west (3%) areas. Results were very similar when only trees of similar ages were compared.

4.4.2 Reclassifying Health Categories with Ring Widths

Recent Radial Growth Ratio (RRGR) values for 141 trees of similar ages ranged widely from 0.198 to 2.794. The mean (± standard deviation) RRGR values for visually-rated healthy, medium, and declined trees were all significantly different at 1.191 ± 0.348, 1.001 ± 0.340, and 0.725 ± 0.308, respectively. There were no significant differences between RRGR values of trees grouped according to city area or proximity to roadways.

When trees were reclassified into health categories based on the RRGR values, the ring ratings tended to agree with the visual ratings in the healthy and declined categories (Figure 17). However, the visual rating of medium contained nearly equal numbers of trees classified as healthy, medium, and declined based on ring width patterns. It should be noted that there were also considerable numbers of ring-rated medium trees in the healthy and declined visual categories. As well, 30% of the healthy trees had RRGR values below 1.000, and 15% of declined trees had RRGR values above 1.000, meaning their growth rates were the opposite of what was expected in the past decade. There were only small numbers of ring-rated healthy or declined trees in the opposite extreme's visual rating category.

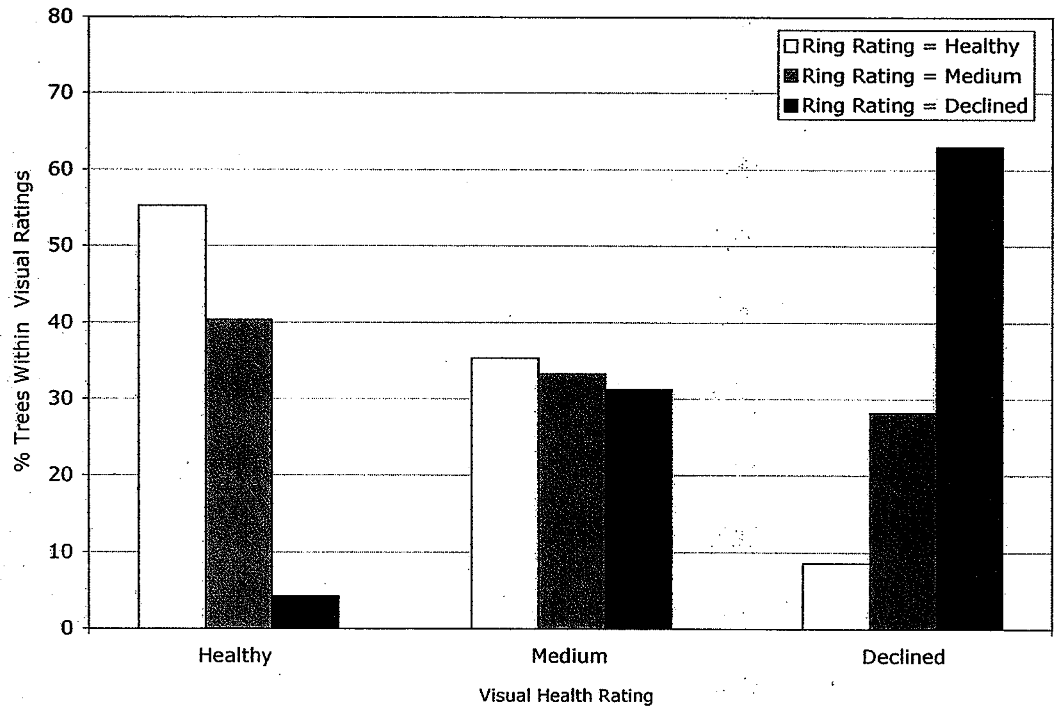

Figure 17. A summary of ring-width ratings for 141 bur oak trees of similar ages in Winnipeg, Manitoba, within the visual rating categories of healthy, medium, and declined. The proportions were significantly different among the visual rating categories ($P<0.05$).

4.4.2.1 A Comparison of Extremes: Vigorous and Ailing Trees

Visual tree health ratings were generally consistent with extreme RRGR ratings (Figure 18). The vigorous category was composed of 57% healthy, 37% medium, and 7% declined trees from visual ratings. The ailing category was composed of 0% healthy, 23% medium, and 77% declined trees. There were roughly even numbers of trees from each city area in both the vigorous and ailing categories. Roadside and non-roadside trees were in nearly equal numbers in the vigorous category, but 67% of ailing trees were non-roadside specimens compared to 33% roadside trees.

When other aspects were compared between vigorous and ailing trees, the results were in general agreement with those for trees visually-rated as healthy and declined of similar age. For example, there were no significant differences in tree age, height, proportion of trees with buttresses, foliar percentages of Ca, P, K, or Mg, and distance to nearest urban disturbance between vigorous and ailing trees or healthy and declined trees (data not shown). Ailing trees also had smaller stem girths and more overall competition from surrounding trees than vigorous trees, similar to the results for healthy versus declined trees.

On the other hand, there were differences among visually-rated and ring-rated tree categories (Table 13). Wound severity was more severe in declined trees than healthy trees, but surprisingly did not differ between vigorous

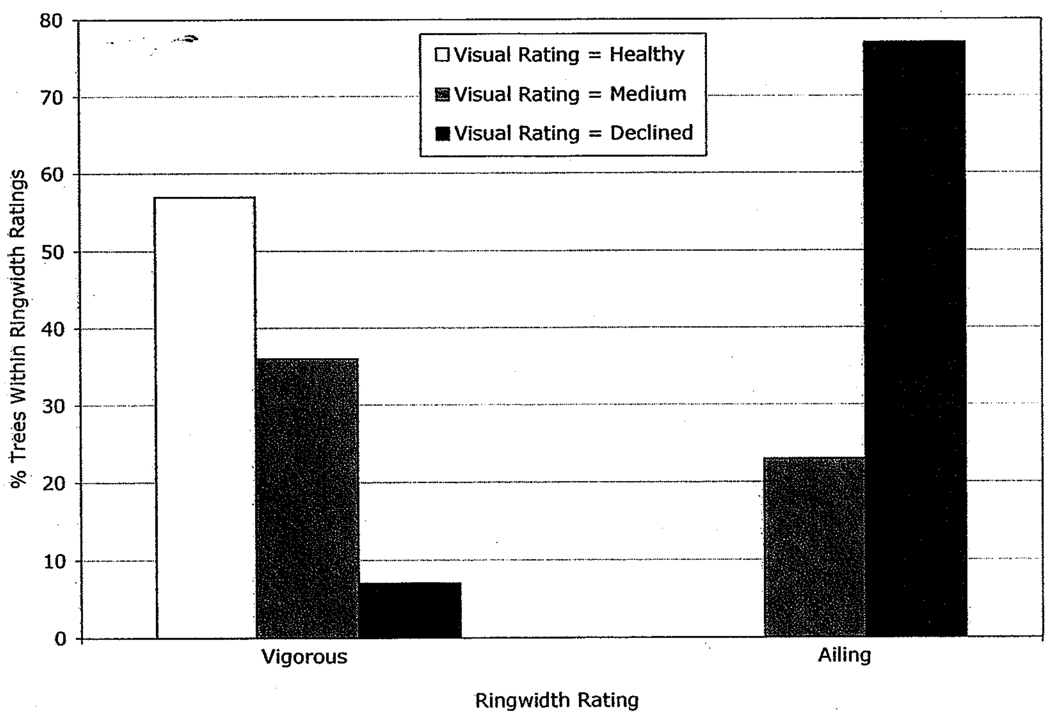

Figure 18. A summary of the visual health ratings (healthy, medium, and declined) of trees found within the categories of vigorous (n=30) and ailing (n=30) bur oak trees in Winnipeg, Manitoba. The proportions were significantly different ($P<0.05$).

Table 13. A comparative summary of the results for vigorous vs. ailing trees that differed from those of healthy vs. declined trees of similar ages. Values within the two groupings with no letters in common were statistically different ($P<0.05$).

Categories	Number of Trees	Wound Ratings	Foliar %N	Foliar %S	%Trees with Urban Space
Vigorous	30	Same	2.74 ± 0.27 *a*	0.17 ± 0.03 *a*	63% a
Ailing	30	Same	2.43 ± 0.31 *b*	0.15 ± 0.02 *b*	37% b
Healthy	47	Less Severe	2.68 ± 0.28 *a*	0.16 ± 0.02 *a*	59% a
Declined	47	More Severe	2.63 ± 0.40 *a*	0.16 ± 0.05 *a*	44% a

and ailing trees. Conversely, while there were no significant differences in foliar percentages of N and S or the proportion of trees with urban space in their growing areas for visually-rated trees, vigorous trees had significantly higher values of all three variables than ailing trees.

5.0 DISCUSSION

The mean age of the 180 bur oaks sampled in the study was 104 years, confirming reports that many surviving bur oaks in Winnipeg predate much of the urban disturbance surrounding them (Allen and Kuta, 1994). This finding was reinforced by considering that the age values of the trees were underestimated by a minimum of the number of years required to reach breast height, estimated to be 5-6 years in ideal nursery conditions (Rick Durand, personal communication), and even longer in a forest understory environment where oak seedlings may grow very slowly and have recurring shoot dieback (Abrams, 1996). Declined trees were older than healthy trees, as was the case in oak decline studies conducted in the Southern USA (Oak et al., 1996; Tainter et al., 1990) and Sweden (Sonesson, 1999). Upon closer inspection of the data in this study, there were approximately equal numbers of healthy and declined trees with high age values, but very few declined trees with low age values. This suggested that increasing tree age may have been a predisposing factor in bur oak decline in Winnipeg, consistent with previous observations (Allen, 2000) and the general notion that trees may lose vigour with age (Franklin et al., 1987; Manion, 1981a). Therefore, the most informative comparisons were those among healthy and declined trees in the upper age brackets, as each would have been in similar physiological stages and exposed to similar environmental conditions and changes over time.

The annual growth ring data from trees of similar ages revealed many key points about bur oak decline in Winnipeg. The most basic information was that the selected healthy trees had a fairly steady, and somewhat increasing radial growth rate during the 20th century, while ring widths of declined trees decreased by more than double the amount observed in undisturbed bur oaks over a similar period of time (St. George and Nielsen, 2002). The difference in average radial growth patterns of healthy and declined trees confirmed that visually-rated crown dieback categories can be used as reasonable indicators of decreased growth in bur oak.

When the average tree ring series of healthy and declined bur oaks were compared (Figure 13), three distinct growth periods were apparent as follows: 1) 1900-1943, the period where healthy and declined trees were not significantly different; 2) 1944-1974, the "Critical Period", where healthy trees rings were sporadically larger than those of declined trees; and 3) 1974-2001, the time period when ring widths of healthy trees appeared to increase, and were consistently larger than rings of declined trees, which got progressively smaller. The observed pattern indicated that healthy and now-declined trees behaved similarly for many decades in the early part of the 20th century. This did not support hypotheses made by other studies that now-declined trees may be more (Houston, 1973; Jenkins and Pallardy, 1995; Oak et al., 1996; Standovar and

Somogyi, 1998) or less (Amorini et al., 1996; LeBlanc, 1998; Pedersen, 1998) vigorous than healthy trees in the early parts of their lives and thus have different energy demands. The divergence in growth between healthy and declined bur oaks in this study was similar to a pattern observed in oak of the same categories in the southeastern USA (Tainter, 1990). Widespread symptoms of bur oak decline in Winnipeg were first noted in the 1980s (Allen and Kuta, 1994), however the observed ring width patterns indicate that the decline actually began in the 1940s, much earlier than estimated by preliminary investigations (Allen, 2000; Allen and Kuta, 1994). This finding is consistent with reports in the literature that a decrease in annual ring widths in declining trees is evident much sooner than the onset of visual symptoms (Greve et al., 1986; Hornbeck and Smith, 1985; Kairiukstis and Dubinskaite, 1986; Kenk, 1983), and that declining trees grow slower than their healthy counterparts for decades before death (Jenkins and Pallardy, 1995; Pedersen, 1998). It would be interesting to date the dead branches in the crown by measuring and crossdating their ring widths with those from the trunk cores to detect when they died back in relation to a decrease in overall growth and the timing of potential disturbances. This could indicate if dieback remains in the crown after a tree has recovered from a stressful period (as suggested in Appendix C), and could perhaps lead to a system where decline can be detected using ring width patterns prior to crown dieback.

The similarity in growth patterns between healthy and declined trees in the early part of the 20th century, followed by divergence, suggests that something about the now-declined trees or their environments changed in the 1930s or 1940s that led to their decline. The trees were on average approximately 60 years old at the time of divergence, well below the upper lifespan of bur oak, reported to be several hundred years in Manitoba (Hildahl and Benum, 1987; Wolfe, 2001). As previously stated, age may have been a factor in bur oak decline in Winnipeg, and it is possible that its effects were compounded by genetic differences between healthy and declined trees, as declined trees tended to have homozygosity at more alleles than healthy trees in two species of oak in Germany (Hertel and Zaspel, 1996). Because there are no data available on the abundance of declined bur oaks in Winnipeg, it is possible that the specific selection criteria used in this study led to the inclusion of the most extreme cases of declined bur oaks in the city, and that those trees were simply genetically inferior to their healthy counterparts. However, because the difference in growth between healthy and declined trees was so strong and external factors can expose genetic vulnerabilities (Kozlowski et al., 1991; Steiner, 1995), it is reasonable to presume that environmental factors were at least partially involved in the decline. Further study is necessary to determine if declined bur oaks in Winnipeg are predisposed to decline or less adaptable to environmental change for genetic reasons.

The divergence in growth rate between healthy and declined trees corresponded with a period of intense urbanization in Winnipeg, where many neighbourhoods were constructed in a short time in previously undeveloped areas to accommodate the demand for housing after World War II (Dafoe, 1998). It appears that urbanization can have positive or negative effects on bur oak growth (Appendix C), and it is possible that healthy oaks were unaffected or positively affected (hence the increase in growth), whereas now-declined trees were negatively affected by urban development. The negative environmental effects caused by this widespread disturbance could have predisposed bur oaks across the city to decline, depending on their specific site conditions, as established oaks are noted for their poor adaptability to the changes caused by urbanization (Ware, 1970). The continuing spread of urban development as the city expanded over time likely assisted in causing the ongoing decrease in average ring widths in the declined category. More and more of the 48 now-declined trees were likely harmed by development as time went on, which would have brought down the average ring widths in later years.

Manion (1981a) proposed that tree decline is caused by the combined effects of predisposing, inciting, and contributing factors, in that particular chronological order. For example, contributing factors in oak decline in North America, widely known in the literature to be the two-lined chestnut borer (*Agirilus bilieatus* Weber.) and *Armillaria* root rot (Dunbar and Stephens, 1975;

Haack and Benjamin, 1982; Wargo, 1977), were not included in this study because their effects would be limited without the prior weakening of potential host trees by predisposing and inciting factors. Likewise, inciting factors would not be nearly as harmful to trees if they were not already weakened by predisposing factors. And finally, new predisposing and inciting factors are no longer important once contributing factors become established in declining trees, because by that time too much damage to the trees has already been inflicted by the secondary pathogens. Tree recovery is generally possible only before contributing factors invade weakened trees (Manion, 1981b).

The results of this study suggest that predisposing factors could have begun to affect now-declined bur oaks before or at the beginning of the divergence in ring widths between healthy and declined trees in the 1940s (Figure 13). Major inciting factors appeared to occur in some years from 1944-1974, as the sporadic differences between the categories were likely triggered by episodic environmental effects that affected healthy and declined trees differently. Contributing factors may have become important after 1974, when growth of declined trees became consistently slower and progressively worse compared to healthy trees.

Urbanization typically results in environmental changes unfavourable to tree growth (Houston, 1974; Houston, 1985; Sinclair et al., 1987; Wargo et al., 1983), and this study attempted to quantify and relate the effects of these changes to decline of bur oak trees. For example, present-day surroundings were quantified to gauge the amount of environmental disturbance affecting sample trees. The fact that surroundings did not differentiate significantly between healthy and declined trees may be interpreted as revealing that disturbances such as concrete or building construction were not as harmful to bur oak as hypothesized. This idea is supported by the fact that a higher percentage of vigorous trees (as determined by ring width patterns alone) in this study had urban space in their growing environments than ailing trees. Oak specimens have been known to survive and thrive in certain urban environments if changes are made gradually (Ware, 1970). However, this interpretation is offset by the unknown timing and severity of the visible disturbances, as well as the exclusion from the data of non-visible disturbances such as excavation for installing or repairing underground utility lines. Therefore, the lack of differences in the present-day growing environments surrounding healthy and declined trees did not eliminate urban disturbances as potential factors causing bur oak decline in Winnipeg. Rather, it is possible that some predisposing and inciting factors were simply not captured in the data collection process, or that they occurred at times when they would not have been important in causing decline, such as after infection by contributing factors.

One of the most obvious effects of urban development is the physical damage inflicted on the trees, especially in terms of damage to the root systems.

Roots can be severed by excavation, smothered by soil grade changes or coverings such as concrete, and prevented from growing from soil compaction or the occupation of former growing space by building basements. Although it was not possible to excavate the root systems of the sample trees in this study, an indirect measure of root system health was provided in the form of foliar nutrient levels (Mitchell, 1936). These values were generally within acceptable ranges for deciduous trees (Davidson et al., 1988), and were similar to values measured in white oak (McVickar, 1949). The lack of differences between healthy and declined trees suggested that even if declined trees had suffered some root damage, they still had the capacity to absorb sufficient amounts of nutrients from the soil, as was the case in declined oaks in Spain (Jacobs et al., 1993). The exception in this study was in the most severe cases of decline, where ailing trees had significantly lower levels of foliar N and S compared to the most vigorous trees. This finding was similar to a pattern of decreased foliar N seen in declining sugar maples (*Acer saccharum* Marsh., Dyer and Mader, 1986), and suggested that ailing bur oaks had suffered severe root damage.

Nutrient availability has previously been shown not to be the limiting factor in oak growth (Evans, 1986) and oaks are known to be efficient at extracting required nutrients from the soil (McVickar, 1949). This may explain the general lack of correlation between most soil and foliar variables in this study and in white oak (McVickar, 1949). However, similar to a pattern seen in sugar maple (Mader and Thompson, 1969), foliar percentages of Ca and Mg were weakly but significantly correlated with soil levels. It is possible that these two nutrients were limiting in the soil for bur oak in Winnipeg. In any event, soil composition did not appear to be a strong determining factor in bur oak leaf nutrient content, although other aspects of the soil and site factors may influence oak foliar nutrient levels (McVickar, 1949).

Soil factors measured in this study rarely differentiated between healthy and declined trees. The fact that a higher percentage of non-roadside trees had buttresses compared to roadside trees suggested that the absence of a buttress likely represented a raise in the original soil grade around a tree's base. However, the similarity in proportions of healthy or declined trees without buttresses suggested that bur oaks may be able to handle raises in soil grade to a certain extent, as was observed in white oak (Day et al., 2001). A hypothesized negative effect of factors such as a lack of available soil space or root smothering by soil coverings and building basements was also not represented in the growing area data. In addition, present-day soil bulk density values did not differ between the healthy and declined trees. However, soil compaction cannot be ruled out as a causal factor in bur oak decline based on these results because the number of trees chosen for soil analysis was low. Moreover, sample trees presumably surrounded by the most compacted soils were not included due to possible interference with underground utilities. Therefore, it was surprising that bulk density values of soil surrounding healthy and declined trees, at 1.75 g/cm^3 and 1.70 g/cm^3, respectively, were both well over the value of 1.40 g/cm^3 considered to be limiting to root growth in clay soils (Daddow and Warrington, 1983). Finally, some aspects of soil fertility may have been higher around healthy trees than declined trees, but this was difficult to conclude, again due to the small number of trees sampled. More study is needed on soil conditions surrounding healthy and declined bur oaks in Winnipeg.

Trunk base wounding of trees, presumably from construction and lawnmower damage, differentiated between healthy and declined trees, indicating that this consequence of urbanization can impact bur oak decline. However, trunk wounds did not differentiate between vigorous and ailing trees, suggesting that factors other than minor trunk wounds were responsible for the most extreme cases of decline. Interestingly, more non-roadside trees had small trunk wounds than roadside trees, possibly because of lawnmower damage caused by city park workers.

Another major effect of urbanization on existing bur oaks is the drastic alteration in surrounding vegetation. In this study, the amount of different types of vegetative groundcover surrounding sample trees, such as turfgrass or riverbottom forest, did not differ between healthy and declined trees, suggesting that present-day turfgrass was not an important stressor for bur oaks. Removal of competing trees is generally one of the consequences of urbanization that has been known to be harmful to remaining oaks as it may lead to the loss of the forest environment and leave previously sheltered oaks exposed to damaging winds (Ware, 1970; Ware, 1982). However, in Winnipeg, it appears that removing competing trees may in some cases be beneficial to remaining bur oaks, as it may release growth suppression of non-dominant trees (Appendix C). Less competition from surrounding trees in general may have been advantageous to sample trees in this study, as both healthy and roadside trees had less competition and higher growth rates than their corresponding counterparts. This effect may have been responsible for the increase in average growth seen in healthy bur oaks beginning in the 1960s, as rapid urban development in Winnipeg continued (Dafoe, 1998), considering that such an increase would not be expected in an undisturbed environment (St. George and Nielsen, 2002). The main competing species around sample trees was bur oak, which could have caused declined sample trees to be out-competed for the same resources by other more vigorous bur oaks, known as a species self-thinning response (Adler, 1996; Spurr and Barnes, 1980). Bur oaks may be encouraged to grow in groups as seedlings because they share beneficial ectomycorrhizae (Dickie et al., 2004); however, it is possible that once trees are weakened, living in close proximity to each other is disadvantageous because it allows for the easy and rapid spread of pests (contributing factors) through the stand. Since health conditions of competing trees were not noted in this study, it is not possible to determine whether declined sample trees were surrounding by declined competing trees. Casual recollection of the sites indicated that this was only occasionally the case.

A change in natural drainage patterns is often an unfortunate outcome of urban development, and oaks in formerly well-drained areas that are suddenly left under standing water suffer greatly from the lack of soil oxygen (Ware and Howe, 1974), a known causal factor in oak decline (Gaertig et al., 2002). In this study, potential changes in drainage around now-declined trees were deduced indirectly by comparing the differences between healthy and declined ring widths with precipitation data for the years during the Critical Period, when inciting factors were thought to have occurred. The association of wet years with poor growth by now-declined trees, but not healthy trees, during this time period suggested the possibility that trees in the two health categories were being exposed to different levels and durations of soil moisture, possibly because of alterations in drainage patterns around now-declined trees. While healthy trees were likely growing well because they were in their natural well-drained environments, now-declined trees could have been suffering from impeded drainage that reduced their growth during wet years. Considering the low tolerance of bur oak to flooding (Johnson, 1990), and the poor internal drainage of Winnipeg's heavy clay soils, this potential change would have been a major stress for now-declined sample trees. Mature bur oak trees have been classified as being able to survive up to 30 consecutive days of saturated soil during the growing season, compared with more flood tolerant species such as cottonwood (*Populus deltoides* Bartr. ex Marsh.) or white ash (*Fraxinus americana* L.) that can survive an entire growing season under deep flooding (Whitlow and Harris, 1979). High precipitation levels could have incited decline in now-declined trees because they were predisposed to the problem by altered drainage patterns from urban development. This suggests that the damaging effects of urbanization to bur oaks may stretch far beyond immediate physical impacts at the site of development, particularly in naturally forested areas where no man-made drainage systems exist. This phenomenon was thought to be the main cause of a decline in a stand of bur oak in southern Manitoba near a newly constructed road (Boone, 2003), as well as in decline of bur oak in Assiniboine Forest and a forested area in the south end of Winnipeg (Appendix E). Soil moisture levels from April to June had an effect on white oak in Illinois, as radial growth was slower when soil was near field capacity than when it was drier (Fritts, 1960). Perhaps comparing present-day soil moisture levels throughout the growing season among healthy and declined trees in a future study would support this theory.

Contrary to many studies on oak decline (Pedersen, 1998; Tainter et al., 1990) and hypotheses made specifically for bur oak in Winnipeg (Allen and Kuta, 1994), drought did not appear to be a major causal factor in the decline of the bur oaks in this study. Rather, healthy and declined trees behaved most similarly during the Critical Period in dry years, which may not be surprising considering that bur oak is known to be a relatively drought-tolerant species (Johnson, 1990). Declined trees always had less growth than healthy specimens during the Critical Period, even in dry years, although the differences were not always statistically significant. Nevertheless, the fact that now-declined bur oaks were less able to absorb moisture from the soil in dry years than healthy trees and did not capitalize on possibly favourable growing conditions in wet years (if properly drained), further supported the idea that they were suffering from root damage (Innes, 1990; McClenahen and Dochinger, 1985). Whether this damage was a direct (i.e. root severance) or indirect (i.e. changed drainage patterns) result of urbanization or other factors, is not clear and probably varied with specific site conditions.

Late-spring frost damage has been previously cited as harmful to oaks (Balch, 1927; Beal, 1926), and if severe enough, can be an inciting factor in tree decline (Manion, 1981a). Anatomical ring features indicated that such an event occurred in Winnipeg in 1946, based on damaged conductive tissues in many sample trees in this study. However, similar numbers of healthy, medium, and declined trees were affected, and therefore frost damage was likely not an inciting factor in bur oak decline in Winnipeg.

The addition of chemicals such as fertilizers and pesticides can influence performance of oak in the urban environment (Ware and Howe, 1974). In this study, nearly 3 in 4 homeowners surveyed applied fertilizer to the lawns in their yards where sample bur oaks were growing. Since these trees were mostly classified as roadside specimens, this survey result may explain why roadside trees had higher levels of foliar N than non-roadside trees, and that fertilizing may be partially responsible for their higher growth rates. However, fertilized oaks have been known to have increased nutrient uptake but not increased growth (Evans, 1986). In any case, because there were no differences among the proportions of healthy or declined trees in fertilized yards, lawn fertilizers did not appear to be a major factor affecting decline in the sample trees. Interestingly, soil in golf courses where cultural management is intense had higher levels of electrical conductivity and NO_3^-, presumably from increased levels of fertilization.

The use of lawn herbicides has been previously suggested as a main causal factor in bur oak decline in Winnipeg (Allen, 1999), as excess herbicide may leach through turfgrass and affect oak roots (Ware, 1970; Ware and Howe, 1974). The main chemicals applied to yards to control broadleaf weeds are the group 4 herbicides 2,4-D, dicamba, and mecoprop; and drift and leaching from these herbicides are known to be harmful to trees (Manitoba Agriculture and Food, 2001). However, the results of the survey in this study indicate that considerably more healthy trees than medium or declined trees were found in yards where herbicide was applied to lawns. This is the opposite of what was expected and reasons for this are not clear. One possibility is that some herbicides may encourage development of mycorrhizae and thus have a positive effect on tree growth (Kozlowski and Pallardy, 1997). A study in Italy found that healthy specimens of English oak had a higher proportion of roots infected with mycorrhizal fungi than declined specimens (Causin et al., 1996). These results indicate that more research is needed on the effects of lawn herbicides on bur oak growth in Winnipeg.

Deicing salt applied to roads in the winter has previously been suggested as a predisposing factor in oak decline (Kessler, 1989). Because of the known harmful effect of salt on trees (Kozlowski et al., 1991), selected trees in this study were required to be 100 m from salted roads, and this was reflected in the negligible amounts of %Na determined by the foliar analysis. Therefore, salt did not seem to be a predisposing factor in the decline of the sample bur oaks, but probably only from lack of exposure.

In this study, present-day environmental characteristics were quantified in an attempt to describe conditions at the time of onset of decline. Therefore, because this study was a survey and not an experiment, any associations between the present-day environment and tree health conditions could only be speculated as potential causal factors of decline. As was the case in this study, strong relationships between decline symptoms and individual environmental characteristics do not generally appear because decline is caused by a complex of factors in sequential order (Ciesla and Donaubauer, 1994; Manion, 1981a; Manion, 1981b). As well, important site factors may exist but are not always captured in the data. In this study, few of the site conditions surrounding sample trees were severe enough to individually cause their rapid death because only living trees were sampled and visible disturbances generally appeared to be well established. The possible exceptions to this assumption were relatively recent cases of dieback, which could have been caused suddenly by a dramatic change in the tree's growing environment. This possibility reaffirms the usefulness of dating crown dieback in a future study because considerable year-to-year fluctuations in ring width patterns in some individual trees can make the time of the onset of decline unclear.

Medium trees were generally intermediate between healthy and declined trees for most variables measured, particularly age and average ring width. This was likely because the visually-rated medium category did not represent a uniform subpopulation of bur oaks in the city, but consisted of approximately equal proportions of trees rated as healthy, medium, or declined based on their ring width patterns. This study demonstrated that average ring widths became narrow before crown dieback was visible in declining trees. Therefore, it is possible that at the time of study, some medium trees were in the early stages of decline from recent exposure to predisposing and inciting factors, while others could have been suffering or recovering from chronic mild stress. Finally, some medium trees could have been in fairly good condition but were attacked by the two-lined chestnut borer because there was an abundance of pests seeking host tissue as a result of a high amount of severely declining oaks in the vicinity (Allen and Kuta, 1994), or because beetles were attracted to stress-induced volatiles released by nearby declining oaks (Haack and Benjamin, 1982). In any event, the major information provided by trees in the medium category was that the decline status of bur oaks with small amounts of dieback is quite variable, a situation also observed in moderately declined sugar maples (Dyer and Mader, 1986). In a future study of this nature, it may be best to exclude medium trees and focus resources on the extreme cases of healthy and declined trees.

Comparisons among sample trees located in the three city areas demonstrated that unexpected geographical differences existed among bur oaks in Winnipeg. Although there was no significant difference in the age of trees among the three city areas, the trees in the west area were the smallest, had the lowest growth rates, and lowest foliar contents of some nutrients. In contrast, the northeast area had the largest trees with the highest growth rates and highest foliar levels of some nutrients. The southeast area was intermediate between the two others. This pattern could have resulted from non-uniform climatic factors throughout the city, as demonstrated by the regional differences seen in the 1946 frost damage in this study. As well, geographical variability in the sample trees could have been a result of different growing environments surrounding different rivers. Trees in the west were exclusively near the Assiniboine River, while those in the northeast and southeast were near the Red, Seine, or LaSalle rivers (Figure 3). Perhaps there are inherent differences in the soil around these rivers, as they likely have different flooding and sediment deposition histories. This could have been reflected in the slightly different silt levels of the soil collected in the three city areas. However, no other soil characteristics, including nutrients, varied among the areas. This may not be surprising since the foliar levels of the 22 trees sampled also did not vary geographically (Appendix D). Further research into this question is needed because of the low number of soil samples collected.

It was not initially clear whether the significant differences in foliar nutrient levels among city areas arose from legitimate geographical differences or were simply the result of the timing of sample collection. Although leaf samples were collected in late summer as recommended by Davidson et al. (1988), trees were visited in groups within the same city areas to reduce travel time over the 16-day sampling period, resulting in a non-random sampling method over time. Oak leaf nutrient contents are known to change throughout the growing season (Jayasekera and Hans Schleser, 1991; McVickar, 1949; Ponnuvel et al., 1996; Sampson and Samisch, 1935). However, in this study only a few nutrients changed significantly with time over the sampling period, and the patterns were generally not consistent with those observed in other oak species (McVickar, 1949; Sampson and Samisch, 1935), with the possible exceptions of Ca and S. Therefore, it appears reasonable to conclude that the geographical differences in foliar nutrient contents were legitimate, and not related to time of sampling. Nevertheless, in a future study it would be preferable for sampling to be completed over a much shorter time frame. McVickar (1949) recommended July as the optimum time for sampling as that was the time when nutrient levels were most stable in white oak.

6.0 GENERAL DISCUSSION

The results from this study revealed that similar to many other documented cases of tree decline, bur oak decline in Winnipeg is a complex problem that began decades before visible symptoms were noticed. The information collected allowed for the development of a region-specific version of a well known tree decline model, specifically in terms of identifying potential predisposing and inciting factors involved in bur oak decline in Winnipeg.

The bur oak population in Winnipeg is centred around the city's four main rivers, and predates most urban development in the city. Prior to the 1940s, healthy and now-declined trees had very similar growth patterns as they were presumably growing in their natural habitats of undisturbed upper riverbanks. However, now-declined trees may have been predisposed to decline from increasing tree age, poor genetic composition, and the disturbances associated with rapid and widespread urban development in the city during the 1940s and onward, which changed the environments in which the trees had adapted during their lifetimes. It is proposed that healthy trees were either unaffected or positively influenced by urbanization in Winnipeg, while the decline status of trees in the medium category was so variable that it was not possible to make a generalized statement about factors leading to their current state.

Disturbances detrimental to now-declined trees may have included, but were not limited to, physical damage to tree root systems, rooting environments or tree trunks, chemical pollution from herbicides, and the general loss of the forest environment, which could all be considered predisposing factors. However, this study provided some indirect evidence that the most notable predisposing factor suggested may have been the altered drainage patterns associated with urbanization, particularly in forested areas where there were no obvious urban disturbances in the immediate growing environments of the trees and no man-made drainage systems were constructed.

The proposed predisposing factors are hypothesized to have stressed the now-declined bur oaks and made them vulnerable to the inciting factor of flooding caused by high precipitation levels. The detrimental effects of the changed drainage patterns surrounding the now-declined trees and other weakening factors probably magnified the effect of high precipitation levels, leaving many now-declined trees under very damaging conditions of excess soil moisture or even flooding. Since the proposed change in drainage patterns was indirectly deduced, further investigation, possibly involving detailed analysis of historical drainage and development patterns in Winnipeg, is necessary to support this hypothesis. Neither drought nor frost damage were shown to be major inciting factors in bur oak decline in Winnipeg, although it is not possible to dismiss their potential importance in individual cases depending on the severity of the stress and the health condition of the trees.

The present-day environmental data examined in this study generally did not support the notion that seemingly detrimental urban disturbances such as high amounts of concrete or building construction were directly involved in bur oak decline. In fact, according to the information collected on present-day site conditions, bur oaks can decline in apparently favourable environments and remain healthy in seemingly stressful conditions. However, this conclusion was generally counterintuitive and demonstrated the problems with trying to represent past disturbances by examining present conditions. Many predisposing and inciting factors, including the above urban disturbances, were probably involved in bur oak decline in Winnipeg but were not represented in this study. More research into the nature and timing of these and other potential factors is necessary. It would also be very informative to study the lag times between predisposing or inciting factors and tree response in terms of both ring width growth patterns and crown dieback.

Once now-declined trees were weakened sufficiently by the predisposing and inciting factors, they were vulnerable to attack by contributing factors, which are well established in oak decline literature as the two-lined chestnut borer and *Armillaria* root rot. Because these factors were not examined in this study, more research is needed on understanding the behavior of these pests or other potential contributing factors in Winnipeg's urban forest.

Contrary to the initial hypothesis, urban development was not always detrimental to bur oak growth. This was demonstrated as trees classified as healthy showed an unexpected increase in ring widths during the later part of the 20th century, while roadside trees grew faster than non-roadside trees in recent years. These positive effects were thought to be a result of the removal of surrounding competing trees, or perhaps from the effects of lawn fertilizers. Further study, perhaps including a comparison with undisturbed trees outside of the urban environment, is needed to rate the effects of these factors.

Based on the proposed decline model emanating from this study, it is recommended that not only direct site disturbances around bur oaks be considered prior to urban development, but also widespread effects on drainage patterns, particularly in undisturbed areas containing bur oaks. As well, because the incidence of decline increases with tree age, it is important to replenish the bur oak population by planting new individuals in urban landscapes, as young trees have more ability to adapt to stressful conditions than older specimens.

An additional outcome of this study was the generation of basic, baseline information regarding Winnipeg's bur oak population. Data on bur oak locations, ages, sizes, growth rates, ring width patterns, foliar nutrient contents, as well as soil information and competing tree species are potentially of value to the City of Winnipeg in terms of management of the local urban forest, particularly since behaviour of bur oaks showed some geographical variation within the city. Future study, possibly on the history and characteristics of the Red and Assiniboine rivers is required to explore the reasons for these differences.

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APPENDICES

Appendix A: Documents Submitted to Owners of Sample Trees

As required by the University of Manitoba Joint-Faculty Research Ethics Board, the following consent form was distributed to owners of potential sample trees in this study. Those that agreed to allow their trees to be included in the study signed, completed and returned the attached questionnaire.

Oak Decline Study Consent Information

One or more of your bur oak trees has been randomly selected to be included in a two-year study entitled 'An evaluation of bur oak (*Quercus macrocarpa*) decline in the City of Winnipeg' being conducted by the Department of Plant Science at the University of Manitoba.

Background

Oak decline describes the loss of vigour seen in many of the Winnipeg's oak trees since approximately 1986. No specific disease or insect has been shown to cause the syndrome, and it is suspected that the trees are being stressed by unfavourable conditions in the urban environment. This stress weakens the trees, and makes them vulnerable to attack by insects and diseases they are normally able to resist.

The objective of this study is to determine if environmental factors such as soil conditions, or tree properties such as age, are linked with oak decline in Winnipeg. This will be accomplished by collecting, analyzing, and comparing information within a random sample of 200 oak trees throughout the city classified as healthy, moderately declined, or severely declined. Both privately and publicly owned trees will be considered, and analysis will occur throughout the summers of 2002 and 2003. The City of Winnipeg is a project supporter, and has already agreed to allow public trees to be included.

Requests

We are asking your permission to include your tree(s) in the study. Therefore, we require consent to visit your tree(s) for short periods during 2002 and 2003 so that we may collect the following information that will contribute to the understanding of oak decline in Winnipeg:

Location – the whereabouts of the tree(s) in terms of street address. Other measurements, such as the slope of the land and drainage patterns may also be recorded. The tree(s) will have to be tagged for future reference with subtle paint markings or metal labels.

Tree core extraction – as part of a standard procedure to determine tree age and growth history, a small cylinder of wood about 5 mm in diameter will be extracted from the outside of each sample tree to the centre of its main stem. The small hole in the trunk created during this process will pose no more risk to the tree(s) than any other small wound commonly sustained during its lifetime, and will be plugged with a clean wood dowel to prevent disease entry and encourage quick healing.

Soil sampling – we will need to collect approximately four soil samples from the area around each sample tree to determine some physical and chemical properties of the soil. As well, soil strength will be measured using a special soil-penetrating device. The small holes created as a result of these procedures will be immediately refilled with soil, and the grass divots will be replaced, leaving no noticeable damage to the surrounding landscape.

Photography – photographs of the tree(s) and possibly its surroundings will be needed for research purposes. Since the photos may be published in various public forums (not for profit), your permission is requested here. Any private information such as house addresses, or vehicle license plate numbers will be edited out of the photos.

Branch and Leaf Sampling – small amounts of leaves and branches may have to be harvested for analysis in the future.

Site history – you will be asked to complete the attached short questionnaire to give us an idea of the history of the environment surrounding the tree(s) such as past disturbances like flooding, drought, or construction damage. No sensitive personal information will be requested, and you may choose to ignore questions you are uncomfortable answering.

Future permission – it is possible that the study may be followed up in years to come. Therefore, we would like to keep your name, address, and contact information on file as the owners of a tree(s) to visit in the future.

Future modifications – if you were to give permission to include your tree(s) in the study, we would request that no major changes were made in its vicinity from the summer of 2002 to the fall of 2003. Modifications such as construction around the tree(s), heavy pruning or fertilizing, and obviously tree removal would change the results of the study.

Returns

In exchange for your cooperation, we will provide the following information at the completion of the study:

Tree age – it may be interesting to you to know the age of your oak tree(s).

Soil analysis results – these results may tell you if your soil is low in any particular nutrients, which may be limiting plant growth on your property.

Study results – find out if any environmental factors or tree characteristics are linked with oak decline throughout the city, and how their impacts can be reduced.

Details

This study has been approved by the University of Manitoba Joint-Faculty Research Ethics Board. Data collection will conducted in a respectful manner, and will pose little, if any, risk to the oaks. However, the University of Manitoba assumes no responsibility for the health of the trees following the sampling procedures. As well, any samples (soil, wood, foliage) and photographs collected during the study will become property of the Department of Plant Science. Personal information will be kept private, however the tree information may be published. You may choose at any time to withdraw from the study and/or refrain from answering any questions you prefer to omit, without consequence.

Permission

If you are interested in including your oak tree(s) in the study, please give your permission by completing and signing the enclosed consent form/questionnaire and returning it in the provided envelope *as soon as possible*. Thank you for your time.

If you have any questions, please contact Haley Catton at 474-6089, or
umcatton@cc.umanitoba.ca
Concerns or complaints about this study can be directed at the
University of Manitoba Human Ethics Secretariat at 474-7122

Tree # ______

Oak Decline Study Consent Form and Questionnaire

By completing this form, you are giving permission for your oak tree(s) to be included in the study **'An evaluation of bur oak (*Quercus macrocarpa*) decline in Winnipeg'** as described in the attached pages. Even if you are not interested in participating, a quick reply will be very helpful to us. You can indicate this by writing "Not Interested" in the name section and leaving the rest blank – *either way, please return this form in the provided envelope as soon as possible.* Thank you for your time.

Name (printed) ____

Address ____

____

Phone ______________________ Email ______________________________

Date ________________ Signature ___________________________________

Please respond to as many questions as possible, you may ignore questions that you are uncomfortable answering.

1. When did you move to this residence and gain ownership of the sample oak tree(s)?

1930s ____ 1940s____ 1950s____ 1960s ____ 1970s____ 1980s ____ 1990s____ 2000s ____

2. When was your house constructed?

1930s ____ 1940s____ 1950s____ 1960s ____ 1970s____ 1980s ____ 1990s____ 2000s ____

3. Are you aware of any construction activity that has occurred within 10 metres (30 feet) of the base of the sample oak tree(s), for example building or sidewalk construction, excavation, removal or addition of soil?

Yes ____ No ____Description____

When?

1930s ____ 1940s____ 1950s____ 1960s ____ 1970s____ 1980s ____ 1990s____ 2000s ____

4. Are you aware of any major flooding that has occurred within 10 metres (30 feet) of the base of the sample oak tree(s)?

Yes ____ No ____Description ______________________________

When?

1930s ____ 1940s____ 1950s____ 1960s ____ 1970s____ 1980s ____ 1990s____ 2000s ____

5. Are you aware of any major physical wounds sustained by the sample oak tree(s), including heavy pruning and defoliation by insects?

Yes ____ No ____Description ______________________________

When?

1930s ____ 1940s____ 1950s____ 1960s ____ 1970s____ 1980s ____ 1990s____ 2000s ____

6. Do you fertilize the sample oak tree(s)? If so, how?

Yes ____ No ____Description ______________________________

7. Do you fertilize the lawn within 10 metres (30 feet) of the base of the oak tree(s)? If so, how?

Yes ____ No ____Description ______________________________

8. Do you aerate the soil around the base of the oak tree(s)? If so, how?

Yes ____ No ____Description ______________________________

9. Do you water the sample oak tree(s)? If so, how?

Yes ____ No ____Description ______________________________

10. Do you have any other comments about the tree(s)?

____

____

____

Thank you for your time! Please return this page in the enclosed envelope.
If you have any questions, please contact Haley Catton at 474-6089, or
umcatton@cc.umanitoba.ca

Concerns or complaints about this study can be directed at the
University of Manitoba Human Ethics Secretariat at 474-7122

Appendix B: Tree Ring Sample Sizes and Detailed Preparation Methods

This appendix contains supplemental information regarding the tree ring analysis in this study. Figure B.1 details the sample sizes of trees in different categories in the health and city area groupings used in each year from 1900-2001 in Figures 13, 14, and 15. The following text supplements the generalized tree core preparation methods described in the Materials and Methods section (Section 3.2.3.1).

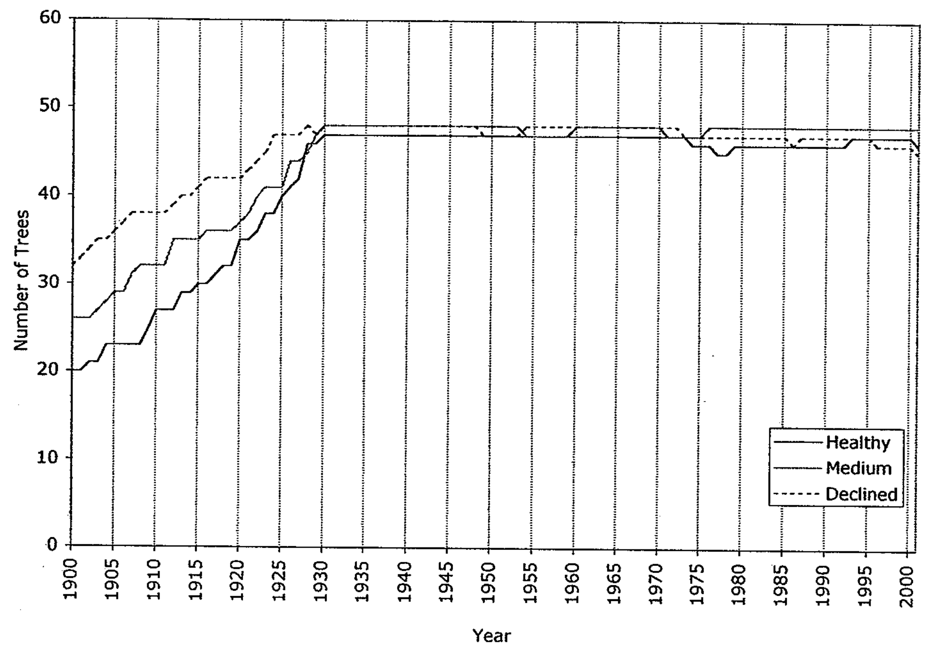
Core Storage

Once extracted, cores were stored in labelled plastic straws with open ends for several months to dry. Most cores came out in once piece, but many broke into several pieces and had to be glued together under a microscope with Carpenter's glue. In extreme cases, the core could be in more than 10 pieces. Due to humid conditions in the storage area many cores developed green mold after approximately one month in the straws. To remedy this problem, the cores were soaked in a 10% bleach solution and rinsed thoroughly with water before being replaced in straws partially cut open to encourage air circulation. The cores were then allowed another 2 months to dry out completely.

Core Preparation

A fully prepared core is one that is permanently secured onto a sturdy mount and finely sanded so that a cross section view of individual vessel and

(a)



(b)

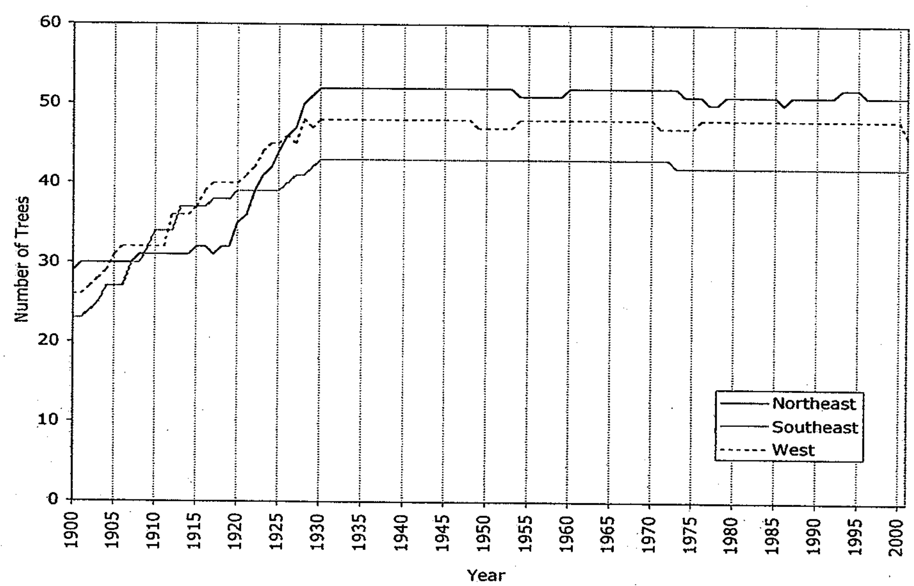


Figure B.1. The number of bur oaks in the tree ring chronology from (a) each health category, and (b) each city area for each year in Winnipeg, Manitoba, from 1900-2001. This figure supplements (a) Figures 13 and 14, and (b) Figure 15. Note that not all sample trees were present before 1930 because trees ranged in age, and some years had missing or distorted rings.

tracheid cells are visible under the microscope. This allows for proper annual ring counting and measuring as well as visual analysis of cell structures. Cores were glued with carpenter's glue into longitudinal grooves 1/4" (0.635 cm) in diameter and 1/8" (0.3 cm) deep on 2/3" x 2/3" x 14" (0.17 x 0.17 x 35.6 cm) pieces of pine wood. Depending on their size, one or two cores were glued to each mount and all had their vessels running vertically to allow for the proper view when sanded.

The glue was allowed 24 hours to dry, then cores and mounts were clamped onto a steady table in groups of approximately 10 and sanded. Two types of electric sanders and six grades of sandpaper of decreasing coarseness were used to smooth the cores and mounts to the desired texture for proper microscope viewing. A DeWalt Random Orbit Palm Sander with a rotating 5" disk was used with sandpaper grades of 60, 100, 150, and 220 grit for quick smoothing of large areas. Finer smoothing was done with a DeWalt 1/4 Sheet vibrating sander with sandpaper grades of 400 and 600 grit. At this point the cores were completely prepared for data collection.

Appendix C: Ring Widths and Urban Development

Observations of individual tree ring series and limited information available on the timing of local building construction, gravesite excavation around cemetery trees, and other disturbances revealed that in most cases, tree ring width series did not respond dramatically to known disturbances. This was surprising in many cases, where it seemed obvious that disturbed trees would have suffered badly from root loss or other detrimental effects. However, in some trees, one of two distinct patterns was recognized in response to known urban development: growth suppression or growth release.

Case Study 1: Growth Suppression

A ring width suppression pattern after urban disturbance was clearly seen in 9 of the 180 trees based on visual interpretation. A good example of this was seen in a declined tree in the northeast part of the city (Figure C.1). This tree was approximately 9 m tall and 9 m away from a church (with a basement) that was constructed in 1961. The dramatic drop in ring width at that time suggested that the tree may have been severely harmed by the excavation and construction activity, likely from root loss and soil compaction. However, after approximately 10 years of slow growth, the tree began to recover and return to producing more normal ring widths. The tree once again had a dramatic drop in growth in 1997-

2001 for reasons unknown, and it is not clear if the dieback seen in the crown in 2002 was from the 1990s, the 1960s, both, or neither. More research, specifically dating the dead braches using their tree rings, could reveal when the dieback occurred.

Case Study 2: Growth Release

Urban development could have a positive effect on tree growth, as was seen in 10 of the 180 trees based on visual interpretation. A good example of this was seen in a declined tree located in a front yard in an established neighbourhood in the western part of the city (Figure C.2). This tree was approximately 20 metres tall and was 13 metres away from two houses built in 1914. Prior to the construction of the houses, the tree consistently had relatively narrow rings. However, immediately after the construction, rings more than doubled in width, indicating that tree growth was released with the construction of the houses. This is possibly because the tree was suddenly exposed to more resources (especially light) as larger, competing trees were likely removed to construct the houses. The tree rings slowly became narrower with time, especially during the 1950s, for reasons unknown. More site-specific historical research would be needed to learn about the reasons for the decline in this tree.

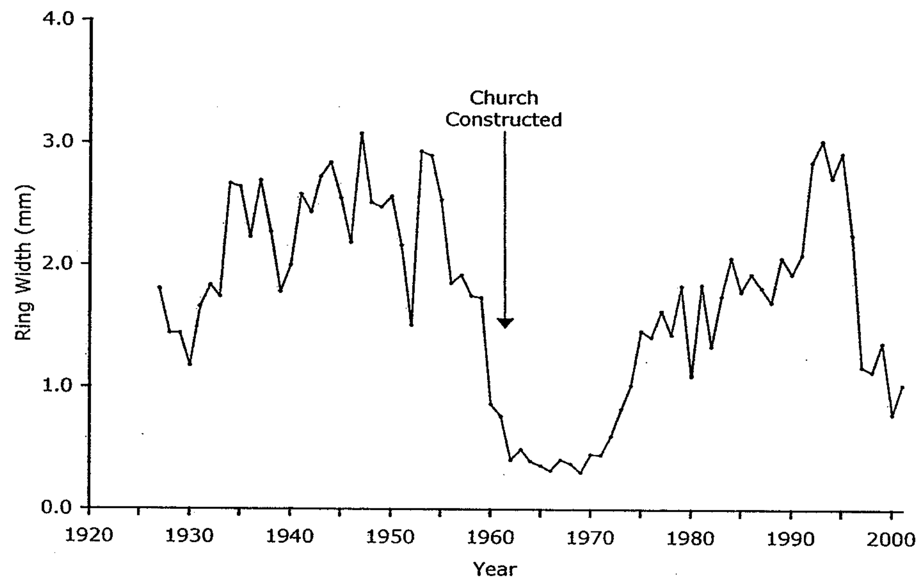


Figure C.1. Annual growth ring widths for a declined bur oak tree near a church constructed in 1961, in Winnipeg, Manitoba. The pattern demonstrates growth suppression and recovery after urban disturbance.

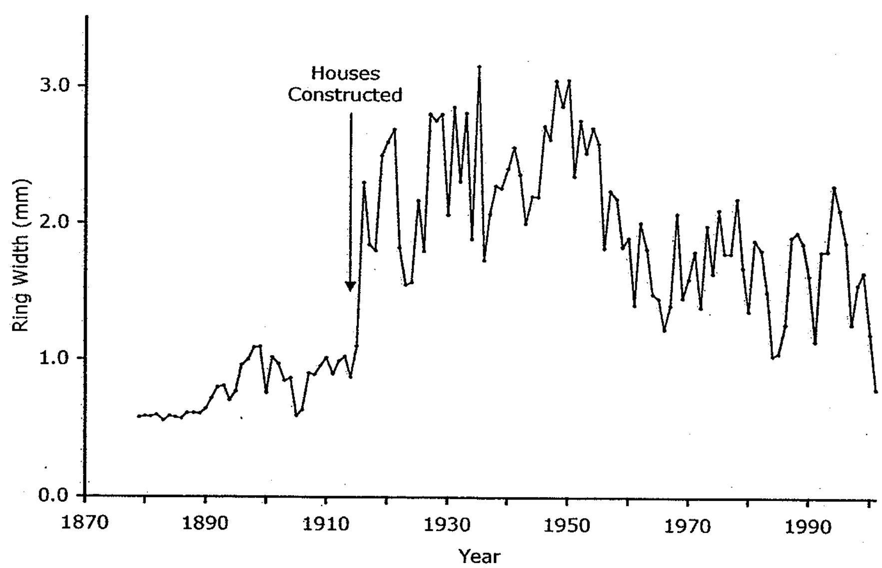


Figure C.2. Annual growth ring widths for a declined bur oak tree near houses constructed in 1914, in Winnipeg, Manitoba. The pattern demonstrates growth release after urban disturbance.

Appendix D: Foliar Nutrient Levels of Trees in Soil Study

The foliar nutrient levels of the trees sampled in the soil study are presented in Table D.1.

Table D.1. Leaf nutrient levels (mean ± standard deviation) for the 22 bur oak trees in Winnipeg, Manitoba, where soil was analyzed (see Table 9). Trees were grouped by health category, city area, and their surroundings. Category values within the three groupings with no letters in common were statistically different ($P<0.05$).

Categories	Number of Trees	%N	%P	%K	%S	%Ca	%Mg
Healthy	12	2.63 ±0.27 *a*	0.22 ± 0.06 *a*	0.86 ± 0.13 *a*	0.16 ± 0.02 *a*	0.99 ± 0.16 *a*	0.39 ± 0.08 *a*
Declined	10	2.55 ± 0.22 *a*	0.23 ± 0.05 *a*	0.84 ± 0.19 *a*	0.16 ± 0.03 *a*	1.05 ± 0.32 *a*	0.37 ±0.12 *a*
Northeast	8	2.72 ± 0.24 *a*	0.21 ± 0.05 *a*	0.87 ± 0.16 *a*	0.18 ± 0.03 *a*	1.04 ± 0.23 *a*	0.37 ± 0.11 *a*
Southeast	7	2.41 ± 0.19 *b*	0.26 ± 0.05 *a*	0.90 ± 0.15 *a*	0.14 ± 0.01 *b*	1.09 ± 0.19 *a*	0.40 ± 0.08 *a*
West	7	2.63 ± 0.22 *ab*	0.20 ± 0.06 *a*	0.77 ± 0.14 *a*	0.16 ± 0.01 *ab*	0.92 ± 0.29 *a*	0.36 ± 0.11 *a*
Urban	10	2.62 ± 0.21 *a*	0.25 ± 0.06 *a*	0.91 ± 0.17 *a*	0.16 ± 0.02 *a*	1.07 ±0.24 *a*	0.39 ± 0.10 *a*
Forest	6	2.54 ± 0.33 *a*	0.22 ± 0.05 *a*	0.71 ± 0.09 *b*	0.15 ± 0.02 *a*	1.12 ± 0.21 *a*	0.37 ± 0.11 *a*
Golf Course	6	2.60 ± 0.22 *a*	0.19 ± 0.04 *a*	0.89 ± 0.08 *a*	0.17 ± 0.02 *a*	0.84 ± 0.20 *a*	0.37 ± 0.08 *a*
Total	22	2.59 ± 0.24	0.23 ± 0.06	0.85 ± 0.16	0.16 ± 0.02	1.02 ± 0.24	0.38 ± 0.10

Appendix E: Drainage and Urban Development

During the course of this study, several cases were observed in Winnipeg where altered drainage patterns appeared to lead to subsequent decline of bur oaks (Figure E.1). The first was in Assiniboine Forest, where the construction of a walking path was presumed to have impeded existing drainage patterns in an adjacent area containing aspen and bur oak. Declining bur oaks in this newly wet area were large, indicating that growing conditions had been changed because the trees would not have been able to reach their current sizes under unfavourable growing conditions. The second case was in a residential area in the south part of the city where the construction of a neighbourhood, school and skating arena are hypothesized to have changed drainage patterns enough that bur oaks in a nearby forested region declined and died, with the original understory being replaced with moisture-loving grasses (D. Walker, personal communication).

It is possible that oaks in forested environments are more subject to drainage issues than urban oaks, because residential areas are equipped with man-made drainage systems designed to remove excess standing water. It is also possible that effects of changed drainage in forested areas are not always considered (or valued) during the planning stages of urban development, and therefore those regions are more likely to suffer from water-logged soils.

(a)

(b)

Figure E.1. Bur oak decline sites in Winnipeg with poor drainage, presumably from the effects of urban development. Standing water can be seen at the bases of the trees. Photographs were taken in fall of 2004. Locations are (a) Assiniboine Forest, where the construction of a walking path is presumed to have caused the drainage problem, and (b) a formerly forested area near a new neighbourhood and outdoor skating rink in the south part of the city, where the normal oak forest understory plants had been replaced with water-loving marsh grasses.