The Status of Forest Health in Southern Ontario: An Assessment using Tree Mortality Rates

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Executive Summary

Concerns over forest health and decline in North America continue (Ayers *et al.* 1998). Pollutant-induced forest decline has been documented in at least 25 states across the eastern U.S. (Loucks, 1998a). Similar declines have been recorded in the forests of Eastern Canada and the accumulation and analysis of basic forest data is ripe with opportunity for synthesis (Brydges *et al.*, 2002). Tree mortality is a vital but poorly understood process of forest dynamics (Franklin *et al.* 1987) that must be documented if we are to understand the effects of environmental stresses on our forests (McCune *et al.* 1988). Tree death data has recently been used as a measure to determine long-term trends in forest health over a hierarchy of local, regional, and sub-continental scales (Loucks, 1998a). Theory and field data suggest that in healthy deciduous forests (mature and old-growth) annual basal area tree mortality ranges from 0.2-0.8% and that small sustained changes in mortality can induce large structural and compositional changes over time (Loucks, 1995;1998b; McCune *et al.* 1988; Pedersen and McCune, 1990; 2002).

Forest data for southern Ontario was compiled from Ecological Monitoring and Assessment Network (EMAN) Terrestrial Vegetation Monitoring Plots at Niagara Escarpment (NEBR) and Long Point World Biosphere Reserves (LPWBR), the Ontario Ministry of Natural Resources (OMNR) Growth and Yield Program, the Canadian Forest Service (CFS) Acid Rain National Early Warning System (ARNEWS) and the North American Maple Project (NAMP). Mass-based tree mortality rates were used to establish tree mortality rates across a variety of forest types, determine successional turnover, and assess whether regional forests were experiencing significant decline.

Although the forests of southern Ontario are subject to a wide array of natural stressors (i.e. soil moisture deficiency, extreme weather events, insects, and diseases) and human stressors including fragmentation, historic timber and fuelwood extraction, high loadings of ground-level ozone and in some cases exceedence of acid deposition targets, overall, they continue to exhibit a high degree of resilience. Our assessment concurs with other research indicating that forests in southern Ontario are generally healthy (Bowers and Hopkin, 1997; Lachance *et al.* 1995; McLaughlin *et al*. 2000).Composite data from across divergent environmental and pollutant regimes exhibited surprisingly similar basal area mortality rates within or close to the 0.2-0.8% range as might be expected under natural conditions caused by pest damage and thinning of stands. Divergent mortality rates exhibited by some of the sites analyzed are linked to issues of sampling scale and forest type, stand age, and management. At sites where we can infer that present

mortality rates are higher than the long-term average extant forest stands should be closely monitored.

Although the highest sulphur and nitrogen deposition rates occur in southwestern Ontario decline may not be expressed via tree mortality in southern Ontario forests due to the high buffering capacity of the underlying limestone and dolostone (Arp *et al.* 1996). Consequently a holistic monitoring approach is necessary to account for the range of ecosystem processes that affect forests (i.e. short-term annual tree growth to the slow decades-long process of soil acidification). With growing evidence linking declining soil condition to decreased forest growth and resilience to natural stresses (Likens *et al.* 1994; Ouimet *et al.* 2001; Ryan *et al.*, 1994; Watmough, 2002) there is an obvious need to develop a standardized program for monitoring tree growth and mortality. Continued research and monitoring, joined together in a system model of how forests function to maintain their resilience, are necessary to track forest health, assess the effectiveness of current critical pollutant load targets and ensure that forest health is maintained.

Introduction: Forest Decline in North America
Forests are of critical importance to Canadians because of their ecological, social, and economic value. A healthy forest can be described as one that over time maintains its ecosystem functions and ability to recover from disturbance even under changing environmental conditions. Forest decline on the other hand is a sustained deterioration away from this state, ultimately leading to tree mortality. In recent years concerns have developed over pollutant-induced forest decline occurring in at least 25 states across the eastern United States and at many sites in eastern Canada. At many of the monitoring sites in the U.S. tree mortality has increased two to three times historical rates (McCune *et al.* 1988; Loucks 1998b). A variety of biotic and abiotic stresses, including soil moisture deficiencies, extreme weather events, defoliating insects and root disease influence forest health (Horsley *et al.* 2002). Although the patterns and causes of tree death are complex forest decline has been linked to pollution in combination with naturally occurring phenomenon, such as drought, freeze-thaw cycles, and insect defoliation (Brydges *et al.* 2002; Hall *et al.* 1996).

The chief pollutants affecting forest health include sulphur and nitrogen deposition and ground-level ozone (Canadian Forest Service, 1999). These pollutants affect forests in many ways including: decreasing tree growth; reducing forest productivity; leaching important nutrients such as calcium and magnesium from forest soils; and increasing tree sensitivity to frost (Canadian Forest Service, 1999; Likens *et al.* 1996; Morrison *et al.,* 1992). A recent review of forest health and decline by Brydges *et al.* (2002) documents the mechanisms by which acid rain and other air pollutants damage forests and concludes that pollutants are probably causing additional stress on trees making them more susceptible to insects, diseases, climatic extremes, and nutrient deficiencies.

In Canada it is estimated that 10-15% of our most productive forests have nutrient deficient soils due to decades of acid rain and that these same forests may now be subject to damaging levels of air pollution (Brydges *et al.* 2002). In Ontario 40 million hectares of forest, primarily on the Boreal Shield and Mixedwood Plains, are subject to sulphur

and nitrogen deposition in excess of the critical load (Watmough *et al.* 2004). The cumulative effect of acid rain deposition coupled with extreme climatic conditions (i.e.frost or drought), insect and disease damage, have contributed to decline in areas of Ontario and Quebec (Bowers and Hopkin, 1997; Brydges *et al*. 2002). These prevailing concerns were the impetus for Environment Canada's Ecological Monitoring and Coordinating Office (EMCO) to initiate a research project investigating tree mortality rates in southern Ontario.

Assessing Health in Southern Ontario: Project Overview
The project study area covers the Mixed-Wood Plains (MWP) ecozone of southern Ontario, which includes the Lower Great Lakes–St. Lawrence River Valley (3.7 million ha of forest) and is underlain by carbonate-rich Palaeozoic bedrock (Figure 1). This area is of particular interest because pollutant deposition is higher than in other ecozones of Canada (Miller *et al.* 1990) due to incoming pollution from the American midwest and high urbanization. Many large urban and industrial areas within the MWP are also sources of air pollution (Environment Canada, 1996). Sulfate deposition has been decreasing since 1984 and currently ranges from 21-38 kg/ha/yr (Canadian Forest Service, 1999). Nitrogen deposition rates remain high currently varying from 16-25 kg/ha/yr (Canadian Forest Service, 1999). Ground-level ozone in the MWP reaches the highest concentrations in Canada, at levels and of duration, that are enough to induce short-term damage to sensitive plant species (Pearson and Percy, 1997). In large areas of Ontario and Quebec acid deposition rates are presently higher than the buffering capacity of soils and associated forest stands are projected to decline by 30-40% (Canadian Forest Service, 1999). Such projections of pollutant-induced decline raise a number of pressing research questions including:

- What are current tree mortality rates for forests in southern Ontario?
- Are changes in forest condition greater than can be attributed to typical trends and levels of natural variability?
- What patterns, if any, exist in forest condition (i.e. overall basal area growth; basal area tree mortality) and how do these patterns relate to pollutant exposure?

Figure 1: Study Area showing the location of Forest Monitoring Plots Assessed

Ontario

132

133

134

135

Monitoring Sites

▲ NAMP

▲ ARNEWS

▲ LPWBR (4)

▲ NEC
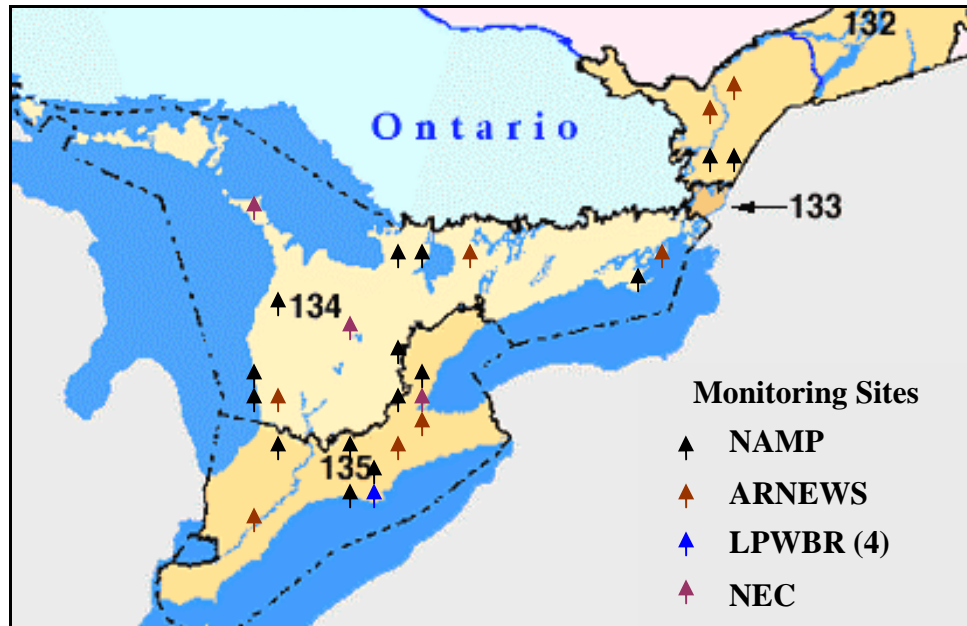
In order to maintain the health of our forests we must understand them as dynamic systems and track how these ecosystems respond to change. Answering the above research questions is a first step to anchor the development of a long-term monitoring program to track forest health.

Available forest data enabled us to determine current basal area mortality rates. Answering the second question however is complicated by the fact that tree mortality data exists only over short periods of time covering the past 10-20 years while impacts from acid rain are thought to have begun in the 1950's (Cogbill and Likens, 1974). Ideally, we would compare present basal area mortality rates in southern Ontario forests with historic rates that predate the compounding influence of pollution. This would enable us to establish a baseline for tree mortality before the onset of pollution impacts, compare pre and post 1950's rates, describe to what degree forest processes may be changing and determine whether this may be of concern. In lieu of such data we relied on theory and accompanying historical data from the floristically similar eastern U.S. that suggest the typical range for basal area mortality is 0.2-0.8 % of total basal area (Loucks, 1995; 1998b; McCune *et al.* 1988; Pedersen and McCune, 1990; 2002). Over a ten-year period we would expect to see 2-8% successional turnover, while over a hundred years this would amount to 20-80% of the forest. Even a doubling of the mortality rate (0.4-1.6%) would induce significant change in forest succession in terms of rates of turnover, composition, biodiversity, age distribution and stand structure including an altered understorey with excess canopy gaps and coarse woody debris (Loucks, 1995; 1998a). Such increases in the rates of tree mortality during the seventies and eighties across deciduous forests in a large portion of eastern North America (i.e. Tennessee, Wisconsin, Illinois, Indiana, Kentucky and Ohio) have been linked to anthropogenic stress, the effects of which are still being felt in these forests (Loucks, 1998b).

Although important, determining whether recognizable patterns in forest condition relate to natural stressors and pollutant exposure is not the intent of this initial study. Some

recent work has linked patterns in forest decline in Ontario to critical load exceedances (Watmough *et al.* 2004). Where appropriate such knowledge informs analysis of the basal area tree mortality rates and provides direction for future research.

In light of the above limitations the primary purpose of this research was to compile and analyze available data sources to determine current basal area tree mortality rates and develop a present-day baseline against which to measure future change.

Mass-based Tree Mortality Rates: A Rationale

Tree mortality is a vital but poorly understood process of forest dynamics (Franklin *et al.* 1987) that must be documented if we are to understand the effects of environmental stresses on our forests (McCune *et al.* 1988). Tree death data has recently been used as a measure to determine long-term trends in forest health over local, regional, and sub-continental scales (Loucks, 1998a). Total forest growth has been shown to be fairly constant in forests over long periods. Peet and Christensen (1987) have also shown mortality to be relatively constant in mature forests. The amount of biomass loss due to mortality continues to increase up until it nears the total annual biomass increment at which point it exhibits quasi-equilibrium over long periods of time (Figure 2). This means that the rate of mortality (%), expressed as the annual mortality increment of standing biomass over total standing biomass, should be relatively stable in healthy, mature (+100 yrs) to old-growth forests (stable or declining biomass).

The dynamic balance of biomass is a result of the constant probability of tree death as forests age (Harcombe, 1987). Although the number of trees dying annually declines the trees in older age classes that do die are relatively large and their effect on total biomass is noticeable. Mature and semi-mature forests are expected to exhibit lower rates of basal area mortality because although more stems are dying during this successional stage dying stems are on average smaller than in later old-growth stages and this basal area loss is offset by the vigorous growth of the competing cohort. Tree basal area mortality (basal area lost/hectare/year) is an effective surrogate measure of biomass change, and energy allocation and retention by the forest.

Figure 2: Annual Change in Biomass showing Periodic Growth and Mortality Rate
(IBP Woodlands Dataset 1964-1974; after Gardner and Mankin, 1981)
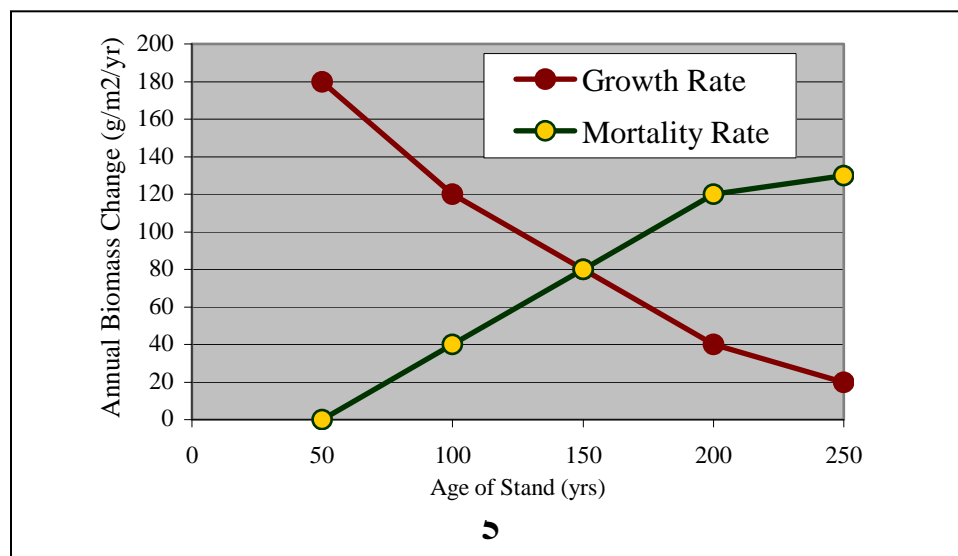
Methods: Calculating Basal Area Tree Mortality
The ongoing collection of forest data and reinventory of established forest monitoring plots in some areas of Ontario allowed for temporal comparison and assessment of changes in tree mortality. Forest data was compiled from EMAN Terrestrial Vegetation Monitoring Plots at the LPWBR and NEBR, OMNR Growth and Yield plots, the CFS ARNEWS and NAMP sites. Data sharing with the Ontario Ministry of the Environment is also being pursued. Partnering with various organizations that have been gathering forest data provided a robust dataset from 87 plots that cover the MWP ecozone. The datasets cover the period from 1985-2004 although the longest period of any individual dataset is 15 years. Please refer to agency manuals for methods of data collection (D'Eon *et al.* 1994; Hayden *et al.* 1995; NAMP, 1998; Roberts-Pichette and Gillespie, 1999).

Data analysis followed the methodology of Loucks (1995). Basal area tree mortality rates were used to assess whether regional forests were experiencing significant decline. Basal area is simply a measure of the cross-sectional area of a tree trunk at a standard height of 1.3 m above the ground. Basal area mortality, the basal area lost/hectare/year, was calculated using the following five-step methodology:

Basal Area Mortality Rates
1. Calculate total basal area (m^2) of live stems/area (ha) for each sample year.
2. Calculate periodic growth (basal area) increment for the periods between samples
   Eg: 2000-2003 growth increment = 2003 basal area – 2000 basal area/3yrs
3. Calculate periodic mortality (basal area) increment for the same periods between samples. Eg: 2000-2003 periodic mortality increment = the 2000 alive standing basal area of trees found dead in 2003/3yrs
4. Calculate Total periodic growth rate for the same periods
   Eg: 2000-2003 total periodic growth rate = periodic growth increment + mortality Increment
5. Calculate basal area mortality rate (%) for each period
   Eg: 2000-2003 basal area mortality rate = 2000-2003 periodic mortality increment / mean total basal area of 2000 and 2003

Output is simplified if the period used for calculation is per annum. Basal area mortality rates can also be delimited by species or size (dbh) classes. An Excel® spreadsheet template was developed into which all data was entered and analysed. Basal area mortality rates were calculated for all periodic reinventories of each dataset and then compared to the range (0.2-0.8 % of total basal area) suggested by Loucks (1995; 1998b). There are a number of notable differences between the forest data on which the baseline mortality range is based and the forest data available for Ontario.

Limitations of Data and Comparison
- Although forest datasets in the US and Canada are drawn from deciduous forests that may differ in species composition, studies indicate that mortality rates from

low pollutant areas/eras are frequently within the 0.2-08 % range although forest types may be diverse. Nonetheless, tree species composition and underlying soils do vary considerably between the US data and that of Ontario (sandstone versus southern Ontario's limestone and dolostone) and this may have some effect on natural baseline mortality rates.

- In most cases Ontario sites have not yet reached maturity and are still accumulating biomass. In comparing younger stands to a mature-old growth mortality index one must account for the fact that lower total biomass under accumulation will tend to decrease the basal area mortality measurement. High mortality rates in young stands are cause for concern. A confounding factor is that no absolute age data exists with which to correlate basal area growth/loss.
- Basal area mortality only begins to exhibit equilibrium when calculated over relatively long periods of time in mature forests. At most the longest period of any individual Ontario dataset is 15 years with four reinventory periods. This time frame is somewhat short relative to the successional dynamics of an aging forest.
- Plot size is also a major factor influencing calculated rates basal area mortality. The purposes of forest monitoring programs in Ontario are diverse as are the sizes of plots from which they draw data. Some of the smaller plots assessed in this research exhibit high variability because of the large influence of individual trees and may simply be too small to accurately reflect stand level mortality rates.

These limiting factors are considered when interpreting the available forest health data. Despite the challenges in using the 02-08% range for comparison it is the only such measure available and is useful even if only as a general index to measure how similar mortality rates in Ontario are to those in other deciduous forests.

Basal Area Tree Mortality Results
The summary of each agency dataset includes considerations regarding the data available, plot size, and stand type and history. Tree mortality rates for each site are discussed in light of these factors. Detailed data on all forest plots and datasets can be obtained through the EMCO.

EMAN Plots at LPWBR and NEBR
The EMAN plots in the Long Point and Niagara Escarpment Biosphere Reserves provide indepth information on trees within a 10 000 m^2 area. Backus Woods is an old growth upland hardwood Carolinian forest dominated by oak (*Quercus* sp.*)* and maple (*Acer* sp). Over the eight-year period of monitoring at LPWBR (1995-2003), basal area accumulation in Backus Woods tapered off considerably by over an order of magnitude, while basal area mortality increased only slightly which suggests that the forest is reaching internal biomass quasi-equilibrium. The annual mortality rates observed in this mature forest, 0.38% from 1995-2000 and 0.65% from 2000-2003, are well within the natural range expected for old growth forests (Figure 3). The recent reinventory shows a noticeable increase in broken trees however at the current level "snap offs" are not significant in relation to total stems or biomass. The increase in "snap offs" and higher ratio of dead fallen trees in the most recent survey, perhaps suggests the plots experienced more severe weather in the years prior to the 2003 inventory. A major storm

was reported for the area in 2001 (Craig, 2003). It is also possible that it is not the weather that has changed significantly but the susceptibility of trees to weather events.

Wilson Tract is a similar forest to Backus however it is a managed forest. Basal area mortality in Wilson Tract is low (0.14% 1995-2003) likely because it is still maturing and has been subject to historic timber harvest and fuelwood extraction. Data on tree ages in these two stands would be valuable.

The eastern flowering dogwood (*Cornus florida*) dieback first noted in 2000, has continued to increase over the last eight years and to date 72% of the dogwood in Backus Woods have died. A similar pandemic has occurred in Wilson Tract. This is primarily the result of *Discula destructiva*, a fungus that kills dogwoods of all sizes but is particularly severe on seedling and understorey trees. If left unchecked, *D. destructiva* has the potential to destroy the significant dogwood population found in the LPWBR.

Red (*Quercus rubra*) and black oak (*Q. velutina*) have been shown to be less stress tolerant than other deciduous species (Pedersen and McCune, 1990). Due to the dominance of these species in Wilson Tract and Backus Woods combined with the near decade-long reinventory period mortality rates of these two species were investigated. At both sites oak mortality was low, reaching 0.38 % and 0.35% for Wilson Tract and Backus Woods respectively. Although well within the expected range, the rate at Wilson Tract is higher than that of the site overall. While basal area growth is increasing onsite, at this successional stage oaks are exhibiting relatively slow basal accumulation (0.07 cm^2/yr) compared to the stand as a whole as they are out competed by other species. The current mortality rate is a result of these stand dynamics combined with the death of one large oak.

The Turkey Point 1 and 2 plots are located in oak parkland (primarily black oak) and natural oak-pine forest (primarily oak, white pine [*Pinus strobus*] and black cherry [*Prunus serotina*]) respectively. The important ecological role of fire in maintaining Oak parkland is evident in a comparison of the two Turkey Point plots. Fire acts as a successional release by killing trees and understorey vegetation and freeing formerly locked-up light and nutrient resources for colonizers (Kimmins, 1987). In the undisturbed parkland of Turkey Point 2 the mortality rate was 0.99%. Turkey Point 1, which underwent prescribed burns in 1993 and 1999 has had a 7.27 % annual mortality rate. The halted succession has produced a canopy that is patchy and colonizing species including black cherry and young, shade-intolerant trees, black and white oak (*Quercus alba)* have begun to appear.

NEBR plots are in mature upland deciduous forests comprised of a diversity of species with sugar maple (*Acer saccharum*) being dominant. The mortality rates in the NEBR plots are just above the upper limit of the range for healthy mature deciduous forests. Cabot Head had a 0.87% annual mortality rate from 1998-2003. Hockley Valley was somewhat higher at 0.96% for 1997-2003, while Hilton Falls (1996-2001) was highest at 1.36%. These forests are semi-mature with a dynamic mortality and recruitment in the understorey (Laurence, 2004). Second-growth forests do exhibit pulses of high mortality

due to internal stand dynamics including aging, competition, and thinning (Loucks, 1998b), which may account for the higher observed rates. The higher basal area loss at the Hilton Falls site is a combination of factors including death of suppressed trees accounting for nearly 50% of basal area mortality (no trees over 40cm dbh died) and possibly the harsh growing conditions of shallow and gravely soils. Some selective harvesting has occurred on the site, but additional historical disturbance factors are not known. The site is also in an area of excess sulfate (>26kg/ha) and nitrate (>20kg/ha) deposition.

Figure 3: Basal Area Tree Mortality Rates in Forests of Long Point Biosphere Reserve and Niagara Escarpment Biosphere Reserve
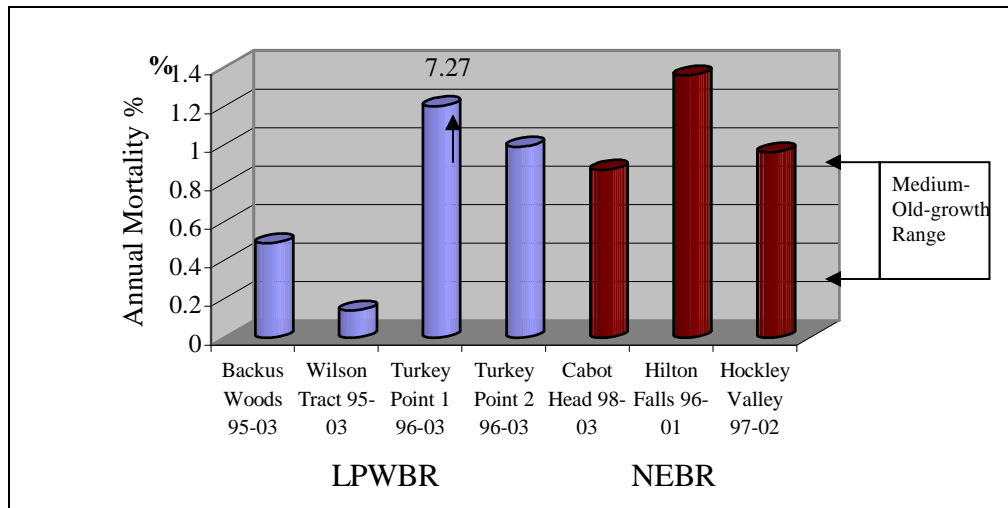
ARNEWS Plots
The ARNEWS plots, established in 1984 by the CFS to monitor the effects of acid rain on Canadian forests, provide data from 1985-2000. The eight plots in the MWP ecozone are comprised of white spruce *(Picea glauca)*, white pine, sugar maple, black cherry, black oak and white oak.

All but one plot exhibited low mortality rates over the 15 year period (Figure 4). A variety of diseases and insects were the ultimate cause of many of the trees deaths. In plot 506 webworm and trump skeleton killed the one tree lost from 1990-95, while root flare rot was responsible for the tree loss of 1985-90 in 507. On plot 517 one tree was lost to white pine blister rust. In the early 1980s P.E. and basal stem canker were evident in plot 518 and between 90-95 armillaria was the causal agent of tree loss. Bark beetle holes were evident in one of the trees lost on plot 519 in 1998, however, there it is also possible that the elevated rate for 95-00 is due to ice storm damage in 98 and residual effects through to 2000. Both plots 525 and 526 had no measurable basal area lost during measurement from 1985-1995.

The elevated mortality in plot 508 is due to the death of one large tree in each of the three

5 year sampling periods as a result of storm damage and Maple webworm infestation. The tree lost in 1998 was a result of ice storm damage. During the highest period of loss (90-95) the dying tree showed a 46-55% decline in crown condition before succumbed.

Due to the small size of ARNEWS plots (400m^2) mortality rates are strongly influenced by individual tree deaths particularly if individuals are large. This small sampling scale results in mortality rates that exhibit high variability over the 5yr reinventory periods for each plot (see Figure 4). A larger sample area would better reflect stand level mortality rates at these sites.

Figure 4: Basal Area Tree Mortality Rates in ARNEWS Plots 1985-2000
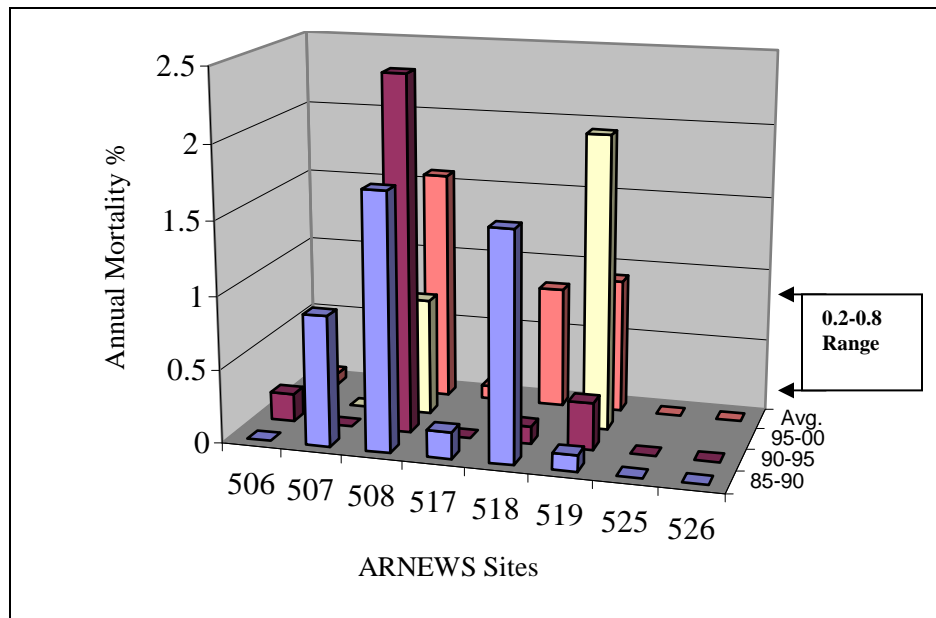
The minimum ages of stands in these ARNEWS plots range from 36-103 years. Although minimum tree age data does not allow us to develop confident correlations between stand age and mean basal area or its accumulation it does provide some insight into past mortality rates. The case of plot 508 is particularly interesting as it has the highest mortality rate, 1.58 % over the last 15 years and is also at a minimum 103 years old. This high rate of mortality translates into a complete 100 % turnover of trees within 63 years. A sustained annual loss rate of 1.58 % would result in a forest where trees do not reach mature-old growth states. In plot 508 however, there are trees on site that are over 100 years old meaning that historically lower mortality rates must have been the norm on this site. We can infer from this that the present mortality rate is higher than the long-term average and that at this rate the extant forest ecosystem will undergo considerable change. This stand should be closely monitored over the coming years.

NAMP Plots
The NAMP was a joint undertaking initiated in 1988 by the CFS and the United States

Forest Service to monitor the health of sugar maple across its range. The 16 maple-dominated plots assessed also include hemlocks (*Tsuga sp.*), hickory (*Carya sp.*) cherry, ash (*Fraxinus sp.*), beech (*Fagus sp.*) and conifers.

The results of the tree mortality assessment of NAMP data is somewhat complicated by the fact that eight of the stands are managed sugar bushes. Also because the plots are intermediate in size (2000m^2) any tree harvest has large influence on basal area mortality rate. The high mortality rates (+ 0.8%/yr) at sites 1, 5, 15, and 19 are attributable to harvests on the site (Figure 5). When human harvest is removed as a mortality factor rates are all within the 0.2-0.8 range. Tree harvesting has occurred on all sites except 4, 14, and 17 and contributes to elevated mortality rates overall. Results suggest that sugar maple in these stands are healthy.

Figure 5: Basal Area Tree Mortality Rates in NAMP Plots 1988-1998
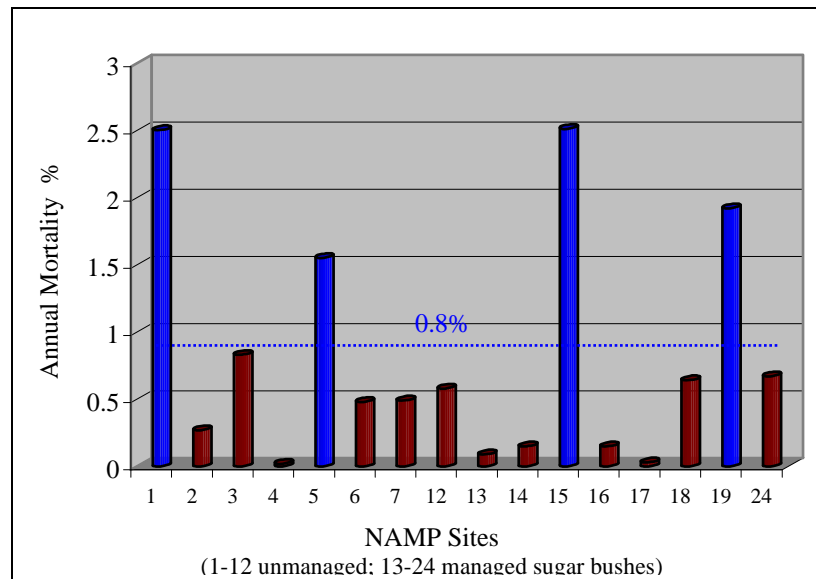
Of note is the variability in mortality rates over the two 5 year reinventory periods (Figure 6). In plots where harvests have occurred the mortality rate is elevated immediately in the harvest year while in subsequent years mortality is often quite low as new trees become established increasing basal area and offsetting mortality. Plots 1, 3, 5, and 13 are good examples of this phenomenon. Plots 4, 14, and 17, which have not experienced harvest, exhibit much less variability and mortality rates that are on average lower by over an order of magnitude (0.07% vs. 0.97%). These unaffected rates are the most accurate reflection of the natural rate of mortality in similarly young maple stands.

Figure 6: Basal Area Mortality Rates for 5 yr periods (1988-1998) in NAMP Plots
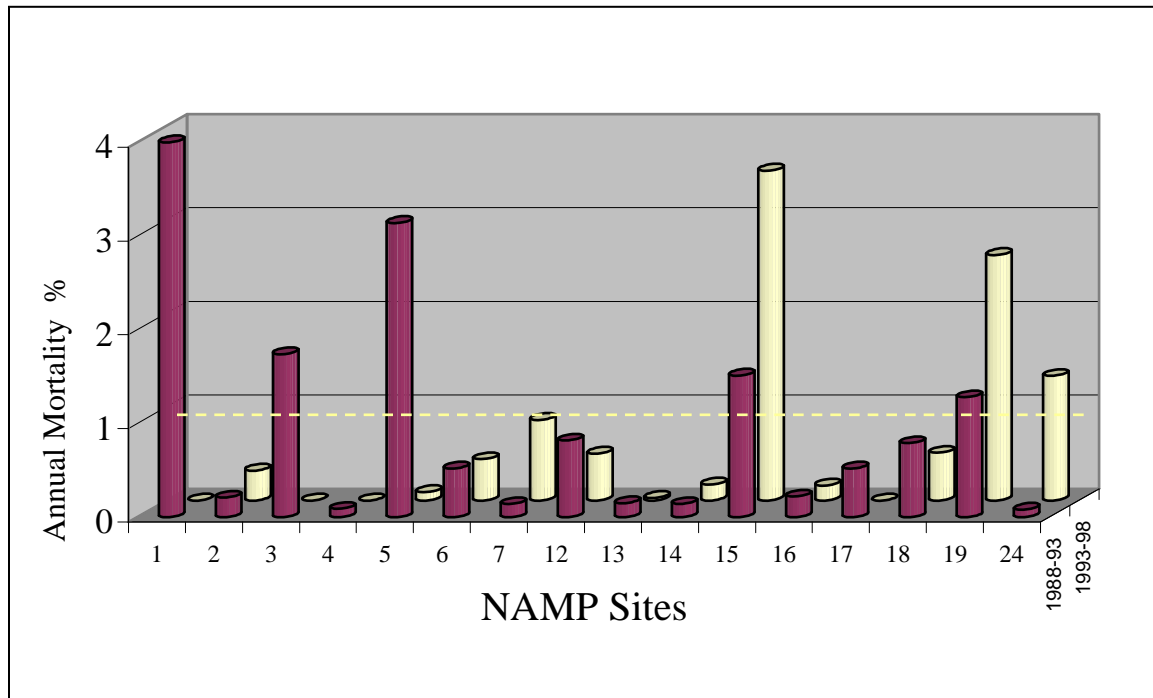

OMNR Growth and Yield Plots

The OMNR Forest Growth and Yield Program is a collection of 4000 permanent sample plots designed to monitor the growth and dynamics of Ontario's forests in order to create computer models to predict future growth and dynamics (Hayden *et al.* 1995). The three growth plots at each site were used for a total plot area of 1600 m^2. As a group the data from the 52 unmanaged sites analyzed spans 1993 to 2001, however, most plots only have data for a 3, 4, or 5 year period. The predominant tree species onsite include: sugar maple, white ash, basswood, oaks and beech.

Of the 52 sites assessed 7 have mortality rates below 0.2%, 15 are between 0.2-0.8%, while 30 have mortality rates >0.8%. As a group average mortality is 0.96%. There are some sites (i.e. 13, 217, 1203, and 5209) that exhibit very high mortality rates (3.9% being the highest). The elevated rate on plot 13 is due to the death of one very large tree, 72.3 cm dbh, while the rate on plot 217 was similarly influenced, though less so, by the death of a 63.9cm dbh tree. Although, there is no forest age data available with which to investigate its relationship with mortality rates or infer maximum historical mortality rates the maximum dbh on these sites (66.1-72.3 cm) suggests that these are not young forests. All sites analysed were mature or rated as sawlog stands meaning that mortality would be expected to be near the upper limit of the 0.8% range although not consistently above this range. The time period over which mortality rates have been measured on these four sites ranges from 3 years to 7 years. Over this short time period there is no significant correlation between mortality rates and maximum tree dbh. Sites across southern Ontario from the district of Kemptville in the east to Cambridge in the west,

ranging from sugar maple-beech stands to black and red oak stands of low and high productivity exhibit elevated rates. Under natural conditions future annual rates at these sites should decrease considerably especially on sites where single large trees have succumb over the reinventory period. More moderate long-term stand mortality is expected unless of course other stressors are present. Continued monitoring will be essential.

Figure 7: Basal Area Tree Mortality Rates in OMNR Growth and Yield Plots 1993-2001
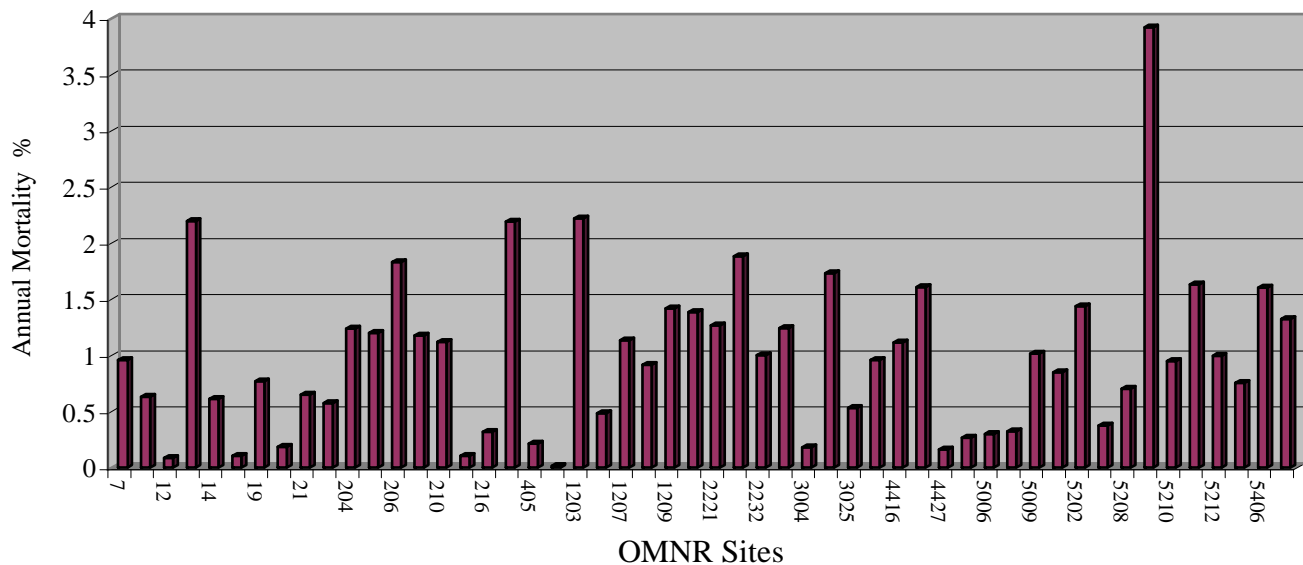
Summary Discussion

Although the forests of southern Ontario are subject to a wide array of natural stressors (i.e. extreme weather events, insects, and diseases) and human stressors including fragmentation, historic timber and fuelwood extraction, high loadings of ground-level ozone and in some cases exceedence of acid deposition targets, overall, they continue to exhibit a high degree of resilience. For the most part tree mortality rates indicate healthy turnover which if sustained will allow forests to progress along expected successional trajectories towards a state of old-growth. Composite data from across divergent environmental and pollutant regimes exhibited surprisingly similar basal area mortality rates within or close to the 0.2-0.8% range as might be expected under natural conditions caused by pest damage and thinning of stands. This consistency across different deciduous stands lends credence to the use of this range as a baseline for comparison. A continuing and challenging aspect of this research is to determine comparative historical mortality rates. Pedersen and McCune (2002) offer a non-invasive method for determining relative tree mortality rates which may be useful in establishing onsite baseline rates back two decades.

This research is the first to compile existing data and calculate basal area tree mortality rates for Ontario forests. Analyzing data collected for other purposes makes it difficult to

comprehensively assess mortality rates Despite limited periodic data and the small size of many of the monitoring plots from a variety of programs, taken together, the datasets provide complementary information on the health of Ontario forests:

- *EMAN:* These plots provide the most recent data available and their large size attenuates variability when reinventory periods are short. The Carolinian forest sites and their respective oak populations have healthy mortality rates. Younger stands at Hilton Falls exhibit higher rates due to a mix of factors including suppression of sub-dominant individuals. There is a need to obtain information on the historical disturbances and impacts onsite. Future reinventory of the oak parkland site will allow for understanding successional and basal area changes following natural disturbance.

- *ARNEWS*: These plots are small and therefore overly influenced by individual dynamics as opposed to those at the stand level. The one site that exhibits higher than expected mortality is a result of high variability due sampling scale. The ultimate cause of tree death was storm damage and insect infestation but other predisposing factors cannot be ruled out.

- *NAMP*: These plots were designed to assess maple stands in managed and unmanaged sugar bushes. The rates in the unmanaged maple stands are typical of the expected range. The rates of 0.07% in the unaffected young maple stands corroborate the hypothesis that younger stands exhibit lower mortality than mature stands.

- *OMNR*: The Growth and Yield plots cover a large area of Ontario though only over short time periods between 1993 and 2001. A large percentage of these sites, across a diverse geography, have annual mortality rates above 0.8%. Some of these high rates are explained by the large influence of mature tree deaths in the intermediate-sized plots measure over short time frames. Moderation of these rates is expected. Future research should investigate the available information on deformities, insects, and diseases on these sites in concert with critical load data.

Our assessment concurs with other research indicating that forests in southern Ontario are generally healthy (Bowers and Hopkin, 1997; Lachance *et al.* 1995; McLaughlin *et al.* 2000). This is not to say that decline is not happening on a species-specific level; the unprecedented decline of eastern flowering dogwood across its range due to the *Discula destructiva* fungus is a case in point.

Given that trees weakened or stressed are not detected by this coarse-filter basal area mortality assessment it is prudent to interpret monitoring results using a multi-factor system model of forest health. Manion's (1981) decline-disease theory which considers successive causes of decline including predisposing factors, short-term inciting factors, and long-term contributing factors provides a basis for linking the complex factors leading to tree death. Although pollution-induced decline is not immediately apparent the

effects of insects, diseases, drought, and storms were often observed. Air pollution is known to interact with these agents to predispose trees to stress and mortality (Brydges *et al.* 2002). The effects of air pollution may not be evident via increased mortality rates, however, declining soil conditions and tree growth are possible, and diminished radial growth rates have been documented for sugar maple in Ontario (Ryan *et al.* 1994). Ryan *et al.* (1994) propose that decreased growth may be related to air pollution and possibly decreased buffering capacity of soils. Tree decline has been shown to correspond with critical load exceedances (Arp *et al.* 1996; Watmough *et al.* 2004). The tree mortality documented in the northeastern U.S. occurred in areas underlain by sandstone that experienced drastic reductions in soil quality and pH (Loucks, 1998b). Similarly, sites of forest decline in Ontario have been associated with mineral soils in central and northern Ontario where there is low weathering parent materials or organic soils resulting in poor acid buffering capacity (Watmough *et al.* 2004). Although the highest S and N deposition rates occur in southwestern Ontario decline may not be expressed via tree mortality in southern Ontario forests due to the high buffering capacity of the underlying limestone and dolostone (Arp *et al.* 1996). Research indicates that pollution-induced nutrient depletion in soil increases forest susceptibility to environmental stress, which is consistent with the Manion decline-disease model. This hypothesis is also consistent with Holling's (1973) resiliency-based view of ecosystems, which posits that systems continue through successional development absorbing environmental change until a critical threshold is reached where the system no longer assimilates change but is driven into a radically new state. In the case of Ontario's forests acid deposition could force changes in soil pH and nutrients to a threshold such that fundamental ecosystem changes occur (i.e. elevated mortality rates, altered species composition, biodiversity, and stand structure and turnover rates)and reorganize existing forest stands. Abrupt transitions to new system states have been observed in response to pest outbreaks (Holling, 1986) and climate change (Crowley and North, 1988). As Kay *et al.* (1999) suggest we should strive for understanding of the options and alternative futures likely and possible. McLaughlin and Percy (1999) outline some of the potential changes and challenges for forest health under changing climate, air pollution and abiotic and biotic stresses.

Information Gaps and Research Needs
Analysing basal area tree mortality can be an effective approach to quickly assess forest health across large geographic areas using disparate data sets. However, there is a need for relatively long term datasets from appropriate-sized plots. Research into how plot size and frequency of periodic reinventory influence rates should continue in order to establish a standardized methodology.

In future studies it may be possible to expand upon this research and investigate whether patterns of forest condition correlate with critical load exceedances. Because tree mortality is the ultimate end result of stress on a tree, assessing a more pollution-sensitive measure such as basal area growth would likely prove more useful in correlating pollution and enable earlier detection of decline. Tree ring chronologies and associated climatic, insect and disease data have been used to explain forest decline in sugar maple (Payette *et al.* 1996). In Ontario, basal area growth data is normally only collected every five years, however, increment coring data collected by the OMNR might be used to age

forest stands and assess annual changes in growth in relation to critical load exceednaces and developmental changes preceding mortality. Increment coring data would also allow for the correlation of tree growth to decades before the onset of pollution.

Detailed examination of soil types onsite in relation to exceedance of critical load and mortality rates would be valuable. It would be insightful to compare the mortality rates calculated in this research with those of more northern forests on poorly buffered soils.

Developing an understanding of how basal area dynamics change as a forest moves through various stages of succession is crucial. This understanding could be garnered by measuring basal area growth and loss rates in forests of similar type at different successional stages and developing a model of basal area change as forests age. Trees have the same probability of death at every age, as evidenced by their typical type 2 (reverse J-shaped age versus abundance) distribution curves (Harcombe, 1987; Peet and Christensen, 1987). If probability of death is a constant percentage of the stems independent of age we can calculate what the mortality rate of stems should be from birth to an old-growth state. If the mortality rate were to change it would be evident by a change in the shape or slope of the line showing numbers over age of stems. Recalculating this relationship over time would allow one to see changes in stand structure and then investigate its cause(s) if deemed significant. Tracking significant changes in mortality would also provide opportunity to assess associated functional changes in forest structure such as the occurrence of downed woody debris.

A View to the Future
This research concurs with others suggesting that overall southern Ontario's forests do not exhibit evidence of decline (Bowers and Hopkin, 1997; Lachance *et al.* 1995; Allen *et al.* 1992). Watmough *et al.* (2004) cautions that "*to accurately interpret forest health data, greater understanding of how soil nutrient depletion impacts forest health and the influence of potentially confounding factors is required*". A holistic approach is necessary to account for the range of ecosystem processes that affect forests (i.e. short-term annual tree growth to the slow decades-long process of soil acidification). The resiliency-based view of ecosystems suggests that management be directed at maintaining the innate resilience of the system to ensure its capacity to absorb process changes (Gunderson and Holling, 2002). In order to foster such ecosystem resilience an understanding of forest ecosystem function is an essential foundation. Unfortunately, at present many aspects of forest dynamics including nutrient cycling, carbon sequestration, and biodiversity are not monitored and there is a subsequent lack of long-term data (Watmough *et al.* 2004).

Despite measurable progress, even with full implementation of the 2010 Canada-U.S. Acid Rain Programs critical loads will still be exceeded and areas of eastern Canada will continue to be impaired (Environment Canada, 1998). With growing evidence linking declining soil condition to decreased forest growth and resilience to natural stresses (Likens *et al.* 1994; Ouimet *et al.* 2001; Ryan *et al.*, 1994; Watmough, 2002) there is an obvious need to develop a recognized method and program for monitoring tree growth and mortality. The implications of reduced forest growth and increased turnover are particularly important due to the potential impacts on ecosystem services, woodlot

operations and forest management as well as policy development for old growth forest protection (Hendrickson, 2003). What's more, as Canada embarks on a carbon sequestration strategy to address climate change an understanding of forest health is essential (Brydges *et al.* 2002). Continued research and monitoring, joined together in a system model of how forests function to maintain their resilience, are necessary to track forest health, assess the effectiveness of current critical pollutant load targets and ensure that forest health is maintained.

Acknowledgements

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