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Via email: Doug@fotmw.ca

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Subject: Literature review on measuring rates of forest evapotranspiration

Dear Friends of the Muskoka Watershed,

Zygoptera Consulting is pleased to submit the following literature review summarizing methods of measuring rates of evapotranspiration by plants and forests. This is to aid in the continuing work of the Friends of the Muskoka Watershed.

Please review the document and we look forward to hearing any feedback. We have enjoyed this assignment and working with you.

Sincerely,

The Zygoptera Consulting Team

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Executive Summary

The negative impacts of acid rain to tree vitality in eastern North America and Europe are well known. Yet, little is known about the indirect impacts to forest evapotranspiration the hydrological cycle from acid rain. It has been suggested that nutrient leaching from forest soils has resulted in decreased tree leaf area, impacting trees' ability to absorb water and evapotranspiration on a wider spatial scale.

The Friends of the Muskoka Watershed (FOTMW) is interested in gleaning information about the effects of soil acidification and nutrient leaching on evapotranspiration at various spatial scales (i.e., leaf, tree, forest, stand, watershed, etc.). The following report reviews scientific literature on forest transpiration and evapotranspiration to provide relevant information to the FOMTW.

Relatively little research has focused specifically on the impacts of soil acidification and the impacts on tree of forest transpiration evapotranspiration. Therefore, this literature review focused on the various methods and models used to estimate evapotranspiration to offer guidance for future FOTMW studies involving calcium -rich residential wood ash and any potential relationship to evapotranspiration when applied to the forest soil.

Estimating transpiration and evapotranspiration is complex. It requires instrumentation, labour, and equipment maintenance, which can be costly and require a certain skill set. There are many factors to consider when assessing forest evapotranspiration, including the objective of the research. Sample size, pre-treatment data collection, site characteristics, and length of study were also noted in the literature as important factors in minimizing uncertainty of nutrient application impact of forest evapotranspiration.

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1.0 Introduction

1.1 About this Document

The objective of this document is to review the current scientific literature on how transpiration is measured from leaves, plants, and evapotranspiration of forests, as well as to provide guidance to the Friends of the Muskoka Watershed (FOMTW) and their partners for future studies on the potential benefits of residential wood ash to forests of Central Ontario suffering from the long-term impacts of acid rain. This review is intended for audiences in Ontario and specifically to those interested in measuring evapotranspiration and the effects of nutrients on tree water use.

While the content of this document focuses heavily on scientific and peer-reviewed literature, it is not an academic document and does not attempt to review all academic literature pertaining to forest evapotranspiration nor the impacts of residential wood ash on forest vitality. Non-peer-reviewed literature was also reviewed during the writing of this report to provide background and context, which not always present in the scientific literature.

1.2 Information Sources

Two online research search engines were primarily used in the development of this document: Google Scholar and the Ontario Council of University Libraries (OMNI). These were used to identify and assemble a list of scientific literature related to forest evapotranspiration at various spatial scales, methods and models used to estimate transpiration and evapotranspiration, soil acidification, and nutrient impacts on plant water use.

The focus of the document is of forests typical to North America, but as there is little research on evapotranspiration specific to this area, studies from around the world, as well as those pertaining to laboratory studies and agriculture were also assessed. Search terms and phrases included:

“Evapotranspiration”
“Transpiration”
“Measure evapotranspiration”
“Measure transpiration”
“Remote Sensing”
“Sap-flux”
“Calcium addition impacts on trees”
“Soil fertility impacts on tree transpiration”
“Alkaline soil improves plants ability to absorb water”
“Effects of acid deposition”

Approximately 52 papers were identified through the online searches. These publications were screened by scanning abstracts and narrowed down to approximately 17 papers to focus on the topic. These papers spanned a period of 1937 to 2022. All relevant literature was read in full, discussed in **Section 2.0**, with the most relevant papers being summarized in **Table 1** and **Appendix A.**

1.3 Limitations to This Document

Research for this review relied heavily on what is publicly available via the internet. Efforts were made to uncover as much relevant material as possible by reaching out to potential sources and reviewing cited articles as well as non-peer reviewed literature. It is important to note that internet searching is limited by terminology and language, how researchers describe their work and use terms. The work in this report is also limited by corporate memberships and paywalls; for example, some scientific journals were not available to Zygoptera Consulting or FOTMW staff. Additionally, some of the information and scientific literature is dated, specifically to that relating to the early research of plant water absorption, making it difficult to access or the access points were defunct.

1.4 Relevance to the Friends of the Muskoka Watershed

The FOTMW is a non-profit, charitable organization with an office in Bracebridge Ontario. The mission of the organization is *"to protect freshwater watersheds using programs that: restore, preserve and defend them, improve management to adapt to major stressors, increase public understanding of their importance, and advance education through research and communicating results."*

Considering the mission, one of the key projects of FOTMW has been to research and communicate "ecological osteoporosis" which is significant nutrient decline, specifically calcium, throughout much of Muskoka's forests due to decades of acid rain. The trees in Muskoka's forests, as well as the organisms that live in the forests continue to suffer from the lack of nutrients.

One goal of FOTMW has been to attempt to repair this environmental problem. Scientific studies have shown that clean residential wood ash (ash obtained from wood stoves used to heat homes) is high in minerals, including calcium, and when added to forest soils can remediate poor tree, forest and, assumingly, watershed, health (Kim et al., 2022). A natural evolution of this research is to explore if ash addition to forest soils, also impacts water absorption and evapotranspiration of trees, and watershed hydrology.

Measuring water absorption is especially of interest to land managers and residents of Muskoka and the surrounding areas as flooding continually threatens private and public property. The frequency of damaging floods has increased in recent years due to global climate change and flooding is expected to happen more frequently into the future (Pielke and Downton, 2000).

2.0 Literature Review

2.1 Defining Evapotranspiration

The term **evapotranspiration** is the merging of two words “evaporation” and “transpiration.” Evaporation is the process by which liquid water is transferred from land to a vapour and into the atmosphere. Transpiration is the process of plants losing water from leaves. Transpiration is a critical physiological mechanism involved in water conservation, which allows for plant growth and survival (Nobel, 2005 in Wu et al., 2021). Collectively, these processes are known as evapotranspiration (Kassuelke et al., 2022), which is used to describe the process by which water moves from the earth’s surface into the atmosphere (Verstraeten et al., 2008). In this report, evapotranspiration is the term used when water is moved from the forest (i.e., soil surface, foliage, etc.) to the atmosphere. The term transpiration is used to describe water as it moves from a tree or leaves into the atmosphere as vapour.

An understanding of how trees absorb and evaporate water via their roots and leaves is required to comprehend evapotranspiration. Briefly, water mostly enters a tree through the root hairs by osmosis. The dissolved minerals and nutrients will travel with the water upward through the inner bark’s xylem and into the leaves. The nutrients feed the tree through the process of leaf photosynthesis (Nix, 2021).

Water is supplied to the leaves through a decrease in hydrostatic or water pressure in the upper leaf-bearing parts of the tree. The difference in pressure between the top (negative pressure) and bottom (positive pressure) of the tree causes water from the bottom to be ‘lifted’ to the top. Water loss from a tree is directly related to temperature and humidity; on hot dry days, more water is lost than on cold humid days. The more transpiration that occurs, the greater the pressure difference and therefore the more water is pulled up the tree (Nix, 2021). Trees will also change their behaviour based on water availability (Wu et al., 2021). Evaporation of water from the leaves, stems, flowers and even roots can also add to a tree’s water loss and if the movement of water from roots to the top of the tree is impacted by drought, or damage to the xylem, the tree may die (Nix, 2021).

Once in the leaves of a tree, 90% of the water is dispersed and eventually released from leaf stomata (small openings on the underside of leaves, and both the underside and topside of needles) (Shaw, 2019). The remaining approximately 10% of water stays in the tree, keeping it healthy and maintaining growth. The ratio of the mass of water transpired to the mass of the dry matter produced by the tree is called the transpiration ratio, and the amount of dry matter produced depends on the efficiency of the tree (Nix, 2021).

2.2 Measuring Rates of Transpiration and Evapotranspiration

Measuring transpiration rates and water use by plants has historically been an important part of plant irrigation management in agriculture, though more recently interest has grown in the relationship of climate change and forest or ecosystem transpiration and large-scale evapotranspiration. Proper evapotranspiration is fundamental for food security, land management, pollution detection, nutrient flows, and **carbon balance** modelling (Verstraeten et al., 2008).

There are several methodologies and techniques used to measure transpiration and evapotranspiration, with advantages and limitations associated with each. Focusing on forests, estimates can be performed on different scales including leaf, plant, field, landscape, and region (Wilson et al., 2001; Shuttleworth, 2008; Verstraeten et al., 2008). Evapotranspiration estimates are based on **mass** or **energy conservation laws** or a combination of both (Verstraeten et al., 2008). Separate contributions at the transpiration or evaporation level can also be used to estimate evapotranspiration. Alternatively, evapotranspiration rates can be modeled by local climate data or the use of stable water isotopes. A few of these methods are summarized in **Table 1**.

Table 1: Scales and measurements to estimate transpiration and evapotranspiration.

Conservation Law	Spatial Scale	Example	Description	Advantages/Disadvantages
Mass balance	Leaf/plant/ field	Porometer	Water vapour loss from a leaf in a chamber measured by increase in humidity or temperature	Advantage: Provides direct estimates of water loss from leaves. Disadvantage: Estimates at leaf level and must be extrapolated for the whole canopy; assumes enclosure chambers do not alter transpiration rate.
Mass balance	Leaf/plant/ field	Lysimeter	Measures change and weight of a plant while measuring precipitation and drainage of sample	Advantage: Provides daily measurements with high accuracy and useful for data collection; measurements can be performed under realistic field conditions. Disadvantage: Limited to measurements of only a few individual trees that are young; installation can be disruptive to vegetation and is expensive.
Mass balance	Leaf/plant/ field/landscape	Water balance of basin	Measures water balance components such as precipitation, groundwater outflow, and soil water storage under realistic environmental conditions	Advantage: Provides area-average measurement for a region. Disadvantage: Expensive and difficult measurement and only longer-time average estimates are possible.
Mass balance	Leaf/plant/ field	Evaporation pan	Measures change of water level of a sample in a pan	Advantage: Widely used technique. Disadvantage: No direct information on transpiration from measured data.
Mass balance	Leaf/plant /field	Soil moisture depletion	Measures water content in a sample while measuring rainfall and run-off	Advantage: Measurements are inexpensive and usually representative of a forest plot.

				<u>Disadvantage</u>: Disturbance during installation of soil water sensor below measurement depth can impact results.
Mass balance	Leaf/plant /field	Sap-flow	Measured by the rate of sap flow using heat as a tracer with an estimate of the area of the wood through which the sap flows	<u>Advantage</u>: Useful and accurate validation of water and energy balance algorithms. <u>Disadvantage</u>: Does not consider evaporation of rainfall interception by forest canopy and requires technical and maintenance efforts; require power supply and electrical distribution.
Energy balance	Leaf/plant /field	Bowen Ratio	Evapotranspiration is calculated from measurements of humidity and temperature at two different heights to estimate heat flux	<u>Advantage</u>: Simple, robust, and low cost. Widespread use to measure evapotranspiration at the local scale. Accuracy within 10%. <u>Disadvantage</u>: Does not consider horizontal fluxes and cannot be used inside canopies. Net radiation and soil heat fluxes must be measured simultaneously.
Energy balance	Landscape	Eddy covariance	Calculates evaporation from the correlation between fluctuations in wind speed and water vapour	<u>Advantage</u>: Very accurate method. Used for site scales and directly measures latent and sensible heat fluxes from vegetated surfaces. <u>Disadvantage</u>: High cost, complex, and time consuming. Measurements can be difficult to interpret during windy periods.
Energy balance	Leaf/plant/field/landscape	Scintillometer	Measures contribution of heat fluxes and atmospheric turbulence over a fixed path using a beam of electromagnetic radiation	<u>Advantage</u>: More cost-effective to measure area average fluxes. <u>Disadvantage</u>: Consumes a lot of power. Unsuitable for longer periods because it is restricted by unsuitable meteorological conditions (e.g., rain, poor visibility).
Energy and	Landscape/	Remote sensing	Estimates	<u>Advantage</u>: High temporal resolution, large spatial observation

mass (water) balance	regional	estimates	evapotranspiration by difference between air temperature and temperature of evaporating surface, and the aerodynamic exchange resistance between the two	scale, and high accuracy. <u>Disadvantage</u>: Source can be affected by atmosphere, wind speed, and surface roughness. Technology still needs improvement.
Mass balance (measurement of isotopes)	Leaf/plant/field/landscape	Stable isotope-based methods	There are distinct isotopic signatures of evaporation and transpiration that can be used to measure the ratio between evaporation and transpiration and to estimate land and atmosphere water exchange.	<u>Advantage</u>: Measurement of isotopes is stable and robust and offers and provides better estimates for transpiration to total moisture flux. <u>Disadvantage</u>: Not as much research using methods to validate them and more research is needed to put it in context.

References: (Wilson et al., 2001; Zhang et al., 2007; Shuttleworth, 2008; Verstraeten et al., 2008; Sutanto et al., 2014; Moorehead et al., 2017; Lui and Xu, 2018; Aron et al., 2020)

A commonly used method, as summarized in **Table 1,** and a component of mass conservation law is sap flow. Over the past two decades, it has been used to quantify transpiration at the stand-scale by monitoring a single tree or multiple trees in a stand (Wilson et al., 2001; Rice et al., 2022; Wu et al., 2021). Sap flow measurements allow the researcher to determine the total quantity of water transported by tree species on a daily basis, and if desired, to characterize the ecological and physiological mechanisms that tree species use to cope with limited availability of soil water (Huang et al., 2011; Wilson et al., 2001; Rice et al., 2022; Wu et al., 2021). **Sap flux density** can be determined based on the thermal diffusion principle and using thermal dissipation probes. Whole-tree daily transpiration can be calculated with the sap flux density, change in temperature and **sapwood area**.

One method that is increasing being applied in the study of water cycling is stable water isotopes. For example, James et al. (2019) found that stable isotopes may provide a quantitative assessment of source water partitioning in streamflow in the Muskoka River Watershed. Aron et al. (2020) investigated the use of stable water isotopes to estimate rates of transpiration and evaporation. They found that isotopic approaches agree with ecohydrological partitioning methods such as eddy covariance and sap flux estimates, suggesting this method may be acceptable when it is logistically or impractical to install senor equipment, such as that required for measuring sap flux.

Regardless of the method or strategy, estimating transpiration and evapotranspiration requires instrumentation, labour, and maintenance, which can be costly and logistically complicated. Furthermore, evapotranspiration is not easy to measure due to many influencing factors (Lui and Zu, 2018). It is difficult to extrapolate measurements from water use of leaves to entire forests (Dawson, 1996). Continued efforts to develop processes and methods to measure and scale evapotranspiration both spatially and temporally are critical for further understanding of its significant role in the terrestrial hydrological cycle.

2.3 Influences on Forest Evapotranspiration

There are several known mechanisms and strategies that trees use which can influence their transpiration, including deep root development, intrinsic **water use efficiency** (WUE) (See **Appendix A**, Wu et al., 2021; Moreno-Gutierrez et al., 2012; Olano et al., 2014), as well as the formation of thicker cuticles or waxy layers on leaves (Barbeta and Penuelas, 2016). Other mechanisms include decreasing **stomatal conductance** and photosynthetic rates or even reducing growth rate (Moreno-Gutierrez et al., 2012; Olano et al., 2014). A tree’s access to nutrients or ability to absorb nutrients may indirectly influence its ability to use water (Wu et al., 2021; Ewers et al., 2001; Rice et al., 2022) and a tree's ability to absorb nutrients is influenced by the pH of the soil (Tsai and Schmidt 2021; DeHayes et al., 1999; Watmough at al., 1999).

When the pH of soil is acidic, a plant’s ability to uptake nutrients, like nitrite and phosphate are negatively impacted (Tsai and Schmidt 2021). Acid rain from the 1960s through to the 1980s resulted in soils throughout much of the northern hemisphere becoming more acidic due to their low acid-buffering capacity (Likens et al., 1998; Moore et al., 2012).

The low soil pH also caused harmful manganese (**Mn**$^{2+}$) levels and the presence of toxic aluminum species like aluminum (**Al**$^{3+}$) to increase (Tsai and Schmidt 2021; DeHayes et al., 1999; Watmough at al., 1999). When aluminum is mobilized in mineral soil by acid deposition, it reduces the soil storage of calcium (**Ca**) and other nutrients and their availability for plant root uptake, affecting plant vitality (Tsai and Schmidt 2021; Lawrence et al., 1995). For example, McLaughlin et al. (1991) found that reduced Ca supply and high concentrations of aluminum in soil may reduce net photosynthesis of red spruce (*Picearubens Sarg*.)

A lasting impact of acid rain is that Ca leaching from forest soils far exceeds rates of replenishment through weathering and atmospheric deposition, making Ca loss a threat to the long-term vitality of forests in Muskoka and other regions prone to acid deposition (Likens et al., 1998; Watmough and Dillion, 2003; Kim et al., 2022). Ca can limit forest primary production, influence forest nitrogen uptake, change cation exchange capacity and alter other ecosystem dynamics (McLaughlin and Wimmer, 1999; Huggett et al., 2007; Kim et al., 2022).

Research has found that Ca application to acidic soil has benefits. To start, when Ca is applied to forest soil, it results in an increase in soil pH (Peters et al., 2004 in Kim et al., 2022; Syeda and Conquer In Progress). Ca has also been found to play a critical role in plant responses to numerous stresses (Hepler and Wayne, 1985 and Sheen 1996). For instance, after applying **calcium silicate** to a New Hampshire forest, Green et al. (2013) had the unexpected result of observing reduced streamflow for three years post application, which was attributed to a 25% increase in evapotranspiration associated with increased foliar production. This supports the concept that watershed hydrology and forest evapotranspiration may be impacted by soil nutritional status. In addition, Ewers et al. (2001) found that when provided nutrients, Norway spruce (*Picea abies*) and loblolly pine (*Pinus taeda*) increased their leaf area index and stomatal conductance, and Moore et al. (2012) found that crown dieback decreased 15 years after applying dolomitic lime to a northern hardwood stand. Another study by Da Silva et al. (2008) in Amazonia, Brazil found that the control forest plot had a higher mean soil moisture content at the end of the dry season, indicating that the treatment plots responded positively to fertilizer additions by taking up additional water. They also noted that trees in the phosphorous (**P**) and Ca plot increased photosynthesis rates.

Rice et al. (2022) sought to verify Green et al.'s research and whether increased tree water use could explain the observed reduction in runoff following calcium silicate application, but poor statistical power due to high tree-to-tree variability prevented detection of potentially important treatment effects. Sap flux density did not differ consistently, nor was there a difference in response to a calcium silicate addition as the number of years post treatment increased (Rice et al., 2022). Rice's et al. (2022) suggestion that nutrient application does not significantly increase water absorption is supported by Kramer (1937) who assessed willow and sunflowers in a laboratory setting and determined that even when roots are immersed in a dilute solution, plants may not absorb water as rapidly as they lose it in transpiration.

To summarize, increases in soil pH via calcium or via other means potentially increases a tree's ability to absorb nutrients which causes the tree to grow more, increasing tree leaf area. Leaf area is a key determinant of transpiration and groundwater absorption (Kramer, 1937). Yet, as indicated by Rice et al. (2022) and others, more statistically powerful research is needed to determine if calcium addition influences forest evapotranspiration and watershed hydrology.

2.4 Going Forward

There are many factors to consider when assessing forest evapotranspiration, including the objective of the research, temporal and spatial scales (as outlined in **Table 1** and **Appendix A**), financial budget, as well as access to technology and resources and experience and interest of researchers. These need to be considered at the onset of an evaluation.

As discussed in **Section 2.2**, estimating transpiration and evapotranspiration is complex, requires instrumentation, access to electricity, labour, and equipment maintenance, which can be costly and require a certain skill set. It is difficult to extrapolate measurements of plant water use of leaves to entire forests (Dawson, 1996), so method and model selection should be considered carefully.

Rice et al. (2022) noted that when assessing a forest stand, catchment area or watershed, sample size is an important factor in determining if nutrient application, such as calcium, has a significant impact on sap flux density and transpiration. The work of Aron et al. (2020) and James et al. (2019) on stable water isotopes could potentially transfer to estimating transpiration and evapotranspiration in Muskoka forests at the catchment scale. However, there are few studies using isotopic approaches to validate its accuracy (Sutanto et al., 2014). Therefore, it is suggested that pre-treatment data collection and additional tree metrics like leaf and sap wood areas all be a part of future studies.

For a study on a larger scale, Verstraeten et al. (2005) recommend either a GIS-modeling approach or remote sensing technique be applied, and Zhang et al. (2016) recommend applying multiple remote sensing methods/models and fusing the data to minimize uncertainty in the results.

Lastly, when planning a forest study involving evapotranspiration, it is important to consider other factors, such as limiting nutrients like N, Mg, P, and K. For example, in a New Hampshire study, the relative basal area of the average tree increased in response to P addition (Goswami et al, 2018) and mature trees grew more in response to N additions (Hong et al., 2022). As made evident by the results of Menon et al. (2007), it is also suggested that studies be extended over several years as evapotranspiration response to nutrient and pollution inputs take time.

2.5 Conclusion

Calcium addition to forests with low-buffering capacity soil has many potential benefits, including changes to evapotranspiration and localized hydrology. But little research has been done on the impacts of nutrient application to evapotranspiration in acid rain affected forests. Therefore, the focus of this review was on methods and models used to estimate evapotranspiration to help FOTMW and its partners develop studies on determining if residential wood ash application can benefit the hydrology of the Muskoka River Watershed.

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Glossary and Acronyms

Al - Aluminum

Ca - Calcium

Calcium silicate- a noncombustible, white or cream-coloured powder that is prepared commercially from lime and diatomaceous earth

Carbon balance - the net result of carbon uptake by photosynthesis and losses by respiration

CO2 - Carbon dioxide

Energy conservation laws- energy can neither be created nor destroyed, only converted from one form of energy to another

Evapotranspiration - the process by which water is transferred from the land to the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.

FOTMW- Friends of the Muskoka Watershed

Heat pulse velocity (HPV) - technique used for measuring water use by trees, specifically sap flow of hardwood trees

Isotopes - different species of atoms of the same chemical element. All isotopes of an element share the same atomic number (the number of protons in their nucleus) and the same arrangement of electrons.

K- Potassium

Mass conservation laws- in a chemical reaction mass is neither created nor destroyed

Mg - Magnesium

Mn - Manganese

P - Phosphorus

Sap flux density - sap flow sensors which track the heat applied to a plant's conducting tissue and monitor water use of plants

Sapwood - also known as the alburnum, the outer living layers of the secondary wood of trees which engage in the transport of water and minerals to the crown tree

Stomatal conductance - the diffusion of gas, such as carbon dioxide, water vapour and oxygen through the stomata of a plant

Time domain reflectometry (TDR) - an electronic instrument used to measure changes in the moisture storage of the woody parts of trees

Water use efficiency (WUE) - the ratio of water used in plant metabolism to water lost by the plant through transpiration

Appendix A: Summary of Literature Review Studies

Topic	Title/ Reference	Location	Description and Key Take-aways
Anthropogenic effects on soil fertility	Soil fertility problems - and agriculture and forestry perspective Huttl and Frielinghaus, 1994	Germany	● The authors investigated soil fertility issues from agricultural and forest perspectives in Germany. ● Agricultural soil fertility has been mostly damaged by soil compaction, and water and wind erosion. ● Agricultural soil fertility was site-specific; therefore, the authors suggested management solutions should be based on site characteristics. ● Magnesium (Mg) deficiency is a common issue in German forests due acidic soils from atmospheric deposition. ● Symptoms of Mg (or potassium (K)) deficiency in coniferous trees (e.g., Norway Spruce) include tip-yellowing and phloem (the tissue that transports assimilate) collapse. ● Fertilization (application of fast-soluble Mg fertilizers and Mg containing lime) mitigated nutrient deficiency, coniferous trees regreened, and phloem was regenerated. ● The authors found fine root growth increased biomass after Mg fertilization. ● They concluded that methods to improve soil fertility and quality must be modified to site specific characteristics.
Metal pollution and acid rain effect on trees	Effects of heavy metal soil pollution and acid rain on growth and water use efficiency of a young model forest ecosystem Menon et al., 2007	Swiss Federal Institute of Forest, Snow and Landscape Research, Birmensdorf, Switzerland	● The authors studied the effects topsoil heavy metal pollution and acid rain on tree growth and water use efficiency of a young forest ecosystem of Norway spruce, willow, poplar, and birch in open air chambers. ● The authors' objective was to investigate the treatment effects of growth of the young trees and overall water efficiency. ● This model was conducted to gain insights representative of field conditions (than pot plants) and for a longer duration (4 years). ● The results indicate that different young tree species respond differently to heavy metal contamination as well as from year to year as stands develop. ● The water use efficiency decreased in the metal treated plots and whole system water use efficiency was reduced by metal stress and higher on calcareous than on acidic soil, but the type of subsoil did have a strong effect on the WUE as well.

			• The authors also found that fine root mass was reduced by heavy metal pollution of three tree species and metal contamination significantly reduced evapotranspiration on both subsoils for two years. • Whole system evapotranspiration was closely correlated with the total above-ground biomass and total leaf area of the trees.
Effects of nutrients on tree water use	Water-use efficiency of tree species following calcium and phosphorous application on an abandoned pasture, central Amazonia, Brazil Da Silva et al., 2008	Near Boa Vista, Brazil	• The authors examined soil moisture and water-use efficiency (WUE) of second growth forests in abandoned pastures in Amazonia Brazil. They tested the physiological responses of three common tree species to nutrient treatments of control, phosphorus (P), P and lime, P, lime, and gypsum. • Trees growing on the P + Ca but not +P alone plots increased, indicating that Ca is an important limiting nutrient in post-pasture secondary succession. • The results indicate that the fertilized plots responded positively to the fertilizer by taking up additional water and the plots with P and Ca had an increase in photosynthesis rates.
Effects of nutrient addition to tree water use	Decreased water flowing from a forest amended with calcium silicate Green et al., 2013	White Mountains, New Hampshire, USA	• The authors aimed to better understand how forest ecosystems respond to changes in a component of acidification stress. They applied calcium silicate to a 11.8 ha watershed to restore available soil calcium to preindustrial levels (i.e., before acid rain) • They found annual evapotranspiration increased by 25%, 18% and 19%, respectively for three years following the calcium silicate and a stream in the study area had reduced runoff, suggesting calcium silicate increased leaf area, increasing water transferal by the vegetation.
Effects of nutrient addition to tree water use	Tree variability limits the detection of nutrient treatment effects on sap flux density in a	White Mountains, New Hampshire, USA	• The objective of the study was to quantify the effect of nutrient availability on sap flux density in a nitrogen, phosphorus, and calcium addition experiment in a New Hampshire forest. • In 2018 Green et al. found the effect of calcium addition to a forested watershed to be a marginally significant increase of sap flux and a decrease in streamflow. • Rice et al. found that the statistical power of Green's et al work was too low to detect a response in sap flux density due to the application of

	northern hardwood forest Rice et al., 2022		calcium. In other words, the authors lack the statistical confidence to either support or contradict the explanation that increased sap flux density accounted for the decline in runoff. ● The authors suggest that other factors may have impacted the streamflow and future studies need to ensure large enough sample size, along with additional metrics.
Effects of nutrient addition to tree water use	The effect of fertilizer on sap flux and canopy conductance in a eucalyptus saligna experimental forest Hubbard et al., 2004	Hawaii, USA	● The authors noted an increase in sap flux density has been observed with the addition of multiple element fertilizers in eucalyptus forests in Hawaii. ● Total water use in fertilized plots increased during five months following fertilization as stand leaf area and sap flux per unit leaf unit sapwood area increased. ● Trees with five years fertilization also used more water than control stands because of greater leaf area in the fertilized stands. ● Adding fertilizer did not make the trees use water more effectively, fertilization impacted leaf area, impacting the hydrostatic or water pressure in trees.
Effects of nutrient addition to plant water use	The Relation between rate of transpiration and rate of absorption of water in plants Kramer, 1937	Laboratory/Greenhouse setting, Duke University, North Carolina, USA	● In a laboratory setting, the authors studied the relationship between transpiration and absorption of willows and sunflowers in a nutrient solution, which indicated that even when the roots are immersed in a dilute solution plants may not absorb water as rapidly as they lose it in transpiration. ● They determined that even when root systems were large, transpiration does not exceed absorption. The rate if water uptake is partly determined by the rate of water loss, which is determined by leaf area.
Measuring Transpiration	Canopy transpiration from a boreal forest in Sweden during a dry year Cienciala et al.,	Norunda Common, Sweden	● The authors scaled up daily canopy transpiration from individual tree flow rates using the quotients of stem circumference of sample trees and applied it to pine stands. Sap flow was measured using the tree-trunk heat balance method. Daytime average canopy conductance was obtained by inversion of the Penman-Monteith equation using canopy conductance as an input variable which permitted analysis of canopy conductance as a function of short-wave radiation and vapour pressure deficit.

	1997		• Canopy conductance is calculated as a ratio of daily water use to daily mean vapor pressure deficit. • Stomatal control is the key for assessment of transpiration and water balance, as well as for estimation of carbon assimilation and net primary production of trees and stands. • The authors noted that when estimating transpiration, it is important to compare the water use for the individual species and age classes.
Measuring transpiration	Comparison between different methods for measuring transpiration in potted apple trees Ferrara and Flore, 2003	Michigan, USA	• The authors compared five methods used for measuring transpiration on potted apple trees in a greenhouse setting at Michigan State University. The five methods included: ○ Gravimetric analysis (control) ○ Heat pulse velocity (HPV) ○ Time domain reflectometry (TDR) ○ Single leaf gas-exchange measurements, and ○ Whole plant infrared gas-exchange measurements • Among the five methods used in the study, the TDR method gave results more similar to the control, whereas the others over or underestimated the transpiration. The TDR method offered better accuracy and precision and was practical but is very expensive and not transferable to a forest setting.
Measuring evapotranspiration	Boreal forest CO_2 exchange and evapotranspiration predicted by nine ecosystem process models: Intermodal comparisons and relationships to field measurements	Thompson, Manitoba	• The authors assessed nine CO_2 and water vapour ecosystem models which had a wide range of approaches, along with some field work in a black spruce forest in central Canada. • The differences between the models and/or their parameterizations were more important to predictions of CO_2 exchange and evapotranspiration than was interannual variability in weather during the study (1994-1996) • The authors found large intermodal differences at all timescales (hours to years) indicating some model inaccuracies and model-measurement differences were often significant for individual models, at all timescales. • The authors also had low confidence in the models when they were applied to long-term model predictions. • As a result of model-measurement comparisons, improvements/modifications to many models are underway.

	Amthor et al., (2001)		
Measuring evapotranspiration	A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance Wilson et al., 2001	Oak Ridge, Tennessee, USA	• The authors conducted a multi-year study to compare different measurement techniques for evapotranspiration in a Southeastern USA forest. Techniques included: soil water budget, sap-flow, eddy covariance and catchment water balance. • Soil water budget measurements: used water content reflectometers co-located with time domain reflectometer at each soil depth and monitored every minute with data loggers. • Sap-flow: thermal dissipation sap flow probes were inserted 30 mm into the sapwood of 15 tree boles on the northern side and collected every minute and hourly means were stored on a data logger. • Eddy covariance: one system was mounted 10 m above the canopy and the other system was placed within the canopy at 2 m above ground. Wind velocity and virtual temperature fluctuations with an anemometer. Humidity fluctuations were measured with an open path, infrared gas analyzer and vertical flux densities were calculated from the mean covariance water and heat fluctuations with fluctuating vertical velocity. • Catchment water balance: relied on existing weirs on two first-order streams that drained the two watersheds near their confluence. Stage height for the weirs were recorded at 15 min intervals and instantaneous discharge was calculated. Annual discharge was calculated by summing the 15 min reading for each weir and the total watershed discharge was calculated by summing the two stream rates. Precipitation was determined using weighing bucket rain gauges and tipping buckets at locations within and bordering the watershed. Annual evapotranspiration was estimated as the residual between total annual precipitation and total annual runoff. • The authors discussed when the methods resulted in similar or different findings and when errors occurred, for example they determined that there may be errors associated with scaling single tree estimates, or measurement errors associated with ring-porous water conducting elements.
Measuring	Seasonal	Chongqing,	• The authors looked at seasonal variations in the transpiration, water-use

transpiration	Transpiration dynamics of evergreen *Ligustrum lucidum* linked with water source and water-use strategy in a limestone karst area, southwest China Wu et al., (2021)	Southwest China	patterns, and water sources for *Ligustrum lucidum* (Chinese glossy privet) through high resolution monitoring of the micrometeorology, sap flow, and soil moisture data, in combination with the carbon stable isotope composition of the tree leaves as well as oxygen and hydrogen stable isotope composition of the tree stem, soil and deep water. ● The study revealed that *Ligustrum lucidum* obtain water from different sources (shallow soil or deep underground pools) based on the season fluxes; the tree also applies different strategies in response to decreased water sources.
Measuring Evapotranspiration	A review of remote sensing based actual evapotranspiration Zhang et al., 2016	Global	● In this article the authors review basic theories underpinning current remote sensing-based evapotranspiration estimations. Some of these methods include: the Monin-Obukhov Similarity Theory and Maximum entropy production theory. ● The authors also discuss approaches used to estimate evapotranspiration using remote sensing, some of which include: surface energy balance methods, one-source surface energy balance methods (does not distinguish contributions from soil and vegetation components), two source surface energy balance (accounts for individual contributions of soil and vegetation to the total heat flux) and Penman-Monteith methods (compute evapotranspiration divided by latent heat of vaporization directly and/or estimate sensible heat in conjunction with the energy balance equation). ● They also discuss the Priestley-Taylor method, which is a simplified version of the Penman-monteith method and is mainly used to estimate evapotranspiration in water stressed conditions, as well as the Maximum entropy production method, the water-carbon linkage method, water balance method and the empirical model. ● The authors discuss the advantages and disadvantages of the different methods and their intercomparison. They conclude that no one method is superior, but rather they suggest reducing uncertainty when estimating evapotranspiration using a remote sensing model, multiple approaches be

			used and data fusion be applied.
Measuring Evapotranspiration	Assessment of evapotranspiration and soil moisture content across different scales of observation Verstraeten et al. 2008	Global	• In this paper the authors do an extensive review of evapotranspiration and soil moisture measuring methods. Of most interest is the section on evapotranspiration assessment at different scales of observation: sap-flow, porometer, lysimeter, field and catchment water balance, Bowen ratio, scintillometer, eddy correlation, and Penman-Monteith equation (See **Table 1** of this report). They also discuss optical and thermal remote sensing. • The authors conclude that most assessment methods of evapotranspiration are at the point, plant or stand scale and that extended networks of field sensors can provide estimates at a larger scale. It is suggested that monitoring is preferred over modeling for large scales, yet field measurements, hydrological models and remote-based models have given considerably different results historically.
Measuring Evapotranspiration	Evapotranspiration Measurement Methods Shuttleworth, 2008	USA/Global	• This is a short review of the two common types of direct ways to measure evapotranspiration: water budget and water vapour transfer measurements. The author provides strengths and weaknesses, assumptions, and potential errors associated with the methods discussed, as well as spatial scale. • Water budget measurements deduce evapotranspiration as a loss of liquid water by measuring or estimating all the other components in a water budget (e.g., sap flow, rainfall interception and soil evaporation). • Water vapour transfer methods measure the flow of water vapour into the atmosphere using meteorological sensors mounted above the surface.
Measuring Evapotranspiration	HESS Opinions: A perspective on isotope versus non-isotope approaches to determine the contribution of	Global	• In this paper, the authors attempt to determine how much transpiration contributes to total evaporation (transpiration, soil evaporation and canopy evaporation) using isotope-based studies by reviewing multiple articles. They provide perspective on isotope-based versus non-isotope-based partitioning studies by looking at isotope-based methods, hydrometric measurements, and modeling. • The authors conclude that estimates based on water isotope balance calculations tend to allocate a fairly large contribution of transpiration to

	transpiration to total evaporation Sutanto et al. 2014		the total moisture flux and are above estimates of the transpiration fraction of other isotope-independent techniques. ● A few studies that the authors reviewed compared estimates of evaporation at the same location and conditions using the isotope-based and hydrometric methods showed that the results are in good agreement. ● Continued measurements of global isotopic composition of soil water and water vapour around leaves are needed to put the isotope-based results into context.
Measuring Transpiration and Evapotranspiration	An isotopic approach to partition evapotranspiration in a mixed deciduous forest Aron et al. 2020	University of Michigan Biological Station (UMBS), lower Northern Michigan, USA	● The authors investigated the use of stable water isotopes for transpiration and evapotranspiration estimates and compared isotope-inferred ratio of transpiration to evapotranspiration with eddy covariance and sap flux data to examine its accuracy for evapotranspiration estimates. ● Subdiurnal variations of isotopes were measured from three deciduous tree species. ● Using water isotopes, they found that transpiration to evapotranspiration was constant during the day, which suggests similar atmospheric and micro-meteorological conditions control evaporation and transpiration. ● There was agreement between mid-day isotopic methods and eddy covariance and sap flux methods, therefore these methods can be used for evapotranspiration partitioning.