Effects of Climate Change on the Probability of Urban Tree Failures from Wind Gusts

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A thesis submitted in partial fulfillment of the requirements for the Master of Engineering Science degree in Civil and Environmental Engineering

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Abstract

Trees grown in urban environments provide environmental, economic and psychological benefits to their surrounding communities. However, urban trees also pose significant risks since damaged trees can cause serious harm to people, housing, and infrastructure by falling on sidewalks, roads, houses or power lines. To better understand the risk posed to trees by wind, models have been developed that estimates the required wind speed needed to damage a tree or group of trees, and the likelihood that such a wind speed is met or exceeded annually. The importance of such models is rising each year as the associated risk grows as well, due to an increase in urbanization, frequency and intensity of wind storms increasing with global warming and growing evidence that elevated atmospheric CO$_2$ concentrations, driven by climate change, cause trees to grow faster and larger, likely increasing their fragility to wind. In this thesis, a model was created to consider the impacts of climate change on trees’ risk using analysis of wind trends globally and locally in the Toronto region, and by considering the impact of the steadily increasing concentration of CO$_2$ in the atmosphere. The CO$_2$ increase impact on trees has been inferred based on meta-analysis data from 219 papers studying the impact of elevated CO$_2$ growing conditions on 293 tree samples of varying age and species. The model functions by estimating the return period of wind storms that can damage an individual tree via trunk rupture or overturning. Meta-analysis data indicates that the density of leaves in tree crowns is likely to change with elevated CO$_2$ concentrations. The aerodynamic impact of this change is currently not well understood. In an effort to improve the model further, experimental wind testing was conducted at the Wind Engineering, Energy and Environment Dome (WindEEE) at Western University, where a 9-year-old, 1.9 m tall red maple (Acer rubrum) was subjected to wind speeds from 6-12 m/s. The testing was repeated 5 times, between each repetition the crown was thinned by 25% to simulate varying crown leaf densities of the tree, and to analyze the relationship between the density of leaves in the crown and the drag coefficient.

Keywords

Wind Damage Modelling, Climate Change, Risk, Resilience, Tree Damage, Crown Leaf Density, Tree Crown Aerodynamics
Summary for Lay Audience

Trees grown in cities provide many benefits to their surrounding communities, but they can also be quite dangerous in the event of a storm. If a tree is damaged in a wind storm, it can cause serious harm to people, housing, and infrastructure by falling on sidewalks, roads, houses or power lines. To better understand the danger that trees present to cities, scientific models have been created to estimate the intensity of a wind storm that would be required to damage a tree, and the likelihood that such a storm will occur each year. The importance of this type of modelling is increasing each year due to rapidly rising urban populations, growing evidence that climate change is frequent and severe storms. Many studies also have shown that climate change is increasing the concentration of CO\textsubscript{2} in the atmosphere which is causing trees to grow faster and larger, making them more likely to be damaged in wind storms. This research proposes a new scientific model that considers the impacts of climate change on trees’ risk to wind damage using data local to the Toronto region, as well global data about the frequency and intensity of wind storms occurring, and by considering the impact of the steadily rising concentration of CO\textsubscript{2} in the atmosphere. The impact of increased CO\textsubscript{2} is estimated from 219 other scientific studies where trees of varying species and age were grown in high CO\textsubscript{2} environments to measure how they grew differently. The model works by estimating how often it is expected that a wind storm will occur that could damage the simulated tree, either through overturning or trunk breakage. The model found that the density of foliage in the tree crown is likely to change with elevated CO\textsubscript{2}. The impact of this change is not very well understood currently in the scientific community, so to improve on this, experimental wind testing was conducted at the Wind Engineering, Energy, and Environment Dome (WindEEE) at Western University. In this testing, a 9-year-old, 1.9 m tall red maple was subjected to wind speeds from 6-12 m/s (21-43 km/h). During this testing, approximately 25% of the leaves on the tree were removed at a time to simulate a change in the density of leaves in the tree crown, helping us learn more about how the leaf density impacts the wind forces experienced by the tree, and improving the model.
Co-Authorship Statement

Chapter 2 is an article and will be submitted for publication under the co-authorship of Sam Woolsey, Horia Hangan, Hassan Peerhossaini and Danielle Way.

Chapter 3 is an article and will be submitted for publication under the co-authorship of Sam Woolsey, Horia Hangan, Hassan Peerhossaini and Danielle Way.
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1 Introduction

1.1 General introduction

Trees grown in urban environments provide environmental, economic and psychological benefits to their surrounding communities [1]. However, urban trees also pose significant risks since damaged trees can cause serious harm to people, housing and infrastructure by falling on sidewalks, roads, houses or power lines. More than 600 insurance claims are made against the city of Toronto each year due to fallen trees and branches causing property damage [2]. Tree failure can be caused by wind in two ways: (1) overturning, where the roots are pulled from the ground and the tree topples over, or (2) trunk rupture, where the trunk of the tree cannot support the load applied by the wind, and the trunk is broken. To mitigate tree failure, arborists estimate the likelihood of a failure event for urban trees and assess the damage that such an event would cause. This is done through one of a few currently relevant methods of wind damage modelling: (1) qualitative assessment, which offers a broad overview of risk but lacks detail, (2) mechanistic modelling, which can provide detailed results but requires detailed knowledge or assumptions about the tree composition, or (3) empirical modelling, which aims to provide a compromise between accuracy and ease of calculation.

Wind damage models function by answering the following questions: (1) What force is required to cause damage to the tree? (2) What wind speed is required to generate such a force? (3) What is the likelihood that such a wind speed occurs at the location of the tree? From this, further analysis to understand the vulnerability of the tree by estimating the exposure of the tree’s surrounding area, that is the damage that would be caused in the event that the tree is damaged by the wind. Through answering these questions, the risk of tree damage by wind can be effectively managed by arborists and other stakeholders, such as city urban planners in the case of urban trees.

Several models have been designed to assess the risk posed to trees by wind. The three most widely used and referenced are HWIND [3], a mechanistic model that integrates regional wind profiles and the SIMA ecosystem model [4] to assess risk for forest stands. ForestGALES [5] integrates soil characteristics and GIS data to improve estimates of overturning risk compared to HWIND. Lastly, FOREOLE [6] employs a mechanical model to better represent the risk of trunk rupture, and is capable of evaluating heterogeneous forest stands with different tree species and ages of trees. All
three models simulate forest stands and cannot assess wind risks to a single tree. These models also
all exclusively consider coniferous trees, and none account for how the aerodynamic properties of
trees may be affected by changing climatic conditions.

Climate change is significantly increasing the risk posed to trees by wind, but this is not repre-
sented in current models. It is known that anthropogenic activity is causing many changes to our
environment, including the rapid increase in the concentration of CO$_2$ in the atmosphere [7] [8].
Higher CO$_2$ concentrations result in larger, faster-growing trees [9]. This shift in tree growth and
potential shifts in allometry are not currently represented in wind tree damage models, but can
have significant impacts on both the likelihood of a tree being damaged by wind, as well as the cost
to repair the damage. The frequency and intensity of windstorms is also changing as the climate
warms: both mean and maximum wind speeds have increased in the past 40 years in the Toronto
region [10]. These underrepresented factors are implemented into our new model to determine how
they affect the return period of urban tree failure events through overturning or trunk rupture, and
what cities can do to better mitigate this risk. The proposed methodology will assess the risk of
a 30-year-old silver birch tree failing via overturning or trunk rupture from wind for atmospheric
CO$_2$ and wind conditions local to Toronto from 1990, 2020, 2050 and 2080.

After creating the model, it was found that the model was limited due to a lack of empirical
data quantifying the relationship between the density of leaves in a tree crown and the tree’s drag
coefficient, $C_D$. This relationship was shown to change as the tree is grown under higher CO$_2$
concentrations in future, decreasing by 8.3% from 1990 to 2080. Only a limited number of studies
have examined this concept [11] [12], showing that changing leaf density significantly impacts the
drag coefficient of the tree, which our model is highly sensitive to. This thesis aims to ameliorate
this limitation by performing a series of wind tunnel tests examining how the drag coefficient of a
9-year-old red maple (Acer rubrum) changes at four different wind speeds (5.9, 8.2, 9.9, 11.7 m/s)
and five different crown leaf densities (100%, 75%, 50%, 25%, 0% total leaf area).

1.2 Motivation and objectives

The objective of this work is to develop a model to predict the risk of individual broad-leaf trees
from being damaged in a wind storm. The risk of individual trees being damaged will be predicted
for future climate conditions expected by the Intergovernmental Panel on Climate Change (IPCC)
for atmospheric CO₂ concentrations and wind storms amplitude and frequency. This will be done theoretically by creating a computational model to compile, interpret and integrate modern wind damage modelling techniques with biological data regarding the effects of elevated atmospheric CO₂ on tree growth, and climate data regarding historical trends of peak wind speeds observed globally and locally in the Toronto, Canada region.

The model will be further improved through the collection of experimental wind testing data about how broad-leaf trees interact with wind, and the impact of varied crown leaf density on the aerodynamic performance of broad-leaf trees. A 9-year-old red maple (Acer rubrum) was subjected to wind speeds from 6-12 m/s while it’s crown had 100%, 75%, 50%, 25%, or 0% of its initial leaves. This was done after our model and the underlying meta-analysis data indicated a significant change in the leaf mass, leaf area, and tree size once subjected to elevated concentrations of atmospheric CO₂.

The tested techniques can be applied to other trees both for risk assessment and management, as well as for aerodynamic performance of trees, which is historically not well understood due to the complex structure and flexibility of trees. The model also presents a novel technique for integrating the effects of climate change with traditional wind damage models, where there is data readily available about how the physical properties of trees are changed by climate conditions that are affected by climate change, such as increased temperature, limited water or nutrient access due to droughts or other storms that are shown to be increasing in frequency and intensity with climate change [10] [13] [14].

1.3 Thesis Layout

The thesis follows the integrated article format in conformity to the submission requirement of Western University. The thesis contains two articles to be submitted for publication, described in Chapter 2 and Chapter 3, respectively.

Chapter 1 provides an introduction to the problem of wind damage modelling for trees, and reviews the main studies and models related to this problem. The literature review of the expected impacts of climate change on wind damage modelling is also presented. The main objectives of the thesis are discussed: (i) create a wind damage model that considers the impact of increasing atmospheric CO₂...
concentrations, and the likely change in global and local winds due to climate change; (ii) improve the created wind damage model by identifying gaps in current research and conducting wind testing at the WindEEE Dome to fill these gaps.

Chapter 2 describes the wind damage model developed for this thesis, including the integration of elevated atmospheric CO$_2$ concentration on tree growth and the analysis of global and local wind trends. The model is tested in this chapter, and the results are discussed along with considerations to improve wind damage modelling in future. It is found that the relation between drag coefficient and crown leaf area is not well understood while it produces large variability in the model results. Therefore, this relation is further investigated in Chapter 3.

Chapter 3 describes the wind tunnel testing that was performed at the WindEEE Dome, the results from that testing, and the integration of test data into the wind damage model discussed at length in Chapter 2. A 9-year-old red maple (Acer rubrum) is tested under a straight wind flow profile at speeds between 6 m/s and 12 m/s. After testing the tree across the range of wind speeds, 25% of the tree's leaves are removed and the testing is repeated until all leaves are removed from the tree. Using a Kinect V2 depth camera, the crown frontal area is measured throughout the testing, and this data coupled with leaf area data from the tree measured using a Licor LI 3100C area meter are used to calculate the frontal leaf area index (FLAI) of the tree throughout the testing. FLAI is the ratio of the one-sided area of all leaves on the tree to the area of the crown as viewed from the front, and is used to quantify how dense the foliage is in a tree crown. The drag coefficients of the tree in each test are calculated and correlated to the FLAI to quantify the relationship between crown leaf density and the aerodynamic performance of the tree. This relationship is used in the wind damage model to improve its precision. In addition, when our results are correlated with previous results at lower wind speeds, a complete relation between the drag coefficient and wind is obtained for the first time. This relation explains how the dynamic behaviour of trees is different at low speeds compared to high speeds.

Chapter 4 summarizes the conclusions made from the work undertaken in the thesis, and makes recommendations for further research.
1.4 References


2 Effects of climate change on the probability of urban tree failures from wind gusts

2.1 Introduction

Trees grown in urban environments provide environmental, economic and psychological benefits to their surrounding communities [1]. However, urban trees also pose significant risks since damaged trees can cause serious harm to people and infrastructure by falling on sidewalks, roads, or power lines. More than 600 insurance claims are made against the city of Toronto each year due to fallen trees and branches causing property damage [2]. Tree failure can be caused by wind in two ways: (1) overturning, where the roots are pulled from the ground and the tree topples over, or (2) trunk rupture, where the trunk of the tree cannot support the load applied by the wind, and the trunk is broken. To mitigate tree failure, arborists estimate the likelihood of a failure event for urban trees and assess the damage that such an event would cause. This is done through one of a few currently relevant methods: (1) qualitative assessment, which offers a broad overview of risk but lacks detail, (2) mechanistic modelling, which can provide detailed results but requires detailed knowledge or assumptions about the tree composition, or (3) empirical modelling, which aims to provide a compromise between accuracy and ease of calculation.

Several models have been designed to assess the risk posed to trees by wind. The three most widely used and referenced are HWIND [3], a mechanistic model that integrates regional wind profiles and the SIMA ecosystem model [4] to assess risk for forest stands. ForestGALES [5] integrates soil characteristics and GIS data to improve estimates of overturning risk compared to HWIND. Lastly, FOREOLE [6] employs a mechanical model to better represent the risk of trunk rupture, and is capable of evaluating heterogeneous forest stands with different tree species and ages of trees. All three models simulate forest stands and cannot assess wind risks to a single tree. These models also all exclusively consider coniferous trees, and none account for how the aerodynamic properties of trees may be affected by changing climatic conditions.

In this study, we propose a model to address these limitations by simulating anthropogenic climate change effects on a lone silver birch (Betula pendula) tree grown in an urban environment (Toronto, Canada). Specifically, atmospheric CO$_2$ concentrations are rising at an unprecedented rate [7].
Higher CO₂ concentrations result in larger, faster-growing trees [8]. This shift in tree growth and potential shifts in allometry are not currently represented in wind tree damage models, but can have significant impacts on both the likelihood of a tree being damaged by wind, as well as the cost to repair the damage. The frequency and intensity of windstorms is also changing as the climate warms: both mean and maximum wind speeds have increased in the past 40 years in the Toronto region [9]. These underrepresented factors are implemented into our modelling to determine how they affect the return period of urban tree failure events through overturning or trunk rupture, and what cities can do to better mitigate this risk. The proposed methodology will assess the risk of a 30-year-old silver birch tree failing via overturning or trunk rupture from wind for atmospheric CO₂ and wind conditions local to Toronto from 1990, 2020, 2050 and 2080.

Silver birch was selected as the test species for the model because a concurrent experiment was conducted at Western University’s Biotron Experimental Climate Change Research Centre, where paper birch (Betula papyrifera) trees were grown with an ambient CO₂ treatment (AC, 450 ppm), and an elevated CO₂ treatment (EC, 750 ppm), to collect data that is used in our model. Silver birch and paper birch are closely related tree species, having a similar mature size and structure, as well as similar leaves. Since some areas of the proposed model were lacking data, these two experiments were conducted together to improve the model.

The objective of this study is to propose a method for estimating the return period of a failure event for an urban tree due to windstorms, and how this return period will change due to climate change as the concentration of CO₂ in the atmosphere is rising at an unprecedented rate, and windstorms are possibly changing in both frequency and intensity globally. The proposed method is broadly applicable to any urban tree where data are available about the size, shape and strength of the tree at maturity. To show how the method can be applied in practice, results are presented for an average silver birch tree (Betula pendula). The physical and aerodynamic properties of the tree, and the changes the tree would experience in future CO₂ conditions, will be estimated from the literature and supplemented with experimental data.

The model works by first estimating the size and shape of the tree in current CO₂ concentrations. Then, we estimate how the tree’s size and shape would change with different concentrations of atmospheric CO₂ in the past and in the future. Once the tree traits are defined, we calculate what
drag force is required to cause tree failure (through trunk rupture or overturning). We find the wind speed required to create this drag force, and what the likelihood of that wind speed being reached or exceeded annually is, both under current conditions and by projecting wind speed trends into the future.

2.2 Model methodology

2.2.1 Defining tree size and shape

The size and shape of the silver birch tree was estimated using the United States Department of Agriculture (USDA)’s Urban Tree Database of allometric equations [10]. This database is comprised of empirical relationships between different size parameters for 171 distinct tree species measured across the United States. 14,487 individual trees grown in urban environments were measured, and different types of functions were tested to relate each pair of parameters to determine the best fit. The USDA equations for silver birch are fitted to data from 29 trees grown and measured in the inland valleys climate zone, including Sacramento, Modesto, and Santa Monica, California. These cities have on average 8 °C warmer daily high temperatures during the growing season compared to Toronto, and similar night temperatures [11]. California also receives 0-5 mm of rainfall per month during the summer, while Toronto receives 60-80 mm of rainfall [12]. Although these climates differ, the USDA database is the only large set of data where birch trees are observed into maturity, so the size and shape of the silver birch were estimated using these equations:

\[ D = 2.53 + 0.880 \cdot \text{age}, \]  
\[ \text{CrownDiameter} = -1.41 + 0.885 \cdot D - 0.0338 \cdot D^2 + 0.00044 \cdot D^3, \]  
\[ \text{CrownHeight} = \exp(-0.532 + 2.38 \cdot \ln(\ln(D + 1) + 0.0730/2)), \]  
\[ \text{TreeHeight} = \exp(0.168 + 1.93 \cdot \ln(\ln(D + 1) + 0.0365/2)), \]
\[ \text{Leaf Area} = \exp(0.195 + 3.92 \cdot \ln(\ln(D + 1) + 0.185/2)), \]  \hspace{1cm} (5)

where \( D \) is the diameter of the trunk at breast height [cm], \( \text{age} \) is the age of the tree [years], \( \text{cdia} \) is the diameter of the crown [m], \( \text{chei} \) is the crown height [m], \( \text{thei} \) is the tree height [m], and \( \text{LA} \) is one-sided green leaf area [m²]. All equations had r-squared values between 0.751 and 0.859, indicating a good fit to the measured data.

Figure 1: Schematic drawing showing the dimensions of the silver birch tree that are used in the model

Figure 1 shows a schematic drawing of the USDA tree size and shape dimensions, defined above in Equations 1 - 5. Additionally, the perpendicular distance from the soil surface to the center of pressure of the crown, \( L \), is defined and the location of the center of pressure, \( \text{CoP} \), is shown. Due to lateral and longitudinal symmetry of the crown, the center of pressure is located at the centroid of the crown when viewed from the front. From the top view looking down upon the tree, the covered ground area, \( A_{\text{ground}} \), is shown as the total ground area covered by the tree crown from this perspective.
Some additional values that will be used in aerodynamic calculations were found using the geometry of the crown shape. Since a silver birch crown grown in open air closely resembles an ellipsoid, the crown was approximated as such (Figure 1). The primary dimensions of the tree crown determined above from the USDA equations are used to determine the frontal area, $A [m^2]$, and the covered ground area, $A_{ground} [m^2]$, along with the leaf area index, $LAI [m^2/m^2]$, and the volume of the crown, $V_{crown} [m^3]$ using the following equations:

$$A = \pi \cdot \frac{cdia}{2} \cdot \frac{chei}{2},$$  \hspace{1cm} (6)

$$A_{ground} = \pi \cdot \left(\frac{cdia}{2}\right)^2,$$  \hspace{1cm} (7)

$$LAI = \frac{LA}{A_{ground}},$$  \hspace{1cm} (8)

$$V_{crown} = \frac{4}{3} \cdot \left(\frac{cdia}{2}\right)^2 \cdot \frac{chei}{2}.$$

(9)

2.2.2 Estimating the impact of elevated CO₂ concentrations on tree growth parameters

The effects of climate change were simulated at 30-year intervals for a silver birch tree for 1990, 2020, 2050 and 2080. Atmospheric CO₂ concentration data are available from March 1958 from the Mauna Loa observatory in Hawaii, USA, [7]. By beginning the analysis in 1990, more than 30 years of data were available to train the model.

To investigate how elevated atmospheric CO₂ concentrations affect tree growth and tree resilience to high wind speeds, the Web of Science database [13] was searched for studies that imposed an elevated atmospheric CO₂ treatment on trees, with all other factors kept constant, and then measured at least one of the variables of interest, shown below in Table 1.

To be included in the meta-analysis, papers must have listed the CO₂ concentrations used, the tree species, the sample size, the duration of growth, and the age of the trees used. Individual
observations were required to be statistically independent, so only one measurement point per treatment per study was used. In total, 766 papers were found using these search terms. From these criteria, 219 papers were collected, encompassing 293 tree samples. 23 variables were measured across these studies, eight of which will be used in this study: total biomass, root biomass, leaf biomass, stem biomass, total leaf area, stem height, stem diameter, and stem density. Data presented in tables in the studies were taken directly, while data presented in figures were extracted from graphs using DataThief III [14].

Changes in tree parameters that affect how much force a tree can withstand from wind were calculated by adjusting the tree parameter values using the mean results of the meta-analysis. We assumed that the variables of interest change linearly between the control CO$_2$ concentration (~365 ppm) and the elevated CO$_2$ concentration (~700 ppm). A limited amount of data was available to model how gradual increases in CO$_2$ concentration will affect tree growth, as 248 out of the 293 tree samples studied were grown under elevated CO$_2$ concentrations greater than the predicted 2080 level used in the model. A linear relationship was selected since no clear trend was present from the remaining 45 tree sample data. Since the USDA allometric equations are made from empirical data of current trees, tree properties for the current (1990-2020) period are solved for directly from Equations 1-5. From the meta-analysis results, we observed what mean percentage change each tree property shows when the growth CO$_2$ concentration is increased by 335 ppm (from 365 ppm to 700 ppm CO$_2$). Using the current period tree properties as a reference, our model scales the meta-analysis results by the change in CO$_2$ concentration between the current period and the other three periods using the following linear equation;

\[
V_{ar}(X) = V_{ar}(USDA) \cdot \frac{CO_2(X) - CO_2(2020)}{CO_2(elevated) - CO_2(control)} \cdot \Delta V_{ar},
\]

where \(V_{ar}(X)\) is the value of the relevant tree parameter in year \(X\), \(V_{ar}(USDA)\) is the value of the relevant tree parameter obtained from Equations 1-5, \(CO_2(X)\) is the CO$_2$ concentration in year \(X\), \(CO_2(2020)\) is the mean atmospheric CO$_2$ concentration from the 1990-2020 period, \(CO_2(elevated)\) is the mean elevated CO$_2$ concentration used in the meta-analysis studies, \(CO_2(control)\) is the mean control CO$_2$ concentration used in the meta-analysis studies, and \(\Delta V_{ar}\) is the mean observed change of the tree parameter from the meta-analysis.
The CO$_2$ concentrations used for the 1960-1990 and 1990-2020 time periods were extracted from atmospheric CO$_2$ data measured at the Mauna Loa observatory \cite{7}. To predict CO$_2$ concentrations for the 2020-2050 and 2050-2080 periods, we used the Intergovernmental Panel on Climate Change’s (IPCC’s) RCP8.5 emissions scenario CO$_2$ prediction data \cite{15}. The IPCC produced four representative concentration pathways (RCPs) as part of their Fifth Assessment Report, which are used for making projections of climate change based on different 21st century pathways of anthropogenic activity. The RCP8.5 scenario was selected because it includes the highest level of atmospheric CO$_2$ increase, which has most closely resembled the real atmospheric CO$_2$ concentration trajectory since the four RCPs were published in 2014.

\textbf{2.2.3 Estimating tree strength}

Critical loads to overturn or rupture the modeled tree were calculated, and the lower of the two loads was considered the critical load that will cause failure.

The force required to overturn the tree was calculated using an empirical function, based on tree pulling experiments. These tests, by Schooten \cite{3} and further analyzed by Peltola \cite{16}, involved loading 11 birch, 33 spruce, and 51 pine trees with a winch attached 6m from the ground around their stems, and measuring the bending moment at the tree base required to overturn the trees. The base bending moment values were recorded along with the diameter at breast height (D) of each tree, and a function of the following form was fitted to the data. From the empirical overturning function, the best fitting function for mature birch trees is \cite{16}:

\[
F_{\text{overturn}} = 66.2 \cdot \left(\frac{D}{100}\right)^{2.07} \cdot L,
\]

where $F_{\text{overturn}}$ is the force required to overturn the tree [N], D is tree trunk diameter at breast height [m], and L is perpendicular distance from the soil surface to the center of pressure of the crown. The center of pressure is shown in Figure\cite{1} where, due to lateral and longitudinal symmetry of the crown, it lies along the axis passing through the center of the crown.

The trunk of a tree will rupture when the shear stress within the trunk exceeds the modulus of rupture. To calculate shear stress within the trunk, the tree is approximated as a cylindrical cantilever beam, where it is fixed to the ground by its roots and is free to move at the crown. The
force that can be supported is found based on the equation for the maximum bending stress within a cantilever beam fixed in this way:

\[ F_{\text{rupture}} = \frac{\pi \cdot (D/100)^3 \cdot \text{MoR}}{32 \cdot L}, \quad (12) \]

where \( F_{\text{rupture}} \) is the force required to rupture the tree trunk [N], and \( \text{MoR} \) is modulus of rupture of the tree trunk [Pa] which is used in place of maximum bending shear stress, \( \sigma_{\text{bend,max}} \).

The USDA reports the modulus of rupture for silver birch trees to be 57 MPa [17]. In the model, values of 85% of the modulus of rupture derived from static tests on clear samples of green wood were used, based on data for birch that suffered stem breakage during tree pulling experiments [18]. This correction is made to account for the presence of knots and other wood imperfections which are present in naturally grown trees but are avoided in mechanical properties reference manuals.

Due to the non-conclusive data found in the meta-analysis regarding the relationship between CO\(_2\), tree growth, and modulus of rupture, no assumption was made about changing modulus of rupture with each time period. This is an aspect of wind damage modelling that would benefit from future work to better define the load capacity of the simulated tree for trunk rupture failure.

### 2.2.4 Estimating damaging wind speed

The wind speed required to create a critical drag force is found based on the drag equation;

\[ V = \sqrt{\frac{2 \cdot F}{\rho \cdot A \cdot C_D}}, \quad (13) \]

where \( V \) is wind speed [m/s], \( F \) is drag force [N], \( \rho \) is air density [kg/m\(^3\)], \( A \) is crown frontal area [m\(^2\)], and \( C_D \) is a non-dimensional drag coefficient.

An important note to make is that the drag coefficient of a flexible object, like a tree crown, is not constant with wind speed. The tree crown expands as the forward branches are bent perpendicular to the wind at low wind speeds and then streamlines at higher wind speeds, as recently described by Enus et al. [19]. The extent to which a tree crown can be reconfigured varies between species, and between trees of the same species due to variations in crown shape, leaf size and shape, branch
stiffness, crown density, and other factors that impact the flexibility and aerodynamics of the tree. Mayhead reported an example of this, where Pinus trees ranged in drag coefficient from 0.3 to 0.45 at 9 m/s wind speed, and from 0.2 to 0.3 at 25 m/s wind speed [20]. The drag coefficient of a tree decreases as wind speed increases since the tree leaves and branches are reconfigured and streamlined by the wind. At lower speeds, Enus et al. reported a 27% decrease in drag coefficient when wind speed is varied from 1.4 to 6.3 m/s [19]. Experimentally, Mayhead found that silver birch trees tested at the maximum wind speed they could withstand before being damaged had a drag coefficient of 0.29 [20], the value used in this work as the baseline value for the modeled tree.

2.2.5 Estimating damaging wind speed return period

To determine the likelihood of the critical wind speed being exceeded annually, historical wind gust data from Toronto Pearson International Airport, were analyzed. Daily maximum 3-5 second wind gust data are available from January 1957, providing the longest available record of wind data in the region. The data were filtered to consider only days from April to October, when trees are likely to have their full foliage in Toronto. A Weibull distribution was created of the annual maximum wind gust speeds using linear regression to show the historical probability of a given wind speed being exceeded in any year with recorded data.

A Weibull distribution is a continuous probability distribution that is frequently used in the field of wind engineering, due in part to its simple form and high flexibility. This model uses the cumulative distribution function (CDF) form of the Weibull distribution to estimate the likelihood of a given wind speed being reached or exceeded on a specified interval. The fitted Weibull CDF has the following form:

\[ P_{exc} = \exp(-V^c)^K, \]

where \( P_{exc} \) is the probability that the gust wind speed, \( V \), will be exceeded during an interval, \( c \) is the unitless scale parameter, and \( K \) is the unitless shape parameter of the distribution.

The return period, \( T \), of a certain gust wind speed is found as the reciprocal of the probability of exceedance:
\[ T = \frac{1}{P_{exc}}. \]  

To investigate how peak wind speeds have changed over time, the Pearson Airport daily maximum wind gust data were divided into two periods: 1960-1990 and 1990-2020. A Weibull distribution was fitted to the entire data set using linear regression (Figure 2). A Weibull distribution was then fitted to the data from each 30-year period, and the two 30-year data sets were compared against each other (Figure 3). A student’s t-test was performed between the two 30-year periods of data to quantify the significance of trends in the data. To evaluate any trends in wind climatology over wider region, broader papers were referenced. Romanic et al. studied wind trends in the greater Toronto area [9], and the IPCC studied wind trends in northern-mid latitudes [21] and across all latitudes [22].

2.3 Results

2.3.1 Tree size, shape and strength

The meta-analysis results are integrated in the tree growth model as follows: (1) leaf mass changes the crown volume, \( V_{crown} \); (2) stem height changes trunk height, \( h_{ei} \); (3) stem diameter changes diameter at breast height, \( D \). Data on how elevated CO\(_2\) conditions alter stem density, the modulus of rupture, and the modulus of elasticity were also sought in the meta-analysis, but little information was found about the impact of elevated CO\(_2\) on these variables, so no CO\(_2\) effect on these parameters was assumed in the model. The CO\(_2\) concentrations used in the model for the 1960-1990 and 1990-2020 periods were 332 ppm, and 380 ppm, respectively. These values were taken directly from the Mauna Loa observatory data. For the 2020-2050 and 2050-2080 periods, the concentrations used were 475 ppm and 644 ppm, respectively. These values were extrapolated using the IPCC’s RCP8.5 emissions scenario [15].

The above table of tree sizes was generated using the effects of elevated CO\(_2\) on tree growth meta-analysis, which showed the following mean results. The relevant variables studied, and their results are summarized below.
Table 1: Elevated CO₂ concentrations increase the growth of trees. Percent changes in growth parameters for trees grown under elevated CO₂ levels (540-800 ppm) compared to control CO₂ concentrations (320-460 ppm), shown as mean values +/- standard deviations.

<table>
<thead>
<tr>
<th>Variable studied</th>
<th>Number of studies</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Mass</td>
<td>194</td>
<td>42.8 ± 49%</td>
</tr>
<tr>
<td>Root Mass</td>
<td>143</td>
<td>48.3 ± 44%</td>
</tr>
<tr>
<td>Leaf Mass</td>
<td>134</td>
<td>42.8 ± 58%</td>
</tr>
<tr>
<td>Stem Mass</td>
<td>123</td>
<td>46.9 ± 51%</td>
</tr>
<tr>
<td>Leaf Area</td>
<td>102</td>
<td>29.1 ± 32%</td>
</tr>
<tr>
<td>Stem Height</td>
<td>113</td>
<td>20.7 ± 27%</td>
</tr>
<tr>
<td>Stem Diameter</td>
<td>52</td>
<td>15.4 ± 12%</td>
</tr>
<tr>
<td>Stem Density</td>
<td>9</td>
<td>0.4 ± 5.8%</td>
</tr>
</tbody>
</table>

Trees are 43% heavier when subjected to elevated CO₂ treatments compared to ambient CO₂. Slightly more of this increased mass is concentrated in the roots compared to the leaves and stem, indicating that tree resilience to overturning should improve by lowering the center of mass. This allometric shift is not reflected in our current tree wind resilience model though, since how the strength provided by the roots of a mature tree will change with different root sizes and orientations is not well understood. Current wind damage models circumvent this by using empirical relationships from tree pulling experiments to relate the force required to overturn a tree, and the trunk diameter at breast height [3].

The variance in each variable in Table 1 is high, owing to the wide variety of tree species and study duration included in the meta-analysis. Of the 183 tree samples collected, 23 were birch (*Betula spp.*), three of which were silver birch (*Betula pendula*). However, given the small sample size of *Betula*, the results from all tree species and all durations were used for our modelling.

Due to the high variance, only the mean values from the meta-analysis data were used to define tree growth parameters for each CO₂ level. This could be improved in future by performing a sensitivity analysis, or by increasing the data set size most relevant to the specific tree being examined in age, species, and climate.
We estimated an average tree size and shape for a mature (30-year-old) silver birch tree by first solving the USDA allometric equations for a tree grown under current conditions (year 2020) by inputting \( \text{age} = 30 \) into Equation 1, then inputting the resulting trunk diameter at breast height \((D)\) value into Equations 2, 3, 4, 5. To determine the tree properties in the other periods of interest, the tree meta-analysis properties described in Table 1 are scaled for each time period using Equation 10. The results of this interpolation of growth properties for each year of interest are summarized below.

Table 2: Model predictions for a 30-year-old silver birch tree’s height, trunk diameter, leaf area, and perpendicular distance from the soil surface to the center of pressure of the crown. Predictions are made for the tree’s properties in the years 1990, 2020, 2050, and 2080 based on meta-analysis data studying the impact of increasing atmospheric CO\(_2\) concentration on tree growth.

<table>
<thead>
<tr>
<th>Year</th>
<th>Tree Height ([m])</th>
<th>Trunk Diameter ([cm])</th>
<th>Crown Frontal Area ([m^2])</th>
<th>L ([m])</th>
<th>FLAI ([m^2/m^2])</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>12.4</td>
<td>28.2</td>
<td>54.7</td>
<td>6.95</td>
<td>2.92</td>
</tr>
<tr>
<td>2020</td>
<td>12.7</td>
<td>28.9</td>
<td>56.9</td>
<td>7.17</td>
<td>2.88</td>
</tr>
<tr>
<td>2050</td>
<td>13.3</td>
<td>30.3</td>
<td>61.3</td>
<td>7.61</td>
<td>2.80</td>
</tr>
<tr>
<td>2080</td>
<td>14.5</td>
<td>32.7</td>
<td>69.7</td>
<td>8.40</td>
<td>2.68</td>
</tr>
</tbody>
</table>

The tree is larger under future growth CO\(_2\) conditions, but not equally across all the parameters. The largest increase is seen in the crown frontal area, \(A\), at a 27% increase. The increasing trunk diameter, \(D\), will improve the resistance of the tree to wind damage, while the increasing tree height, \(thei\), and crown frontal area, \(A\), will make the tree more vulnerable to wind gusts.

Once all updates to the tree’s size and shape were made, the model was run to determine the wind drag force required to damage the tree via overturning \(F_{\text{overturn}}\), Equation 11 or trunk rupture \(F_{\text{rupture}}\), Equation 12. Whichever failure mode has a lower damaging drag force will be the critical failure mode, and the wind speed required to generate this damaging drag force \(V\), equation 23 was determined. The results of this process are shown in Table 3.
Table 3: Model predictions for the force required to damage a 30-year-old silver birch tree via overturning or trunk rupture, and the wind speed required to generate the critical (lower) force in each year. Predictions are made for the years 1990, 2020, 2050, and 2080 based on meta-analysis data studying the impact of increasing atmospheric CO\textsubscript{2} concentration on tree growth

<table>
<thead>
<tr>
<th>Year</th>
<th>( F_{overturn} ) [N]</th>
<th>( F_{rupture} ) [N]</th>
<th>V [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>9,600</td>
<td>12,900</td>
<td>31.4</td>
</tr>
<tr>
<td>2020</td>
<td>9,770</td>
<td>13,500</td>
<td>31.1</td>
</tr>
<tr>
<td>2050</td>
<td>10,100</td>
<td>14,500</td>
<td>30.5</td>
</tr>
<tr>
<td>2080</td>
<td>10,700</td>
<td>16,600</td>
<td>29.5</td>
</tr>
</tbody>
</table>

Since the force required to overturn the tree is lower than the force required to rupture the tree trunk in all cases, overturning is the critical failure mode and is used to calculate the failure wind speed.

For both overturning and rupture, the force required to damage the tree is increasing in time and with CO\textsubscript{2} levels. The tree is getting a larger diameter and height at about the same rate, but the impact of larger diameter is much greater on the strength of the tree. The strength of the tree to overturning is proportional to \( D^{2.07} \), and inversely proportional to tree height, from Schooten’s empirical tree pulling test results that relate root strength to trunk diameter at breast height \([3]\). The increase in trunk diameter has a much stronger positive effect on overturning strength compared to the negative effect of the tree growing taller at a similar rate. Similarly for trunk rupture, mechanically the maximum shear stress that the trunk can support is proportional to \( D^{3} \), and inversely proportional to tree height. The elevated CO\textsubscript{2} growth conditions that will be present in the future will increase the force that trees can withstand.

Conversely, the wind speed required to damage the tree is shown to decrease as time advances. This is due to the increase of crown volume, and subsequently crown frontal area, \( A \), as the crown diameter (\textit{cdia}) and crown height (\textit{chei}) are increased within the model (equations \([9, 6]\)). This increases the drag force experienced by the tree for a given wind speed (equation \([23]\)). As the crown frontal area increases by 27% from the 1990 scenario to the 2080 scenario, the wind speed required to create a critical drag force is lowered by by 6% (1.9 m/s). Despite the silver birch tree being modeled to have a more resilient woody structure through increasing trunk diameter, it will become
more fragile due to the growing crown size and trunk height.

2.3.2 Wind speed return periods

The model concludes by estimating the likelihood that the critical wind speeds, $V$, found above, are met or exceeded annually. To do this, the Toronto Pearson Airport data set of annual maximum wind speeds from April to October is fitted by a Weibull distribution. This is shown in Figure 2, where the maximum wind speed recorded at the airport in each year is plotted in ascending order, alongside the fitted Weibull cumulative distribution function.

![Weibull cumulative distribution function of annual maximum wind speeds recorded at Toronto Pearson International Airport. Data is filtered to only include months from April to October, 1957-2020](image)

Each red X in the figure represents the highest 5 second sustained wind gust that was recorded in
a given year from 1957-2020, during April to October period. These annual maximum gusts are plotted in order from lowest to highest, against annual probability of exceedance. The probability of exceedance is calculated as the likelihood that a certain wind speed will be given in any given year between 1957 and 2020, where the lowest wind speed will have a 64-in-64 chance of occurrence, and the highest wind speed will have a 1-in-64 chance of occurrence. The Weibull distribution is fitted to this data via linear regression, shown as the black hashed line. The fitted probability of exceedance function has the following expression:

\[ P_{\text{exc}} = \exp(- (V \ast 0.037)^{10.22}), \]  

where \( P_{\text{exc}} \) is the probability that a given wind speed occurs annually, and \( V \) is wind speed \([\text{m/s}]\). The fitted Weibull has an r-squared value of 0.95, indicating a good fit to the data.

To test whether the wind gust data is consistent between all 64 years in the period, with the same mean and standard deviation, or if these probability factors are changing, the data was divided into 2 sets. The first 30 years, 1960-1990, was plotted, alongside the next 30 years, 1990-2020. These subsets were each fitted with Weibull CDFs following the same linear regression procedure used to fit the full data set. The resulting Weibull CDFs of the two 30-year sets of data are shown below in Figure 3.
These two periods appear to be quite different, particularly in the 28-31 m/s wind speed range, where our model shows most trees will be critically damaged, and these winds occur about twice as often in the 1990-2020 period compared to the 1960-1990 period. However, a student’s t-test was performed to compare the two 30-year periods of data, and no difference was found at the 5% significance level (p = 0.5), making it likely that the apparent increase in frequency of high wind speeds in the 1990-2020 data compared to the 1960-1990 data is due to random chance. Limited data are available to model how the intensity and frequency of windstorms are affected by climate change. Specific to Toronto, Romanic et al. reported a mean wind speed increase of 0.2m/s from 1948 to 2014. This increase was observed primarily during the fall and winter seasons, when wind
speed increased 0.54m/s. In contrast, spring and summer showed "almost negligible and statistically not significant trends" in wind speed over this same period [9]. Due to the low confidence of these findings, the return periods of high wind speeds were therefore not changed in the model.

In a global analysis of changes in climate extremes produced in the Fifth Assessment Report by the IPCC, changes in observed surface winds over land across all latitudes were assigned a low confidence level [22]. The IPCC also published a special report on managing the risks of extreme events and disasters (SREX), wherein a strong decline in extreme winds compared to mean winds was reported for the continental northern-mid latitudes [21]. This result was also assigned a low confidence level. Overall, the data currently available is limited in quality (due to inconsistencies between measuring techniques at different sites), quantity (due to relatively short time spans of data collection), and spatially (where most measuring sites are close to urban centers).

Once all updates to the model are made as described in Sections 4.1 and 4.2, above, the following results were found. The tree size, shape and strength are changed as described in Tables 2 and 3, and no changes are made to the wind speeds for either frequency or intensity due to the aforementioned low confidence in available data. For each 30-year period ending in the years listed below in Table 8, the critical wind speed to damage the 30-year-old birch tree is listed, along with the probability that that wind speed is exceeded annually, and the estimated return period of a damaging windstorm event.

Model predictions for the force required to damage a 30-year-old silver birch tree via overturning or trunk rupture, and the wind speed required to generate the critical (lower) force in each year. Predictions are made for the years 1990, 2020, 2050, and 2080 based on meta-analysis data studying the impact of increasing atmospheric CO$_2$ concentration on tree growth.
Table 4: Model predictions for the wind speed, $V$, required to damage a 30-year-old silver birch tree via overturning, the critical failure mode. For each critical wind speed, the estimated probability of exceedance, $P_{exc}$ is shown and the return period, $T$.

<table>
<thead>
<tr>
<th>Year</th>
<th>$V$ [m/s]</th>
<th>$P_{exc}$ [%]</th>
<th>$T$ [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>31.4</td>
<td>0.78</td>
<td>128</td>
</tr>
<tr>
<td>2020</td>
<td>31.1</td>
<td>1.3</td>
<td>77</td>
</tr>
<tr>
<td>2050</td>
<td>30.5</td>
<td>2.9</td>
<td>34</td>
</tr>
<tr>
<td>2080</td>
<td>29.5</td>
<td>8.3</td>
<td>12</td>
</tr>
</tbody>
</table>

Our model indicates that the critical wind speed to damage the silver birch trees will be steadily declining, with more drastic changes happening as time advances. Although the wind speeds are only declining by about 2 m/s across the entire interval, this results in a massive increase in the frequency of damaging storms occurring. Reviewing the Toronto Pearson data, the highest critical wind speed, 31.1 m/s, was exceeded twice in 64 years, while the lowest critical wind speed predicted for 2080, 29.5 m/s, was exceeded five times. Despite these wind speeds being separated by only 1.6 m/s, The fitted Weibull indicates that the lower critical wind speed is about ten times as likely to occur as the higher critical wind speed.

2.4 Discussion

2.4.1 Modelling results

Based on what is known about how elevated concentrations of atmospheric CO$_2$ impact tree growth, the slightly lower critical wind speed for failure of the simulated silver birch tree as time advances seems reasonable. Low confidence is assigned to the more than ten times greater probability of failure though, which is too drastic. This is due to the limited data available to predict these inherently rare high wind events, and to assess what impact climate change is having on local and global winds. In Figure 2, the 1957-2020 data indicates very few events registered for the wind speeds greater than 29 m/s. Since all available data currently indicates a low confidence in any significant changes to windstorms frequency or intensity, both locally in Toronto as well as globally, the model cannot accurately predict this.

Despite the stated uncertainties, the results from this model are significant because they indicate
a trend of increasing fragility for open-grown trees. Similar models could be constructed using different estimations, assumptions and data, but considering the comprehensive literature review and data meta-analysis that were conducted with the creation of this model, we are confident that the same trend will be found. The model showcases wind risk for trees from a climate change perspective, which is growing in importance as global environmental conditions continue to change at an unprecedented rate. Atmospheric CO\textsubscript{2} is rising and will continue to do so, along with many other factors related to tree’s risk, such as storm intensities and frequencies, and temperature rise. It is more important now than ever before to consider the effects that such changes will have on trees’ strength and resilience so that appropriate action can be taken to mitigate these rising risks.

2.4.2 Comparison to other wind damage and climate models

The present model is a first to estimate how climate change will affect the fragility of trees. Other models, where the growth parameters of trees can be varied, have focused only on current climate conditions. Also, our model is more broadly applicable for any tree species, since we have collected up-to-date information about the growth parameters and impact of elevated CO\textsubscript{2} on a wide range of species. The model is also modular, where the tree strength and wind calculations can be easily adjusted as more precise data becomes available in future about how trees are impacted by climate change.

The results of other models are not directly comparable to the model developed here due to the different species tested and their respective strength properties. As a general indicator of our model’s performance, we recorded that Gardiner and Quine predicted that a 30-year-old stand of Sitka spruce trees would fail at 30.5m/s via overturning in current climate conditions using the ForestGALES model \cite{5}.

For the meta-analysis data collected, our results indicate slightly higher growth in the elevated CO\textsubscript{2} treatment compared to Curtis and Wang’s 1997 meta-analysis on woody plant mass. They found mean increases of 29\% total biomass, 37\% leaf biomass, and 38\% stem biomass \cite{8}. For the purpose of this model, a new meta-analysis was completed instead of using a previous review paper because of our desire to further filter the data. When constructing the model, consideration has been given to how many data points were available that were more specific to the example problem of a 30-year-old silver birch tree than a general meta-analysis of all trees. Data from 3 studies that
included silver birch (Betula pendula), and 23 that included birch (Betula spp.) was considered.

2.4.3 Designing the model

When integrating the meta-analysis results into the model, it was challenging to find growth parameters that are directly measured in typical elevated CO$_2$ growth studies and that relate directly to a tree’s resilience to wind damage. Most of these studies are conducted from a purely biological perspective, measuring photosynthesis and respiration related chemical properties within the trees, along with high-level tree size variables. Due to this, estimations had to be made about how to integrate leaf area, leaf mass, root mass, crown drag coefficient, and stem density that would be impactful to the model and are supported by literature. Due to the lacking available information in literature, many of these factors could not be considered in the model. This is an aspect of the model that could be greatly improved in the future with more targeted studies to begin to answer these unknowns.

The wind damage model of equations proposed in this paper were selected based on their suitability for modelling leafy trees, as well as for the ability to adjust the physical properties of trees that change with elevated CO$_2$. The USDA allometric relationship equations were selected to define the silver birch size and shape because the USDA urban tree database provides a wide range of tree species that are specifically grown in urban areas across the United States. They have good sample sizes and include trees of a wide range of ages. Additionally, to estimate risk for other tree species, the USDA database has a wide range of tree species that can be easily referenced to update the model. The calculation of overturning resistance by following Schooten’s empirical $D$ equation, and rupture force via the mechanical shear stress equation is a standard practice, found in other wind damage models.

To calculate the drag force applied on the tree by the wind, multiple models were considered before the classical drag equation was selected. Other options included the Darcy-Forchheimer equation for flow through a porous medium, which has been used by Koch et al. to characterise the flow of air through tree branches [23], but not enough information about the porosity of the crown of a tree was available in open air to make this feasible. A more detailed mechanistic model for the tree crown was also considered, but too many assumptions about the tree branches, leaves and their interaction with the oncoming air were required to produce confident results for the average
tree. The classical drag equation was selected because it offered a good compromise between model resolution and ease of calculation. The air density $\rho$, wind speed $V$, and crown area $A$, can all be easily assumed, calculated or measured. The main source of variability in this type of model appears in the drag coefficient term $C_D$. In general, there is limited data available about the drag coefficient of different trees and their crowns, but the available studies quantify this relationship between the wind speed and drag force via the non-dimensional drag coefficient $[20], [24], [25]$. The drag coefficient is the simplest method to account for the changing aerodynamic performance of a tree when climate change factors are considered in this model but its evolution with wind speed while somewhat addressed at low speeds $[19]$ needs further investigation for higher wind speeds.

When estimating the likelihood of a given wind speed being exceeded annually, the Weibull continuous probability distribution was used as it is the standard for wind engineering applications. The created function is used to estimate probability of exceedance for a given wind speed input simply and effectively.

Of the many climatic variables changing due to anthropogenic activity, atmospheric carbon dioxide concentration was selected for this study because it is shown to have a measurable, and substantial change on the growth of trees $[8]$. With the goal of integrating a climate change factor with a wind damage model in mind, it was essential to select a variable that had a wide range of data available to properly quantify the effects on tree growth. However, other variables impact this growth, such as the availability of other essential nutrients, like nitrogen $[26]$, and need to be considered in future studies. Another climactic variable that is changing significantly due to anthropogenic activity is air temperature. Rising air temperatures are shown to typically suppress growth, but can have mixed effects depending on the specific region and plant species $[27]$. To model rising temperatures, specific data would need to be collected about the species being modeled, along with the region’s typical air temperature and trends with climate change.

### 2.4.4 Suggestions to improve future modelling

To improve confidence in the results, or to better understand the problem of climate change and trees’ risk to wind damage, future work can improve upon some areas of this modelling that are currently poorly understood. Specifically, the modeled tree is much more likely to fail via overturning instead of trunk rupture, indicating that the tree is weakest due to its roots. The root model used
in this study was based on Schooten’s results \cite{3}, which only include a small sample of trees. In practice, it is difficult to get more detailed results beyond the work of Schooten, since the complex root systems of mature trees are not easily measured. This is an area of wind damage modelling as a whole that would benefit from further analysis, since the HWIND, ForestGALES, and FOREOLE models all use similar empirical functions to the one in this study. As well, as the leaf mass and area of the trees studied in elevated carbon dioxide indicate significant increases, an important area for model improvement is in the impact of these changes on the drag coefficient, $C_D$, of the tree crown. The results of the model are sensitive to any changes in the aerodynamic performance of the tree crown, and only a limited number of studies have examined this topic. By conducting further tests to better understand how the drag coefficient of trees with more dense foliage will change, mostly at high wind speeds, the confidence in this modelling technique can be improved significantly.

Due to the non-conclusive data found in the meta-analysis regarding the relationship between CO$_2$, tree growth, and modulus of rupture, no assumption was made about changing modulus of rupture with each time period. This is an aspect of wind damage modelling that would benefit from future work to better define the load capacity of the simulated tree for trunk rupture failure, since it is possible that with trees growing faster and larger due to rising CO$_2$, the strength of their trunk wood could change.

To reduce the high variance found in the meta-analysis results, further data filtering can be done to remove data from trees that are less relevant to the simulated tree. By only examining data of similar species, age, and climate conditions to those simulated, the confidence in growth trends will be improved. As the data set size is low, more research can be conducted specific to a desired combination of tree species, climate and age.

Due to the high variance, only the mean values from the meta-analysis data were used to define tree growth parameters for each CO$_2$ level. This could be improved in future by performing a sensitivity analysis, or by increasing the data set size most relevant to the specific tree being examined in age, species, and climate.

The meta-analysis is limited in practical application due to the optimal growing conditions that are provided to the trees. All the studies included had provided optimal water and nutrients to the trees, which is not reflected in the real world. This is likely to enhance the effects of the elevated
CO₂ treatment beyond what will be present in reality as the trees are able to increase their growth rate more than if their growth was naturally limited by another source. As mentioned above, the only growth condition that was assessed in this study was elevated carbon dioxide concentration. There are many other climactic conditions that are changing due to climate change, which will all have unique impacts on the growth and subsequent resilience of trees to wind damage. For example, mean air temperatures are rising globally, which can cause a variety of responses in different tree and plant species. Wang et al. observed significant plant growth responses to temperature in a meta-analysis of the effects of elevated temperature and CO₂ growing conditions. Regionally, water and nutrient availability can vary significantly from year to year due to droughts, volatile rainy seasons, wildfires, or other local factors. These natural disasters are occurring more frequently due to climate change and will change the growth response of local vegetation significantly. Yan et al. found that atmospheric deposition of nitrogen has been rapidly increasing since the industrial revolution, and in their meta-analysis of 367 plant species exposed to different forms of nitrogen addition a significant response in growth was observed.

As the CO₂ concentration continues to rise in the atmosphere, our model indicates that silver birch trees will be at a greater risk of failure due to wind damage. Although the critical wind speed only decreases by about 2 m/s by 2080, this lower wind speed is about ten times as likely to occur. With the indication that urban trees will be more fragile to wind damage due to climate change, the importance of understanding and mitigating this risk has never been greater. To help protect urban trees in the future, urban planners can choose to plant tree species that have favourable properties to resist wind damage, like shorter and thicker trunks, thinner canopies, or stronger root networks to resist overturning. As well, arborists who maintain trees in urban environments can trim trees to reduce excess foliage, and trim their tops to promote shorter growth to improve their resilience to wind damage.

2.5 Conclusions

In summary, the synthesis of trees and wind with climate change to model the probability of failure to individual open-grown trees is a novel contribution to risk assessment of urban trees. The approach shown here is not widely used in other disciplines and is limited by a lack of empirical data for a few key parameters to become more robust, but is an effective starting point to better understand this.
problem. The risk of urban tree failure during windstorms will continue to increase in importance as we experience higher atmospheric carbon dioxide concentration and more damaging windstorms. With additional effort devoted to the modelling of more tree properties changing with high CO$_2$, or with other climate change related properties and their impact on trees such as temperature, or precipitation, this modelling technique could become a useful and practical tool for risk assessment of individual urban trees.

2.6 References


3 Examining the correlation between drag coefficient and tree crown leaf density

3.1 Introduction

How the crown of a tree will respond to air flow is highly complex due to its flexibility and porous crown, making it challenging to quantify. Wind-induced reconfiguration of the branches, foliage, and stem of the tree orients the crown in the direction of the flow, decreasing the wind-facing area and allowing the wind to pass more easily around the crown. The extent to which a tree is reconfigured by wind is dependent on the wind speed, as well as the tree’s stiffness, leaf density within the crown, and the size and shape of the leaves. Modelling this phenomenon is important for many fields such as biology, forestry and engineering where the resilience of trees and forest stands is important.

Several models have been designed to assess the risk posed by wind for trees [1] [2] [3] [4]. All these models simulate forest stands and cannot assess wind risks to a single tree. These models also all exclusively consider coniferous trees, and none account for how the aerodynamic properties of trees may be affected by changing climatic conditions. The inclusion of individual broad-leaf trees is growing in importance as modern cities advocate for the planting of more of these types of trees, and higher populations live within cities than ever before. At the same time, the resilience of trees against wind damage is important in the context of increasing climate change predictions.

Trees grown in urban environments provide many benefits to their surrounding areas, including environmental, economic and psychological [5]. However, urban trees also pose significant risks since damaged trees can cause serious harm to people and infrastructure by falling on sidewalks, roads, or power lines. To promote resilience within cities, it is important to better understand, and ultimately mitigate these risks whenever possible by integrating these new factors into wind damage models.

In our previous work, we proposed a model to address these limitations by simulating anthropogenic climate change effects on a lone silver birch (Betula pendula) tree grown in an urban environment (Toronto, Canada) [6]. Specifically, atmospheric CO₂ concentrations are rising at an unprecedented rate [7]. Higher CO₂ concentrations in the air result in larger, faster-growing trees [8]. This shift in tree growth and potential shifts in allometry are not currently represented in wind tree damage
models, but can have significant impacts to both the likelihood of a tree being damaged by the wind, as well as the cost to repair the damage. This underrepresented factor was implemented into our modelling to determine how it affects the return period of urban tree failure events through overturning or trunk rupture, and what cities can do to better mitigate this risk. The methodology in that study assessed the risk of a 30-year-old silver birch tree failing via overturning or trunk rupture from wind for 1990, 2020, 2050 and 2080 climate conditions.

We found that the modelled silver birch tree had increased risk to damage with higher CO$_2$ concentrations, and it is most likely to be damaged via overturning, where the roots of the tree fail and it is pulled from the ground. The force required to damage the tree increases over time as the trunk grows thicker with elevated CO$_2$, allowing it to support higher wind loads. The tree crown is also increasing in size and leaf area with higher CO$_2$. This increases the drag force experienced by the tree for a given wind speed, as the larger crown has a greater reference area, $A$, in the drag force equation (Equation 22) with higher CO$_2$ growth compared to baseline. The increasing trunk thickness and increasing crown size counteract each other when determining the likelihood of the tree being damaged by wind, as the thicker trunk makes the tree more resilient, and the increased crown size makes the tree more fragile. Ultimately, our model indicated that the increased crown size caused a greater impact on the modelled silver birch tree's risk to wind damage, resulting in a lower wind speed damaging the tree in the future.

Our model was limited due to a lack of empirical data quantifying the relationship between the density of leaves in a tree crown and the tree’s drag coefficient, $C_D$. The results of our model were sensitive to changes in the drag coefficient, and only a limited number of studies have examined this concept [9] [10]. The present study aims to ameliorate this limitation by performing a series of wind tunnel tests examining how the drag coefficient of a 9-year-old red maple (Acer rubrum) changes at four different wind speeds (5.9, 8.2, 9.9, 11.7 m/s) and five different crown leaf densities (100%, 75%, 50%, 25%, 0% total leaf area).

The wind speed, drag force, air density and crown frontal area were measured directly during the experiment, then used to solve the drag coefficient during each test combination of wind speed and crown leaf density. The wind speed measurements were taken using Turbulent Flow series 100 Cobra
probes\(^1\), the drag force was measured using a JR3 45E series monolithic six-degree-of-freedom force-torque sensor\(^2\) and the crown frontal area was measured using a Microsoft Kinect V2 depth sensor. Using the Kinect V2 depth sensor to record three-dimensional size and shape data for a tree crown is a novel technique first employed by Enus et al. \cite{11}. This sensor was an optimal choice for our experiment due to its high precision, proven success for this application, and simplicity. Using a depth sensor made the process of filtering the background in each image from the tree crown very easy and precise when compared to a typical color camera. To determine the crown leaf density, we measured the area of each leaf on the tested tree using a Licor LI 3100C area meter\(^3\).

### 3.2 Experimental setup

#### 3.2.1 Wind testing facility

The testing was conducted at the Wind Engineering, Energy and Environment (WindEEE) Dome at Western University, in London, Canada. WindEEE is the world’s first 3D and time-dependent wind testing chamber, capable of producing straight, sheared or swirl winds of variable direction and allowing the reproduction of real wind dynamics over extended areas and complex terrains \cite{12}. The test chamber is hexagonal, with a 25m inner diameter and 3.8m height. There are 106 fans in the chamber, with 60 on one wall configured in 4 rows of 15, 8 fans in a row along each of the remaining five walls, and 6 fans situated above the testing chamber ceiling that communicate with the test chamber below through a bell-mouth, allowing the facility to generate a variety of wind systems \cite{12}. The ground floor of the testing chamber is equipped with automated roughness elements designed to simulate various terrain conditions. For this research, the wind chamber was operated to produce straight flow using only the 60-fan wall.

#### 3.2.2 Instrumentation

Upstream velocity measurements were taken using Turbulent Flow series 100 Cobra probes\(^4\) which are 4-hole pressure probes within a multi-faceted head that are able to resolve 3-components of velocity and local static pressure, and can measure flow fluctuations in excess of 2000 Hz within a

\(^{1}\)https://www.turbulentflow.com.au/
\(^{2}\)https://www.jr3.com/
\(^{3}\)https://www.licor.com/env/products/leaf_area/LI-3100C/
±45° acceptance cone. The Cobra probes can measure flow velocities from 2 m/s to 100 m/s with an accuracy of ±0.3 m/s. The cobra probes were set to sample for 30 seconds at 1250 Hz.

The forces and moments exerted on the tree were measured with a JR3 45E series monolithic six-degree-of-freedom force-torque sensor, which employs foil strain gauges bonded to internal load-bearing elements to produce analog measurements of the forces and moments along the x-, y-, and z-axes. It can process force and moment loads at a frequency of up to 8 kHz. The sensor used could support forces up to 1,000 N in the x- and y-axes (horizontal axes) and up to 2,000 N in the z-axis (vertical axis), and moments up to 125 Nm about all 3 axes with a nominal accuracy on all axes of ± 0.25% of their respective measuring ranges. The force-torque sensor was set to sample for 30 seconds at 1250 Hz.

The analog signals produced by the force-torque sensor were digitally processed using a National Instruments NI cDAQ-9178 USB data acquisition device, which has a nominal accuracy of ±0.0125% of the measured value.\(^5\)

Microsoft’s Kinect V2 sensor was used to capture depth movement of the tree. The sensor is equipped with a color camera with a resolution of 1920 × 1080 pixels and a field of view of 84.1° × 53.8°, as well as an infrared time-of-flight camera with a resolution of 512 × 424 pixels and a field of view of 70.6° × 60°. The depth camera’s operative measuring range is from 0.5 m to 4.5 m from the sensor. For this test the frame rate for the sensor was set to its maximum frequency of 30 Hz. The depth camera has three infrared laser emitters with wavelengths between 800 - 830 nm. The depth precision of the sensor is better than 0.002 m, and the mean wiggling error, which is an imperfect generation of the sinusoidal shape of the modulated infrared light, is approximately 0.02 m. When used indoors with simulated sunlight, Seggers concluded that the infrared camera does not suffer a significant decrease in performance in direct light.\(^6\)

Depending on the reflective properties of the measured object, the Kinect V2 sensor has a few limitations that may affect its accuracy. If the surface of the object is too reflective or transparent, the infrared light is directed away from the sensor, resulting in blank pixels where depth cannot be assessed reliably by the sensor. Other errors can come from an imperfect illumination of the corners of the image, from the light incidence angle and from concave surfaces with high reflectance. Corti


et al. found that the maximum standard deviation due to the incidence angle of the light is reached at 60° and is equal to 0.0018 m [17]. The maximum observed error for different object geometries was found to be 0.010 m and the depth error for concave objects can reach a few centimeters due to the light bouncing between multiple surfaces with high reflectance. To minimize all the potential measurement errors, the tree was placed as close to the sensor as possible and in the center of its field of view.

The area of the tree's leaves were measured using a Licor LI-3100C area meter [6]. The LI-3100C uses a scanning bed and transparent conveyor belt to record the area of individual leaves with a nominal accuracy of ± 0.76 % of the measured area. The dry biomass of the leaves were measured using a 310 g capacity scale which has an accuracy of ± 0.001g, and the dry biomass of the wood was measured using a 3,000 g capacity scale which has an accuracy of ± 0.01g.

3.2.3 Instrument calibration

The Cobra probes were fully calibrated and ready to use before the tests were conducted by the supplying company, and the force-moment sensor was calibrated according to the manual in order to convert the output voltage to loads [7]. To confirm the calibration of the force balance, known loads were applied to the sensor using a stiff rod and pulley system. The force precision was found to be ± 0.25% of the measured load.

Following the procedure of Enus et al. [11] to confirm the calibration of the Kinect V2 depth sensor, wooden blocks were placed at known distances between 0.5 m and 2.0 m from the sensor and compared against readings from the sensor. The depth precision was found to be ± 1 mm. The Licor LI-3100C area meter was calibrated according to the manual prior to measurements being taken [8].

To confirm the calibration of the 310 g capacity scale that was used to measure the leaves, a 10 g reference weight was used which confirmed the manufacturer-rated precision of ± 0.001 g. The 3,100 g capacity scale that was used to measure the wood was fully calibrated before the tests were conducted, which confirmed the manufacturer-rated precision of ± 0.01 g.

3.2.4 Test setup

Four different wind speeds were tested (5.9, 8.2, 9.9, 11.7 m/s) using the straight flow configuration of WindEEE in this study. A uniform profile was targeted given problems with WindEEE achieving a properly scaled atmospheric boundary layer (ABL) flow profile for the desired high wind speeds used in the experiment. Wind velocity profiles were measured with an eight Cobra probe vertical rake placed at $x = -1.65$ m, $y = -2.9$ m, according to Figure 5. The eight probes were at heights of 15, 25, 35, 50, 75, 100, 150, 167 cm above the ground, facing into the wind. Figure 4 shows the mean wind speed profiles normalized with the wind measurement at $z = 1.0$ m, which corresponds to the crown center. The mean wind speeds, the standard deviations and turbulence intensities at the reference height $z = 1.0$ m are presented in Table 5. The Reynolds numbers from the same table were calculated with the tree width of 165 cm as the length scale and with an air viscosity of $18.28 \times 10^{-6}$ kg · m$^{-1}$ · s$^{-1}$.

The mean wind speed plot shows some deviation from the targeted uniform profile, where wind speed at the highest probe (167 cm) measured approximately 7% lower wind speed than the probe at 100 cm height. Turbulence intensities range between 5.5% - 7.5% across all tests. The turbulence intensity plot shows a height dependence which is consistent with a rough-to-smooth transition.
Turbulence intensity is greatest near the floor, monotonically decreasing as height increases.

A red maple tree (*Acer rubrum*) with a height of 1.90 m and a maximum width of 1.65 m was mounted on the force-moment sensor placed in the center of the WindEEE Dome, shown in Figure 6, corresponding to the origin position in Figure 5.

![Figure 5: WindEEE chamber diagram (top down view), showing the placement of all apparatus within the test chamber](image)

![Figure 6: Tested tree in WindEEE Dome testing chamber with measurement apparatus](image)
Table 5: Mean wind speeds, standard deviations, turbulence intensities and Reynolds numbers at \(x = -1.65\) m, \(y = -2.90\) m \(z = 1.0\) m

<table>
<thead>
<tr>
<th>Wind speed</th>
<th>(U_{z=1.0m})</th>
<th>(\sigma_{U_{z=1.0m}})</th>
<th>(I_{U_{z=1.0m}})</th>
<th>Re</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>5.77</td>
<td>0.38</td>
<td>0.065</td>
<td>6.52 \cdot 10^6</td>
</tr>
<tr>
<td>8</td>
<td>8.29</td>
<td>0.54</td>
<td>0.066</td>
<td>9.10 \cdot 10^6</td>
</tr>
<tr>
<td>10</td>
<td>9.99</td>
<td>0.64</td>
<td>0.064</td>
<td>1.10 \cdot 10^7</td>
</tr>
<tr>
<td>12</td>
<td>11.68</td>
<td>0.75</td>
<td>0.064</td>
<td>1.29 \cdot 10^7</td>
</tr>
</tbody>
</table>

The Kinect V2 sensor was placed on a tripod downstream, behind the force-moment sensor and tree, at 2.60 m from the center of the testing chamber and 1.12 m above ground (at \(x = 0\) m, \(y = -2.60\) m, \(z = 1.12\) m, shown in Figure 5). In Figure 6, the tree mounted on the force-moment sensor with the Cobra probes and Kinect V2 sensor are all shown in the wind tunnel prior to testing.

On the test day, the tree was cut through its trunk 30 cm below the lowest branch, then the trunk was shaved to an even, cylindrical shape to fit snugly into the force-moment sensor mount. The force-moment sensor mount was a custom steel mount, featuring a 0.6 cm thick base plate with 4 countersunk screw holes to attach to the force balance, and a 6 cm diameter, 30 cm tall hollow steel pipe welded perpendicularly to the center of the plate. The mount was filled with Bondo fiberglass epoxy resin\(^9\), then the tree was inserted into the mount and secured with a tightening screw. The tree and mount were left upright for 3 hours to fully cure.

The wind tunnel tests were conducted at 5 different tree crown conditions, having 100%, \(\sim75\%\), \(\sim50\%\), \(\sim25\%\), and 0% of its total leaves on the tree, respectively. The tree was subjected to straight flow profiles with steady mean wind speeds of 5.9, 8.2, 9.9, and 11.7 m/s. At each wind speed, the crown shape and drag force experienced by the tree were measured for 30 seconds. Once the tree was tested at all wind speeds for a given tree crown condition, the tree crown was thinned by removing leaves and small branches with the intent to remove 25% of the leaves, both in terms of number of leaves and total leaf area. The crown shape was kept constant, being thinned internally and evenly, leaving all branches near the outer edges of the crown unchanged. Due to the time-limited nature of testing a live tree that is rapidly wilting in the test chamber, each pruning was done by estimating what 25% of the total leaves on the tree were, without counting exactly. After each pruning was

\[^9\]https://www.3m.com/3M/en_US/p/d/b40068240/
completed, the leaves and branches that were removed were temporarily placed in a cool, moist bag.
This process of thinning the tree and testing it across all prescribed wind speeds was repeated, until
the tree was tested with no leaves remaining on the tree.

The day after the test, the leaf area was measured using a Licor LI-3100C Leaf Area Meter\(^\text{10}\). The
leaves, branches and trunk of the tree were dried at 60 °C until constant mass, then weighed. Fresh
mass of the tree components could not be accurately measured as the tree was drying significantly
at the completion of the wind tunnel testing.

### 3.2.5 Data analysis

The crown was extracted from the depth images recorded by the Kinect V2 depth sensor by removing
all depth values less than 50 cm and greater than 320 cm. 50 cm is the minimum depth that the
sensor can measure\(^\text{18}\), and 320 cm from the sensor is beyond the furthest branch of the tree. The
images were also cropped on all four sides such that only the tree crown remained in the frames.
Throughout the paper the frames with the background removed were analyzed. A sample of the
image produced by this process is shown in Figure 7.

![Image of depth data frame](https://www.licor.com/env/products/leaf_area/LI-3100C/)

Figure 7: Sample of Kinect depth data frame from the 100% leaf area, 8.2 m/s mean wind speed
test. Image is coloured to show the depth of each pixel recorded by the Kinect V2 sensor, in [mm]

\(^{10}\)https://www.licor.com/env/products/leaf_area/LI-3100C/
The frontal area of the tree crown was calculated whereby each pixel was converted into its respective area using their corresponding depth information and the following equations, from Enus et al.'s work with the same Kinect V2 depth sensor [11]:

\[ w = \frac{2 \cdot d \cdot \tan(\alpha/2)}{r_h}, \]  
\[ h = \frac{2 \cdot d \cdot \tan(\beta/2)}{r_v}, \]  
\[ A_{\text{pixel}} = w \cdot h, \]

where \( w \) is the width of the pixel, [m], \( d \) is the depth value of that pixel, [m], \( \alpha \) is the horizontal field of view of the depth camera, [°], \( r_h \) is the horizontal resolution of the image (512 pixels), \( h \) is the height of the pixel, [m], \( \beta \) is the vertical field of view of the camera, [°], \( r_v \) is the vertical resolution of the image (424 pixels), and \( A_{\text{pixel}} \) is the area of the pixel [m²].

The crown frontal area in each frame was then the sum of the areas of all 512 × 424 pixels;

\[ A_{\text{tree}} = \sum_{i=1}^{512 \times 424} A_{\text{pixel}}(i), \]

where \( A_{\text{tree}} \) is the area of the entire tree as viewed from the front, [m²].

To quantify the density of leaves within the tree crown, typically leaf area index is used, which is the ratio of one-sided leaf area per unit ground area covered by the tree crown. Since in this study the crown area measurements were taken from the rear of the tree to examine how the wind-facing area of the crown changes with wind speed, frontal leaf area index (FLAI) will be used to quantify the density of leaves within the tree crown. FLAI is the ratio of the one-sided area of all leaves on the tree to the area of the crown as viewed from the front. FLAI is calculated with the following equation;
$$FLAI = \frac{A_{leaves}}{A_{tree}}$$

(21)

where $FLAI$ is the frontal leaf area index, $[m^2/m^2]$, and $A_{leaves}$ is the one-sided area of all leaves on the tree.

Drag coefficients for the tree were calculated using the equation:

$$C_d = \frac{2 \cdot F}{\rho \cdot U^2 \cdot A_{tree}}.$$  

(22)

Where $C_d$ is the non-dimensional drag coefficient, $F$ is the drag force applied on the tree by the wind, $[N]$, $\rho$ is the air density, $[kg/m^3]$, $U$ is the wind speed, $[m/s]$, and $A_{tree}$ is the crown frontal area, $[m^2]$.

3.3 Results

3.3.1 Tree pruning

The results of pruning the tree throughout the wind testing are summarized below. A photo of the tree after each pruning is provided in Figure 8 and the corresponding leaf area data is presented in Table 6.
Figure 8: Tested tree installed in the WindEEE Dome shown at all five leaf area conditions. Snapshots taken from the downwind side of the tree.
Table 6: Results of tree pruning regimen

<table>
<thead>
<tr>
<th>Tree Condition</th>
<th>Leaf area [m²]</th>
<th>% Total leaf area</th>
<th>Number of leaves</th>
<th>% Total leaves</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Leaf area</td>
<td>5.32</td>
<td>100%</td>
<td>4657</td>
<td>100%</td>
</tr>
<tr>
<td>~ 75% Leaf area</td>
<td>3.85</td>
<td>72%</td>
<td>3588</td>
<td>77%</td>
</tr>
<tr>
<td>~ 50% Leaf area</td>
<td>2.15</td>
<td>40%</td>
<td>2082</td>
<td>45%</td>
</tr>
<tr>
<td>~ 25% Leaf area</td>
<td>1.07</td>
<td>20%</td>
<td>1107</td>
<td>24%</td>
</tr>
<tr>
<td>0% Leaf area</td>
<td>0</td>
<td>0%</td>
<td>0</td>
<td>0%</td>
</tr>
</tbody>
</table>

More than 25% of the total leaf area was removed during each of the first two times the tree was thinned (28%, 32%). The third and fourth removals each resulted in 20% of the total leaf area being removed. By number of leaves, each thinning was close to 25% except for the second session, where 32% of the total leaves were removed from the tree. Overall, the total leaf area and number of leaves removed during each thinning were approximately 25%, so the tree thinning process was consistent.

Since the percentage of total leaf area remaining on the tree decreases faster than the percentage of total number of leaves, more larger leaves were removed initially than smaller leaves. By having a higher proportion of smaller leaves, it is estimated that the tree crown will experience a slightly lower drag force and have a lower drag coefficient than if it had a lower proportion of smaller leaves, as the wind will more easily pass around the smaller leaves within the crown, generating less drag.

### 3.3.2 Crown frontal area

The mean frontal area of the tree crown was computed for each pair of wind speed and leaf area conditions using the Kinect V2 depth data recorded during each test and equations 17, 18, 19, and 20. The results of this are shown below in Figure 9.
Figure 9: Mean crown frontal area as calculated from the Kinect V2 depth data vs mean test wind speed

The plot shows the mean crown frontal area from each test, in \( m^2 \), versus the mean wind speed from each test, in \( m/s \). The crown frontal area is decreasing as wind speed increases across all tests where the tree has any leaves. In these cases, the crown area decreases most significantly between the two lowest wind speed tests (5.9 and 8.2 m/s), gradually decreasing less as wind speed increases. The crown is approaching its limit of reconfiguration at the highest tested wind speeds, being forced by the wind to streamline its flexible branches and leaves to better allow the wind to pass through. When testing the tree with 0% leaf area, the crown area increases slightly throughout all wind speed increases. The tree branches are bending in the direction of the wind, towards the Kinect V2 depth sensor, which could cause the sensor to read them as having a slightly larger area as the top branches are bending closer to perpendicular to the sensor positioned below.

To better understand the concept of crown reconfiguration, data collected during this study was combined with data collected by Enus et al. [11], who first employed a similar methodology where crown frontal area was found for a small tree using the same Kinect V2 depth sensor. Enus et al. performed wind testing of a small garden tree in the WindEEE Dome using an atmospheric boundary layer type wind inflow at mean wind speeds of 1.4, 3.1, 4.7, and 6.3 m/s. Due to the low wind speeds tested by Enus et al., WindEEE was able to achieve a properly scaled atmospheric boundary layer flow profile for their testing. This was not possible for our testing, due to the desired
high wind speeds.

By combining the data collected by Enus et al. with the data collected in this study, where mean wind speeds of 5.9, 8.2, 9.9, and 11.7 m/s were tested, the reconfiguration phenomenon of tree crowns is examined across a broad range of low and medium wind speeds. Due to differences in tree size between each study (Enus et al. used a tree with a frontal crown area of ∼0.37 m$^2$, we used a tree with a frontal crown area of ∼1.1 m$^2$), the data between each test needed to be normalized. Both experiments employed one test with a mean wind speed of approximately 6 m/s, so the frontal crown area data from each study was divided by their respective frontal crown area value recorded during the 6 m/s test. In this way, the change in crown area as wind speed is less than 6 m/s in the Enus et al. study, or greater than 6m/s in this study can be compared between the two trees. As well, since Enus et al. didn’t employ a thinning regime on their tree, only the data in this study that was collected with 100% leaf area will be used in the comparison. The results of combining this data as described are shown below in Figure 10.

![Figure 10: Mean crown frontal area as calculated from the Kinect V2 depth data from each test vs wind speed, normalized by crown frontal area when wind speed is 6 m/s ($A_{U=6m/s}$)](image)

Shown above in Figure 10 is the crown frontal area of the respective tree, divided by its crown frontal area when tested at ∼6 m/s wind speed, plotted versus wind speed. Each black circle represents data collected by Enus et al. during their test, and each red circle represents data collected in this...
From 1.4 to 3.1 m/s wind speed tests performed by Enus et al. [11], the crown frontal area is increasing as the leaves oriented against the flow direction are rotating outwards, setting themselves perpendicular to the flow. After the 3.1 m/s wind speed test, the crown frontal area is decreasing across all higher wind speeds. From the 3.1 m/s to 4.7 m/s tests, the area decreases only slightly, as many branches and leaves are still perpendicular to the flow while some begin to be oriented in the direction of the flow. From 4.7 m/s to 8.2 m/s, the area decreases by 25%, showing significant streamlining taking place. The drag force applied by the wind on the tree becomes great enough to overcome the stiffness of the branches and leaves, and bend them in the wind direction. At wind speeds greater than 8.2 m/s, the crown area is still decreasing as further streamlining takes place, but at a much lower rate compared to the 4.7 to 8.2 m/s range of wind speeds. The crown is approaching its limit of reconfiguration, at which is will be fully oriented as much in the wind direction as possible before permanent deformation or damage occurs to the tree from the drag force. Researchers have investigated the limit of reconfiguration of a tree crown, estimating it to be 17-21 m/s [19], 28 m/s [20], and 30 m/s [21]. For the purpose of this study, this could not be tested as it was necessary that the tree returned to its original shape and orientation between tests for continuity between each thinning. However, it is noted that already for the last wind speed tested herein, the crown area tends towards a constant value of approximately 0.75. This is a novel contribution for research on the limit of reconfiguration, as previous studies did not have the capability to measure the crown frontal area throughout testing, made possible now due to the employment of the Kinect V2 depth sensor. The limit of reconfiguration is typically quantified in terms of reduced drag coefficient.

### 3.3.3 Drag force and drag coefficient

The mean drag force from each test is shown below in Figure 11 plotted versus the mean wind speed. The data is presented for each percentage leaf area, representing the nominal (targeted) percentage of the tree’s leaves that remained when the data was collected.
Figure 11: Mean drag force experienced by the tree during each test, measured by the JR3 force-moment sensor vs mean wind speed during each test

As the frontal leaf area index (FLAI) increases, the drag force increases significantly across all wind speeds tested. Similarly, drag force monotonically increases as wind speed increases for all FLAI tested. A primary goal from this study was to better understand the relationship between wind speed and drag force for a broad-leaf tree. As discussed earlier in this paper, due to the flexible and porous nature of tree crowns, the typical relationship between force and wind speed, \( F \sim U^2 \), as shown in Equation 22, does not hold true for calculating drag force on flexible and porous objects. Each line plotted in Figure 11 shows a more linear relationship to varying degrees. This is typical for trees, where the relationship between force and wind speed is found to be closer to linear, \( F \sim U \), compared to quadratic, \( F \sim U^2 \) during experimental testing [21], [22], [23], [24], [25]. This relationship is very complex, as trees are reconfigured by the wind to varying extents, causing the branches and leaves to bend in the direction of the flow, reducing the crown’s wind-facing area and orienting the branches and leaves in the direction of the flow simultaneously. Reconfiguration will significantly reduce the drag force experienced by the tree, but the extent to which a given tree specimen will flex is highly variable. The results from this study are specific to the tested tree, but will have broader implications to how all trees with similar crown compositions and wood stiffness will perform.

When considering how to integrate the effects of streamlining and reconfiguration into estimates of
the drag force a tree will experience in a wind storm, there are three terms that can be varied in the drag equation (Equation 22). Namely, the reference area, $A$, the wind speed exponent, $2$, and the drag coefficient, $C_D$. A case can be made for all three of these parameters being used to make a good fitting curve between the wind speed, $U$, and drag force, $F$, for a tree, but it is our opinion, and the opinion of much previous work in this area, that adjusting the drag coefficient of the tree dynamically with wind speed is the most optimal choice [26], [27], [28].

Vogel suggested that the reference area, $A$ is the most appropriate for streamlined objects at high Reynolds numbers, where the flow is turbulent and drag is essentially the product of dynamic pressure and frontal area the dynamic pressure times the frontal area of the object [29]. The conventional application of this approximation is to solid objects, but due to the porous nature of a tree’s crown, this approximation does not fully account for the aerodynamic changes in the crown. The crown inner composition change, as the crown is streamlined, and the leaves and branches are brought closer together, increasing the density of foliage adds to this complexity. Due to these additional changes in the aerodynamic properties of the tree crown, varying reference area alone cannot adequately account for the reduction in drag force. Also, in an aerodynamic analysis of any object, it is conventional to determine the $A$ term in the drag equation as the wind-facing area of the object when no wind is applied, and maintaining this as a fixed value, the "reference area" [29].

Early aerodynamicists studying this problem noted the poor fit of the drag equation to force vs wind speed data when reviewing their experimental data. Tirén [25], [30]; Sauer et al. [22]; Lai [31]; Fraser [23]; Raymer [24]; Mayhead [21]; and Smiley et al. [32] all noted this poor fit, each suggesting different approximations for what exponent on the wind speed, $U$, term would best fit their data. All of these researchers specifically studied coniferous trees, and none considered broad-leaf trees. From our experimental data, the best-fitting exponent for each leaf area percentage condition of the tree was significantly lower than the standard value of 2, ranging between 1.2 (0% leaf area) to 1.9 (100% leaf area). Since this best-fitting exponent varies drastically, it is unreasonable to consider setting one constant value, and very complex to understand the tree crown conditions that would allow us to predict the appropriate exponent precisely. Another important deterrent from adjusting the wind speed term exponent in the drag equation is that any other object that is wind tunnel tested will have it’s drag coefficient calculated based on the drag equation in its standard form, where the exponent is constant at 2. In an effort to maintain the standardization of wind test
data, it is necessary to use the standard form (Equation 22). When early aerodynamicists suggested altering the drag equation, they deviated from the broad catalog of reference data derived using the conventional form. Cullen suggests that the conventional form, \( F \sim U^2 \), includes the dynamic pressure term, \( (0.5 \cdot \rho \cdot U^2) \), where engineering design standards often use dynamic pressure as a substitute for the full drag equation when applied to tree risk management [33], [34].

It is therefore asserted that the lower drag force experienced by the tree than the drag equation (Equation 22) would predict is best modeled by lowering the drag coefficient of the tree as wind speed increases. The drag coefficient is a dimensionless representation of the ratio between the actual force and the predicted force experienced by an object experiencing a flow defined by the dynamic pressure of the flow \( (0.5 \cdot \rho V^2) \) and the object’s reference area \( (A) \). The drag coefficient is used to account for the intrinsic aerodynamic properties of an object that aren’t captured by it’s reference area. Therefore it is considered that the drag coefficient is the appropriate choice to account for the aerodynamic properties of the tree, and how the aerodynamic properties of the tree will vary as the structure of the tree is changed in relation to the flow due to reconfiguration.

The drag coefficient of the tree was calculated across all pairs of test parameters (wind speed and leaf area percentage). Drag coefficient is calculated using Equation 22, where \( \rho \) is the air density during each test \( [kg/m^3] \), \( A \) is the constant reference area measured at the lowest wind speed (5.9 m/s), highest leaf area percentage test (100%) \( [m^2] \), \( F \) is the drag force experienced by the tree during each test \( [N] \), and \( U \) is the mean wind speed during each test \( [m/s] \). The results of these calculations are presented in Figure 12.
Figure 12: Mean drag coefficient, $C_D$, as calculated for each test using Equation 22 with constant reference area vs mean wind speed during each test.

Figure 12 shows the mean drag coefficient, $C_D$, from each test, versus the mean wind speed from each test, in $[m/s]$. The drag coefficient is decreasing as wind speed increases across all tests, showing the greatest decreases initially between the 5.9 m/s and 8.2 m/s tests. This is attributed to a majority of the crown reconfiguration occurring between these two wind speeds. Beyond 8.2 m/s, much of the crown’s reconfiguration has occurred as it is oriented in the flow direction and the crown has decreased in area considerably, especially in the 100% leaf area condition, as shown in Figure 9. The drag coefficient continues to decrease as wind speed increases at a lower rate until the maximum wind speed tests, 11.7 m/s, indicating that the crown has not yet reached its limit of reconfiguration at this speed.

3.3.4 Drag coefficient vs crown leaf density (FLAI)

A primary goal of this study was to investigate the relationship between drag coefficient and the density of leaves in a tree’s crown. Since a tree is most likely to be damaged at higher wind speeds, as shown consistently in literature [11] [21], as well as in this study in Figure 12 that the drag coefficient of a tree is continuously decreasing as wind speed increases due to reconfiguration, it would be optimal to determine the drag coefficient of the tree at the highest wind speed the tree can withstand before being damaged. Previous studies of coniferous trees tested until failure
indicate that the drag coefficient of a tree will remain constant once the tree has reached its limit of reconfiguration, the point beyond which the tree is unable to bend further in the direction of the flow. This is estimated to be between 20 and 30 m/s wind speed \[21, 35, 19, 26\]. As it was required to prevent permanent deformation occurring to the tested tree, we were unable to investigate the wind speed at which the tree reached it’s limit of reconfiguration. The highest wind speed achieved before risking permanent damage to the tree crown was 11.7 m/s.

To study the relationship between drag coefficient and crown leaf density, we computed the drag coefficient of the tree for each percentage leaf area condition when tested at each tested wind speed. This is the same data shown in Figure 12 except the x-axis is switched from wind speed to frontal leaf area index. FLAI was computed for each percentage leaf area condition using equation \[21\]. The five drag coefficient values (one from each FLAI) were plotted then fitted with a linear trendline. This process was repeated 4 times, once for each wind speed tested, as shown in Figure 13.

![Figure 13: Drag coefficient vs frontal leaf area index (FLAI), coloured by mean test wind speed](image.png)

Figure 13 shows the mean drag coefficient from each test, versus the frontal leaf area index from each test, in \([m^2/m^2]\). The data is coloured according to the mean wind speed in each test. A strong linear trend is present between the drag coefficient and frontal leaf area index across all tested wind speeds. As well, as wind speed increases, the slope of the line decreases. When FLAI is 0, the drag coefficient does not reach 0 as the tree without leaves still experiences a drag force.
without leaves. Since a linear trend line fits the data, it indicates that the addition of leaves to the

3.3.5 Predictions for higher FLAI or higher U

tree corresponds to a linear increase in the drag coefficient. i.e. For each increase of 1 in the FLAI,
the tree experiences a consistent addition of $\sim 0.03$ to its drag coefficient across the entire range.

Across all tested wind speeds, the linear regressions shown in Figure [13] have a slope of $\sim 0.025$,

showing a linear relationship between $C_d$ and FLAI in which $C_D \sim 0.025 \cdot FLAI$.

To predict what drag forces the studied tree would experience if it had more dense foliage than the

initial condition (greater than 100% leaf area), we used the trend lines fitted to the data shown in

Figure [13] to estimate the drag coefficient at 125% leaf area ($\sim 6$ FLAI) for each wind speed studied.

By extrapolating from each trend line, we estimated the drag coefficient of the simulated 125% leaf

area tree for each wind speed, then calculated the drag force such a tree would experience using

Equation [22].

To predict what drag forces the studied tree would experience at higher wind speeds, a quadratic
trend line was fitted to each line shown in Figure [11]. Mean drag force experienced by the tree during
each test, measured by the JR3 force-moment sensor vs mean wind speed during each test. These
trend lines were then extended for wind speeds of up to 16 m/s. The result of these two simulations

are presented in Figure [14].
Figure 14: Mean drag force experienced by the tree during each test vs mean wind speed during each test, with simulated higher leaf area percentage and higher wind speed forces shown as dashed lines.

At the simulated 125% leaf area, the tree experiences consistently more drag force. It is worth noting that with a 25% increase in leaf area, the tree does not experience 25% more drag force though, as a portion of the drag coefficient of the tree is due to the wood, illustrated in Figure 13 where with no leaves the tree still experiences about 50% of the drag force of the 100% foliage condition.

The higher wind speed estimations show an estimate for how the drag force will scale as the tree approaches the critical wind speed at which it is damaged. Since the Reynolds number will be within the same turbulent regime as the wind tunnel tests, it is expected that the relationship shown here will hold fairly well. As shown in Figures 9 and 12, the tree crown is still undergoing reconfiguration beyond the tested wind speeds, which is accounted for in the quadratic fitted trend lines shown in Figure 14.

3.3.6 Updating our model with the new aerodynamic data

In our previous paper, we used the United States Department of Agriculture (USDA)'s Urban Tree Database and Allometric Equations to simulate the size, shape and strength of a 30-year-old silver birch (Betula Pendula) tree. We modified these equations to consider how the rising
concentration of atmospheric CO$_2$ will impact the growth of such a tree in the future based on meta-analysis data collected for that paper. It was found that the crown of the tree will increase in frontal area by 13 m$^2$ (23 %), and the total leaf area of the tree will increase by 23 m$^2$ (14 %) in the next 60 years. Re-calculating the frontal leaf area index for the simulated tree in 2080 results in a decrease of 0.2 m$^2$ (7%) when compared to 2020, as shown in Table 7.

Table 7: Crown properties of the simulated 30-year-old silver birch (Betula Pendula) tree, as estimated using the USDA’s Urban Tree Database and Allometric Equations and adjusted for future time periods using meta-analysis data, as described by Woolsey et al.

<table>
<thead>
<tr>
<th>Year</th>
<th>Leaf Area [m$^2$]</th>
<th>Frontal Area [m$^2$]</th>
<th>FLAI [m$^2$/m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>159.5</td>
<td>54.67</td>
<td>2.92</td>
</tr>
<tr>
<td>2020</td>
<td>163.7</td>
<td>56.86</td>
<td>2.88</td>
</tr>
<tr>
<td>2050</td>
<td>171.9</td>
<td>61.34</td>
<td>2.80</td>
</tr>
<tr>
<td>2080</td>
<td>186.6</td>
<td>69.73</td>
<td>2.68</td>
</tr>
</tbody>
</table>

In that study, due to a lack of reference material, the drag coefficient of the silver birch was kept constant despite the changing crown porosity. This provided the results shown in Table 8.

Table 8: Predicted wind speeds at which the simulated 30-year-old silver birch (Betula Pendula) tree will fail due to overturning, and the estimated return periods of these failure wind speeds, as predicted by Woolsey et al.

<table>
<thead>
<tr>
<th>Year</th>
<th>$U_{failure}$ [m/s]</th>
<th>$T_{failure}$ [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>31.4</td>
<td>128</td>
</tr>
<tr>
<td>2020</td>
<td>31.1</td>
<td>77</td>
</tr>
<tr>
<td>2050</td>
<td>30.5</td>
<td>34</td>
</tr>
<tr>
<td>2080</td>
<td>29.5</td>
<td>12</td>
</tr>
</tbody>
</table>

By using data collected in this study, the drag coefficient of the simulated tree can be re-calculated to vary with FLAI, improving the precision of the results found in our previous paper. Using the linear relationship found between drag coefficient and FLAI, shown in Figure 13 in which $C_D \sim 0.025 \cdot LAI$, we can adjust the drag coefficient of the simulated tree from the baseline drag coefficient value of 0.29.
Once the drag coefficient of the silver birch is updated in our model, we re-calculated the critical wind speed at which tree failure would occur;

\[ V = \sqrt{\frac{2 \cdot F}{\rho \cdot A \cdot C_D}}, \]  

(23)

where \( V \) is wind speed \([m/s]\), \( F \) is drag force \([N]\), \( \rho \) is air density \([kg/m^3]\), \( A \) is crown frontal area \([m^2]\), and \( C_D \) is a non-dimensional drag coefficient.

The return period of such wind speeds were estimated using the technique described in detail in our recent study [6], where a Weibull continuous probability distribution was fitted to historical peak wind speed data from Toronto Pearson International Airport. The fitted Weibull CDF has the following form:

\[ P_{exc} = \exp(-(V \ast c)^K), \]  

(24)

where \( P_{exc} \) is the probability that the gust wind speed, \( V \), will be exceeded during an interval, \( c \) is the unitless scale parameter, and \( K \) is the unitless shape parameter of the distribution.

The results of this recalculation process are summarized in Table 9.

<table>
<thead>
<tr>
<th>Year</th>
<th>( U_{failure} ) [m/s]</th>
<th>( T_{failure} ) [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>31.4</td>
<td>128</td>
</tr>
<tr>
<td>2020</td>
<td>31.2</td>
<td>84</td>
</tr>
<tr>
<td>2050</td>
<td>30.6</td>
<td>41</td>
</tr>
<tr>
<td>2080</td>
<td>29.8</td>
<td>16</td>
</tr>
</tbody>
</table>

Despite only a small change in the drag coefficient of the tree (from 0.29 to 0.284) across the 90 year period, the estimated return period of a damaging event increases by 33% by 2080 (from 12 to 16 years). Such small changes in drag coefficient, and therefore failure wind speed, have a large
impact on the calculated risk posed to trees by wind. This result showcases how sensitive such wind damage models are to small changes in critical wind speed, due to the rarity of such events occurring on record to train the models.

3.4 Discussion

3.4.1 Modelling Results

This study aimed to generate novel information about the relationship between drag coefficient and broad-leaf tree crown porosity. The results from our wind testing indicate a strong relationship that is approximately linear. This holds for the range of wind speeds tested, from 5.8 to 11.6 m/s. Considering this result in the context of tree resilience to wind damage as affected by the rising atmospheric CO$_2$ concentration, our modelling predicts that trees will be less resilient in the future than today, but not to the extent that was originally predicted [6].

The data collected through wind testing are consistent with those published in similar studies. Unique to our work, the relationship between drag coefficient and leaf density was found to be very consistent across a variety of wind speeds and crown leaf densities that were tested. In addition, the crown reconfiguration phenomenon that trees experience when submersed in wind was better understood by combining our results with those of Enus et al [11]. The extent to which a tree is able to streamline it’s leaves and branches during low to medium speed flows was analysed.

In the context of improving resilience of urban trees, we can stress the importance of decreasing the drag coefficient. When updating our model with the new drag coefficient data collected during this experiment, it was found that a 2% decrease in drag coefficient of the simulated tree corresponded to an increase of 33% in the return period of a wind event capable of damaging the tree. Due to the higher amount of care that urban trees receive from arborists when compared to free growing rural trees, and the higher level of damage that urban tree failures cause to their surroundings, it is realistic to see vast improvements in the resilience of urban trees through regular pruning.

Low confidence is assigned to the exact return periods shown for the simulated silver birch tree due to the limited data available to predict these inherently rare high wind events, but the relationship between the drag coefficient and return period is assigned a higher level of confidence.

Current wind damage models do not consider any factors of climate change. The effects of an
elevated CO$_2$ concentration on the growth of plants has been widely studied, showing a high increase in plant growth speed, and in many cases a shift in allometry [8]. With the goal of integrating a climate change factor with a wind damage model in mind, it was essential to select a variable that had a wide range of data available to properly quantify the effects on tree growth. However, other variables impact this growth, such as the availability of other essential nutrients, like nitrogen [38], and need to be considered in future studies. Another climactic variable that is changing significantly due to anthropogenic activity is air temperature. Rising air temperatures are shown to typically suppress growth, but can have mixed effects depending on the specific region and plant species [39]. To model rising temperatures, specific data would need to be collected about the species being modeled, along with the region’s typical air temperature and trends with climate change.

The results presented in this study are limited due to the relatively low maximum wind speeds at which our tree was tested. We reached mean wind speeds of up to 11.67 m/s in the test chamber, while mature trees are typically not damaged by the wind until about 30 m/s. This limitation was primarily due to the strength of the tested tree, where beyond the tested wind speeds it was likely the tree would be permanently deformed by the wind. This would prevent any further testing for different leaf area percentages, as it was essential that the tree structure remained consistent between each pruning. Due to the high Reynolds numbers present in the wind tests, the tree experienced highly turbulent flow. When thinking about scaling the results from this test up to be applicable at 30 m/s for tree failure, the Reynolds number will be within the same turbulent regime for the results to still be applicable.

As well, meta-analysis data indicates that elevated CO$_2$ consistently causes an increase in total leaf area for broad-leaf trees beyond the typical leaf area present on modern trees [8]. It is impractical to grow a tree specimen for this study for 9 years to test the higher leaf area directly, so instead we had to study a current tree and its aerodynamic performance when leaf area was decreased. Figure 13 indicates that the effect of crown leaf density on the drag coefficient of the tree is consistent across all tested wind speeds and leaf densities, giving good confidence that these results will hold true for future conditions.
3.4.2 Comparison to other experiments and models

When working to improve wind damage modelling for trees, other studies have considered other factors that impact the resilience of trees to wind, such as Schooten, who improved the fidelity of the root strength of the modelled trees via a series of tree pulling experiments [1]. As well as Green et al., who collected and published data about the material properties of green and dry wood for many tree species [40], helping to improve the fidelity of the trunk rupture strength of the modelled trees.

The presented study is the first to investigate the relationship between drag coefficient and crown leaf density of a broad-leaf tree in a controlled wind test facility. Other testing has been done for coniferous trees [21] [25] [22], and a limited amount of data has been collected by Smiley et al. about broad-leaf trees tested outdoors via mounting to the bed of a moving truck [9]. Other work has been done by Koch et al., whereby broad-leafed branches are placed in a closed cylindrical wind chamber [41]. Our work improves upon all of these prior experiments by combining the controlled test environment at the WindEEE Dome, a mature broad-leaf tree, and testing in open air where the wind can freely pass through or around the tree.

3.4.3 Experimental design

The WindEEE Dome, Western University, Canada, provided a uniquely optimal set of equipment for the testing due to the very large test chamber. We were able to test a tree greater than 2 m in height and 1.8 m in crown diameter without suffering from wind interactions with any chamber walls, reaching relatively high wind speeds for such a large chamber. Due to the importance of collecting data relevant to fully grown trees to improve wind damage models, where larger trees are most prone to failure and most likely to cause the greatest damage when they fail, it was ideal to be able to test such a large tree at the WindEEE Dome.

Testing the tree at higher wind speeds would have improved the results since wind damage models indicate that trees fail for wind speeds upwards of 30 m/s, but the health of the tested tree was prioritized over reaching higher wind speeds since the data collected regarding the crown leaf density and drag force was paramount for this study. As well, if the tree were to be tested to failure, a custom solution would need to be created to prevent any falling leaves or branches from travelling
into the closed-loop test chamber fan system.

While it would have been valuable to spend longer in the test chamber with the tree, especially when pruning, to ensure as close to 25% of the leaves were removed during each pruning, this was not feasible due to the rapid drying of the tree. Due to the dry test chamber atmosphere, the tree being separated from its roots, and the rapid wind passing by the tree during each test, the tree was only able to be tested for a few hours.

The wind profile target was a uniform flow, having constant mean wind speed across all heights measured. The mean wind speed plot shows some deviation from this target, where wind speed at the highest probe (167 cm) measured approximately 7% lower wind speed than the probe at 100 cm height. This is a recognized source of error in the test results.

### 3.4.4 Suggestions to improve future experiments and models

To improve wind damage models further, other climate change-related factors that are known to affect tree growth should be studied. There are many other climactic conditions that are changing due to climate change, which will all have unique impacts on the growth and subsequent resilience of trees to wind damage. For example, mean air temperatures are rising globally [42], which can cause a variety of responses in different tree and plant species. Wang et al. observed significant plant growth responses to temperature in a meta-analysis of the effects of elevated temperature and CO$_2$ growing conditions [39]. Regionally, water and nutrient availability can vary significantly from year to year due to droughts, volatile rainy seasons, wildfires, or other local factors. These natural disasters are occurring more frequently due to climate change [43] and will change the growth response of local vegetation significantly. Yan et al. found that atmospheric deposition of nitrogen has been rapidly increasing since the industrial revolution, and in their meta-analysis of 367 plant species exposed to different forms of nitrogen addition a significant response in growth was observed [38].

The data presented in this study is limited due to a relatively low wind speeds being tested, and due to the relatively young tree that was tested. Although the wind speed reached during this test is a good indicator of how a similar tree would react to higher wind speeds, collecting precise data about the tree failure phenomenon and the limit of reconfiguration would be invaluable for wind damage
modelling. As well, the impact of elevated CO$_2$ on the aerodynamic performance of a coniferous tree could be considered in future wind testing.

3.5 Conclusions

In summary, the experimental data collected in this study to examine the relationship between drag coefficient and crown leaf density of a broad-leaf tree in a wind testing facility is a novel contribution to risk assessment of urban trees. The approach taken here to utilize a depth sensor for real-time computation of the crown frontal area is not widely used in other studies. The results presented from this experiment indicate that the relationship between crown leaf density and drag coefficient is linear, and that the simulated silver birch tree in our previous study is expected to have 33\% increased resilience to wind damage compared to what was previously estimated, due to a decrease in the tree’s drag coefficient by 2\%. The risk of urban tree failure during windstorms will continue to increase in importance as we experience higher atmospheric CO$_2$ concentrations and more damaging windstorms. With additional effort devoted to the modelling of more tree properties changing with high CO$_2$, or with other climate change related properties and their impact on trees such as temperature, or precipitation, this modelling technique could become a useful and practical tool for risk assessment of individual urban trees.

3.6 References


4 Conclusions and recommendations

Trees grown in urban environments provide environmental, economic and psychological benefits to their surrounding communities [1]. However, urban trees also pose significant risks since damaged trees can cause serious harm to people and infrastructure by falling on sidewalks, roads, or power lines. This thesis presented a novel model that considers some impacts of climate change in trees' risk to wind damage. This includes changing wind storm frequency and intensity trends, both local to the Toronto, Canada region, and globally. As well, the impact of the steadily increasing concentration of atmospheric CO$_2$ is integrated in the model by considering empirical data collected via meta-analysis of 219 studies on the effects of elevated CO$_2$ on tree growth, and how these growth changes will impact the fragility and risk of trees to wind damage.

4.1 Summary

Chapter 1 provides an introduction to the problem of wind damage modelling for trees, and reviews the main studies and models related to this problem. The literature review of the expected impacts of climate change on wind damage modelling is also presented. The main objectives of this thesis are discussed, which are (i) to create a wind damage model that considers the impact of increasing atmospheric CO$_2$ concentrations, and the likely change in global and local winds due to climate change; and (ii) to improve the created wind damage model by identifying gaps in current research and conducting wind testing at the WindEEE Dome to fill these gaps.

Chapter 2 discusses (i) at length, wherein a wind damage model was created with the novel inclusion of meta-analysis data from 219 studies measuring the effects of elevated CO$_2$ growth condition on tree growth. The model is used to estimate the risk a 30-year-old silver birch (*Betula pendula*) being damaged by the wind via overturning or trunk rupture in the years 1990, 2020, 2050, and 2080. The size and shape of the silver birch was estimated using the United States Department of Agriculture (USDA)’s Urban Tree Database of allometric equations [2]. Historical atmospheric CO$_2$ concentration data was collected from the Mauna Loa observatory in Hawaii, USA [3], and future CO$_2$ estimations were made using the IPCC’s RCP8.5 emissions scenario [4]. The impact of elevated CO$_2$ on tree growth was estimated from meta-analysis data collected during this thesis. Critical loads to overturn the modelled tree were calculated using an empirical function created by
Schooten [5], based on tree pulling experiments that relate the diameter at breast height of trees to the base bending moment they could sustain. Critical loads to rupture the trunks of the modelled tree were calculated using the mechanical function for shear stress within a cylinder, where the tree trunk is approximated as a cylindrical cantilever beam fixed to the ground by its roots and free to move at the crown. The critical wind speed required to damage the tree was found based on the drag equation (Equation 2.23), where the drag coefficient is estimated based on Mayhead’s silver birch tree wind testing [6]. To determine the likelihood of the critical wind speed being exceeded annually, historical wind gust data from the closest major airport, Toronto Pearson International Airport, were analyzed. A Weibull distribution was created of the annual maximum wind gust speeds using linear regression to show the historical probability of a given wind speed being exceeded in any year with recorded data. From this model, it is found that the risk of urban tree failure due to wind damage is steadily increasing as CO$_2$ concentration increases over time.

Chapter 3 discusses (ii) at length, wherein wind testing was conducted of a 9-year-old red maple (Acer rubrum) tree. The tree’s response to the wind was quantified using the drag force, crown frontal area, and total leaf area whereby the tree was tested at four wind speeds (5.9, 8.2, 9.9, 11.7 m/s) and five leaf area conditions (100%, 75%, 50%, 25%, 0% total leaf area). The test data was used to analyze the relationships between wind speed and crown frontal area, wind speed and drag coefficient, drag coefficient and frontal leaf area. These relationships were returned to the model described in Chapter 2, improving the precision of the model. The results from this testing indicate a strong linear relationship between crown leaf density and drag coefficient across all test conditions. When considering this result for our previously proposed, we find that the simulated tree in that study will experience a 2% lower drag coefficient by 2080, resulting in a 33% increase in the estimated return period between storms capable of damaging the tree. Enus et al. found that the drag coefficient of their tested tree decreases by 33% from 1.4 m/s to 6 m/s tests [7]. In this thesis, it was found that the drag coefficient decreases by a further 25% from 6 m/s to 11.7 m/s tests. The rate of change of the drag coefficient decreases as the wind speed increases, indicating clearly that the tree is approaching the limit of reconfiguration, where the tree will be as streamlined as its structure will allow.

The methods presented here are directly applicable to improve modelling of current wind damage risk for trees. They also have broader applications in climate change resilience, where similar methods
can be replicated to consider the impact of other climate change factors that will impact trees' risk to damage. The results from this effort improve our understanding of the complex interaction between trees and the wind, and the highly sensitive nature such models have to the drag coefficient of the modelled trees. Our model indicates that by making small changes to urban trees to improve their aerodynamic performance, the risk of wind damage can be reduced by as much as 50%. This is accomplished by thinning some leaves from urban trees, reducing their wind-facing area, or trimming the top branches to encourage the tree to grow shorter and with a thicker trunk. The thesis lays a foundation for future work on wind damage modelling with respect to climate change, where the model methodology, described in Chapter 2, provides an example for how additional climate change factors can be included in wind damage modelling in future, further improving the precision of such models. Relevant additional factors that have been found to impact the risk and resilience of trees to wind damage are nutrient availability [8], local climate and how it relates to the tree species studied (cooler climate trees respond positively to increased air temperature, while warmer climate trees typically respond negatively to increased air temperature [9]), and further analysis on local and global wind trends as longer records become available as more time passes.

4.2 Conclusions

The overall conclusions from Chapter 2 are the following:

- Factors of climate change can be integrated into traditional wind damage models to predict how risk is changing over time.

- The size of trees exposed to elevated CO₂ concentrations will grow faster and larger than trees exposed to control conditions.

- High standard deviation is present in the CO₂ - tree growth meta-analysis data, indicating a broad range of positive responses from trees to elevated CO₂.

- When grown under elevated CO₂, overall trees are 43% heavier, 21% taller, with 15% thicker trunks and 29% more leaf area compared to ambient.

- For both overturning and rupture, the force required to damage the tree is increasing with time and CO₂ levels. This is owed to the increases in trunk thickness.
• The critical wind speed to damage the silver birch trees will be steadily declining, with more drastic changes happening as time advances. This is owed to the increases in leaf area, tree height and crown size which worsen the aerodynamic performance of the tree more than it is improved by the increased trunk thickness.

• From the Pearson International Airport wind data analyzed, in the 63 years of available data on observed annual peak wind speeds a doubling in frequency from the first 30 years of data to the most recent 30 years of data. This observation is assigned low confidence though, where a student’s t-test indicates no significant difference in the two data sets (P = 0.5), making it likely that the apparent doubling is due to random chance.

• Although the wind speeds are only declining by about 2 m/s across the entire interval 1990-2080, the fitted Weibull indicates that the lower critical wind speed is about ten times as likely to occur as the higher critical wind speed.

The overall conclusions from Chapter 3 are the following:

• Overall, the total leaf area and number of leaves removed during each thinning were approximately 25%, so the tree thinning process was a success.

• The crown frontal area is decreasing as wind speed increases across all tests where the tree has any leaves. In these cases, the crown area decreases most significantly between the two lowest wind speed tests (5.9 and 8.2 m/s), gradually decreasing less as wind speed increases. This is owed to the crown approaching its limit of reconfiguration; the maximum amount of bending it can undergo due to the drag force.

• As leaf area percentage increases, drag force increases significantly across all wind speeds tested. Similarly, drag force increases steadily as wind speed increases for all leaf area percentages tested.

• The lower drag force experienced by the tree than the drag equation (Equation 3.6) would predict is best modeled by lowering the drag coefficient of the tree as wind speed increases. The drag coefficient appropriately accounts for the aerodynamic properties of the tree, and how the aerodynamic properties of the tree will vary as the structure of the tree is changed in relation to the flow due to reconfiguration.
• The drag coefficient is decreasing as wind speed increases across all tests, showing the greatest decreases initially between the 5.9 m/s and 8.2 m/s tests.

• The results from this testing indicate a strong linear relationship between crown leaf density and drag coefficient across all test conditions.

• When considering this result for our previously proposed model, the simulated tree in that study will experience a 2% lower drag coefficient by 2080, resulting in a 33% increase in the estimated return period between storms capable of damaging the tree.

• Enus et al. found that the drag coefficient of their tested tree decreases by 33% from 1.4 m/s to 6 m/s tests \[7\]. In this thesis, it was found that the drag coefficient decreases by a further 25% from 6 m/s to 11.7 m/s tests. The rate of change of the drag coefficient decreases as the wind speed increases, indicating that the tree is approaching the limit of reconfiguration.

• Considering the results from this thesis with those from Enus et al. regarding the variation of crown frontal area with wind speed, it is shown that at low wind speeds (less than 4 m/s), the crown frontal area increases as the leaves oriented against the flow direction are rotating outwards, setting themselves perpendicular to the flow. Beyond 4 m/s, the crown frontal area decreases rapidly at first, as the applied drag force becomes great enough to overcome the stiffness of the branches, bending them in the direction of the flow. Beyond 8 m/s, the crown frontal area continues to decrease, but at a slower rate, as the crown approaches its limit of reconfiguration, wherein it will be fully oriented in the flow direction before permanent deformation or damage occurs.

4.3 Recommendations and future work

With regards to the past and current progress made on wind damage modelling, there is still much room for improvement. In this regard, the following recommendations for future work are suggested:

• Other factors of climate change should be integrated with wind damage models to better understand the holistic impacts of climate change on trees’ risk to wind damage.

• More mature trees should be analyzed in wind tunnel testing to better correlate wind test results to larger trees in nature, as these pose the greatest risk when damaged by the wind.
due to their size and weight.

- Trees should be wind tunnel tested to failure to better understand the limit of reconfiguration.

- Further work should be done to better understand the strength of trees to resist overturning, due to all currently popular wind damage models basing this on only Schooten’s tree pulling work primarily [5].

- Further work should be done to better understand if elevated CO\(_2\) growth conditions impact the modulus of rupture of the trunk wood, and subsequently the load capacity of the tree for trunk rupture failure.

- A more detailed analysis of global wind storm frequency and intensity could be conducted to improve confidence in the impact of climate change on damaging wind return periods. Long-term wind records from other airports could be analyzed to increase the data set size, improving confidence in the presented trends.

4.4 References


