FOREST-WATER NEXUS
Interactions between forests and the hydrological cycle on both local and global scales

A Division III Thesis

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Amherst, Massachusetts
December 2019

Preface

I have broken my Division III research into five chapters. The first is an introduction into how I have developed my interests in the larger subject of forest hydrology and lead into a deeper literature review of the importance of this topic. Then, in my second chapter, I elaborate on the research that I have started where I look at water use of black birches and eastern hemlocks presenting the introduction, methods, expected results, and implication of my process in using sap flow to research the potential impacts of the hemlock woolly adelgid on New England forest water use. Although I was unable to complete this project, I outline the work I have done throughout my division III in hopes of continuing my work after I graduate. In my third chapter, I present a manuscript of forest-wind-water research using geospatial analysis software which I am preparing to submit to a peer-review journal after I graduate. For my concluding chapter, I tie together my different research topics and explain how my work during my Division III has prepared me for a future in forest hydrology and my continued pursuit of researching how forest land use influences the water cycle.

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Chapter 1 Introduction

Before I began my senior thesis in forest water interactions, I focused my education on building a foundation of knowledge in forestry, ecology, hydrology, mathematical modeling, and the greater social implications of forest hydrology. My academic interests focused on developing questions, using field work methods, modeling, geospatial analysis, and a bit of social contextualization of the impacts of my research. Within my research I have connected global analysis to plant physiology through my interest and passion for understanding how forests and changes in forest landscape are interacting with each other.

This introduction is broken into three sections explaining my academic career at Hampshire College as it plays into my Division III research. This chapter begins with (1) a background of how I developed my specific interests in forest hydrology, how I have built a foundation of knowledge for my thesis, and the overarching questions driving my greater research goals. (2) Then, I outline the goals and process of each of my thesis projects. Afterward, I contextualize my research concentrations in the greater social conversation of human impacts of my research. I conclude my introduction by connecting the different things I have learned with how I plan to integrate compassion and social dynamics into my research of forest water interactions.

Starting my DIV:

Before I began my senior thesis in forest water interactions, I focused my education on building a foundation of knowledge in forestry, ecology, hydrology, and mathematical modeling and the greater social implications of forest hydrology. My academic interests focused on using field work methods, modeling, geospatial analysis, and a bit of social contextualization of the impacts of my research. Within my research I have connected global analysis to plant physiology through my interest and passion for understanding how forests and changes in forest landscape are interacting with each other.

My hope was to develop the skills to effectively understand and critically examine forest water interactions. Before proposing specific research questions, it was important to outline the current literature available on this topic to inform my research on how forests change the hydrologic cycle. I have explored current understandings of the forest-water nexus to prepare myself to ask inquisitive and useful questions to contribute to the larger field of forest hydrology.

My specific interest in forest hydrology started with me taking water and ecology classes at Hampshire college in 2016. I was able to connect my research interests and the subjects in the classroom to my experiences growing up in Louisiana with increased hurricanes, and other extreme climate events, and how communities ignored the severity of climate change. As I began to dive deeper into my interests in the water cycle, I focused on water availability and changes in water yield by different systems. I was also curious about how extreme climate events and water centered natural disasters would change ecosystem structure and therefore long-term impacts on water cycling.

To build the foundations of my thesis work, I learned about the complexities and importance of forest systems on the water cycle. Forest structure plays a critical role in the water budget through influencing transpiration. However, variations in forest structure also influence evaporation, infiltration, ground water storage, and stream flow. These fluxes also influence water storage which is quantified through changes in ground water.

Studying the forest water nexus is similar to solving an invisible puzzle. I have taken a specific interest in looking at how evapotranspiration impacts forested ecosystems. With this comes with the need to understand a variety of biotic and abiotic variables that influence the complete water budget. Evapotranspiration is, in most forest systems that I have studied, the major influencer of water availability and water recharge.

I have attempted to create a balance in my education and research throughout my undergraduate career by engaging in literature reviews, field work and temporal and spatial modeling of water cycling. In my experiences in the academic communities that share my interests, engaging with forest water interactions through an interdisciplinary lens is the only way to tackle the complex and elaborate concept of forest hydrology. My forest hydrology research begins on a plant physiology level with local ecological and hydrological implications. However, my research stretches to a global analysis of how forests and water interact. The broadness of my Division III research has allowed me to explore passions within the field and address a variety of sub-questions all leading back to the core investigation: How do forests and water interact with each other?

Overarching questions driving my research interests:

1. What are the impacts of changes in land use/ forest management on water yield?
    a. Deforestation
    b. Natural regeneration
    c. Plantation forests
    d. Invasive species
    e. Extreme climate events (i.e. drought, flood, and natural disasters)
2. How does transpiration shift the water budget?
3. What are different ways of measuring transpiration and evapotranspiration on different spatial scales?
4. How does land use within one region influence areas around ("down wind") of it?

5. At what level does land use change significantly impact water vapor transportation (locally and regionally)?
6. How does forest restoration change water storage and release, and how does that change over time?
7. What are the implications of climate change and land use change on water availability and what are the impacts for ecosystem services?

Goals of senior thesis:

My division III research is composed of two research projects:

- Forest density, windspeed, and precipitation recycling: A global analysis of the impacts of forest systems on atmospheric water movement
- Impacts of the hemlock woolly adelgid on water cycling in New England hemlock stands

The major distinction between my two research projects is the scale in which they map water cycling. Forest-water interactions are typically researched on one of three levels: local, regional, or global water cycling. The different spatial scales of studying forest water interactions frequently challenges forest hydrologists and researchers, from a variety of fields. There is an increased sense of urgency in understanding how forests and water are connected due to the pressing influences of climate change on water access. Because of the need for answers of how to manage forests to optimize water access produces one of the largest questions in the field: at what scale should forest water interactions be studied?

In the fall of 2019, I traveled to Curitiba, Brazil to present at the "IUFRO World Congress". While there, I attended a presentation, "Forests, soils and water interactions – a policy perspective", by Dipak Gyawali from Nepal where he discussed the importance of studying water yield at different scales. He highlighted the importance and value of studying global patterns in precipitation relative to land use change, but emphasized the lack of knowledge about local water cycling. The two perspectives were the “eagle eye view” and the “toad’s eye view”. He made a compelling argument for focusing on the toad’s eye view.

The distinctions in these scales is dependent on catchment level and geographic location. Building hydrological models allows for the upscaling of small research projects the results to larger regions. Modeling also allows for temporal predictions of water budgets and forest structure. However, my take away from the talk is that the eagle’s eye and toad’s eye perspectives must be integrated to understand how changes in forests on a local level impact the global hydrological cycle. The eagle’s eye and toad’s eye need to meet in the middle to develop a complete narrative of the interconnected aspects of different forest ecosystems and scales of the water cycle. I spilt my research into looking at water flows on a global level and a local level to begin to speculate within my education about how forests and water are connected over different spatial levels.

For my eagle’s eye view, I conducted a global analysis of how forest cover influences wind speed and therefore precipitation over a single given area and similar patterns across a larger area. I worked with David Ellison, a political scientist associated with the Swedish University of Agricultural Science (SLU). I began this project with a preliminary study of patterns of forest cover, wind speed, and precipitation in South America in spring 2018. This research was presented as a poster at the “Intact Forests in the 21st Century,” conference in Oxford, UK. I decided that I wanted to scale up this research to a global level with latitudinal regions to look at more general trends in forest cover, wind speed, and precipitation and to see if there is variation in correlation or influence of forest cover on the range of water cycling.

The inspiration for this question came as a response of a theory proposed in 2009: The biotic pump theory. The biotic pump theory was developed from a perspective of atmospheric physics hypothesizing that forests create a vacuum through transpiration vectors pulling water across a land mass in the direction of the Hadley cell. The concept essentially was that this vacuum created by downwind regions creates a change in atmospheric pressure (similar to that of vapor pressure deficit (VPD)) outside of the leaf causing the tree to pump more water up and out increasing the about of water vapor available for precipitation. Within this theory, increased forest cover would increase precipitation by allowing for more precipitation cycles to travel across the landscape.

David Ellison and I connected and hypothesized that forest cover actually slows surface level wind speeds allowing for more precipitation recycling within a region, essentially maximizing the time that water will spend in a catchment system. This could be for a few reasons. The first is potentially the influence of forest topography slowing wind speeds, and the second is that forest cover increases transpiration which increases the weight of the air meaning that more wind energy is needed to transport water molecules, so they do not travel as far. One study averaged that water stays in the air as vapor for approximately 8-10 days. With that knowledge, the slower the wind is moving, the more precipitation would be deposited in the areas with slow wind. I conducted a tri-variate spatial analysis of forest cover and wind speed, and precipitation data from multiple meteorological models in order to quantify these relationships and to learn of any geographic patterns or other abiotic variables that may be a part of this cycle. The global analysis was presented at the previously mentioned IUFRO conference where it was enthusiastically accepted by peers. Hopefully a complete manuscript of this research will be submitted for review in a timely manner.

My second, local scale, project focused on a specific invasive species, the hemlock woolly adelgid, and its impacts on water release via transpiration as the forests transition from old-growth eastern hemlock (Tsuga *canadensis*) stands to early successional black birches (Betula *lenta*). To quantify transpiration, measurements were taken at a single tree level through sap flow sensors. I constructed sensors using a build model from the OpenSensing lab at the Oregon State University (OSU). I was not informed by the lab when I began working with them that the final code was not functional and was not ready until after the growing season, so I was unable to collect data. The study was going to be a follow up on a study conducted in 1999 and another in 2007 where they looked at hemlock and deciduous tree sap flow to estimate canopy transpiration at the Harvard Forest.

I used my connections to the Harvard Forest from the REU program where I did the previous summer to work there and have access to their resources. I was planning on collecting sap flow data from 15 hemlocks with a variety of degrees of foliage degradation due to hemlock woolly adelgid predation to capture the cessation of transpiration from hemlocks as they decline due to the invasive species. I plan to compare that to sap flow measurements from 15 birch trees of varying ages and meteorological data collected from the eddy flux towers at the Harvard Forest in the hemlock stand and an adjacent oak-maple dominate stand.

Due to the inability to collect data, I was unable to develop results on the project, but I dedicated a large portion of my Division III work to reading literature, researching methods, and building sensors. I plan on collecting data for this research next summer after I graduate because I believe that it is important to the greater understanding of how water yield and fluxes are changing in forests across the eastern coast of the United States due to an invasive species. I am hoping to model those results to mimic the turnover of hemlocks over their predicted death time post infestation. I hypothesize that birch have a higher water demand with increased transpiration) during the growing season minimizing groundwater recharge while hemlocks have a decreasing annual water use due to defoliation increasing the impact of the forest transition to birches. There is also increased understory biomass in birch forests signifying more water use from increased vegetation during the growing season, which although not quantified in my study should be considered in the discussion. This transition has many implications for water access for vegetation, depth to aquifer, and stream ecology.

Although these two projects differ in their methodologies, geographic location and scale, subsection of focus, and implications, they are both connected by the ways they highlight how changes in forested landscapes will influence where water is and how it is moving. These two different projects are also helpful for my development of methods and knowledge within the field of forest hydrology. I have learned how my future research can vary in scale and impact and I have laid the foundation for many future research projects as I continue my career in academia.

Social implication of my academic interests:

I have attempted to shift the way t I ask questions to be more inclusive of who is involved and what the implications of my research would be. The history of science has made it inaccessible to most marginalized communities. The impacts of climate change, which drive my research interests, disproportionally impact communities of color, low-income communities, and communities whose voices are typically not recognized by institutions in power across the globe. To move forward with a more inclusive and conscious career in education, I have attempted to start transforming how I conduct my own research interests to be more inclusive of a variety of perspectives.

A part of this has been through learning more about different types of knowledge, but the majority of my personal development has been through attempting to implement the feminist scientific method. The feminist scientific method focuses on breaking away from the traditional, linear, tract of asking a question, conducting an investigation, and presenting results. Rather, this shift in scientific methodology incorporates a wholistic form of developing and answering the question which is rooted in acknowledging the position of the researcher, me, in the investigation, which communities are involved in the research, and who could be influenced by the outcome.

The feminist scientific method and other critiques of research within biological sciences frequently center biomedical research or questions more directly connected to humans, but over the past year, I have begun to realize that studies in climate science and forest hydrology are not far removed from the implications on humans. There are currently many other fields of study and an increased development in accessible scientific research. Most of these have come from community empowerment and a widened acceptance of observations of the natural world.

My focus on the future of water cycling in New England has is likely to impact local residence around hemlock forests and potentially communities across the eastern coast of the United States and southern Canada where hemlocks are present. The main concerns are on potable water access due to possible changes in groundwater storage and stream water volume. Another, more concerning impact, is what this research could mean for hemlock conservation. Currently, the only method of hemlock resilience is through injected pesticides. One possible response would be land conservation or restriction that may influence land access and value. This phenomenon has been witnessed globally and, contextualized in New England, would influence low-income communities and people who are dependent on forests for logging.

Analyzing global forest cover and meteorological data includes a larger variety of communities and could have added more strength to arguments of land restoration and conservation globally, more specifically the tropics. I spoke to a woman from Paraguay about my research. She was excited about my results and was hoping for the potential of using my research to inform how large forest restoration sites need to consider precipitation recycling and restore water access. However, it is typically not local communities that make these decisions and rather government structures -- to add another layer, these projects are typically funded by global north with little knowledge of land use). I have had a harder time critiquing myself and the role I am playing in my research process, but this project has pushed me to think about my sense of place when conducting research on areas that are not my own.

Since developing my interests in forests, I have fantasized of traveling to the tropics to research the complex and timely changes in landscape use and reforestation. Over the past year, I have begun questioning that desire. The ability to travel, learn about a new ecosystem, and experience different cultures sounds wonderful, but what is my place in the community that I am researching? In the United States, and other global north, there is a large amount of funds to research the impacts of humans on the natural world. However, countries in the tropics, specifically for my interests Brazil and Peru, have resources for research without the inclusion of other countries. This does not imply that people should only research within their respective homes or regions, but rather to add a sense of consciousness and respect to my future research and where I work to include community input and potentially act as a source of advocacy for local people for land and water rights.

At the IUFRO conference, I spoke to a woman from South Africa who will be receiving her Ph.D. in forest hydrology and used sap flow as a metric for measuring water use by natural forests and eucalyptus plantations because streams are beginning to dry out and local villages are having more difficulty accessing well water. We both found inspiration in sharing interests and passion for understanding the impacts of land-use change on water cycling. She is someone I would strongly enjoy working with. I do not believe that one connection to a region validates the presence of someone with my privilege, but it is a start. The beginning of sharing resources and experiences and working with the people directly impacted by human impacts on the natural environment. I found a new way of thinking about my positionality and the impacts of my place in a research project which I have tried to use to again educate and shift the way I look at the scientific method.

I spent a portion of my second year at Hampshire beginning to build an understanding of the history of how scientific questions are developed. Scientific knowledge has historically invalidated common, traditional, and popular knowledge. In the fall of 2017, I took an environmental anthropology class at Amherst College. We focused on the problematic nature of the field of anthropology. Similar to what I described my sense of place, anthropology has a history of studying areas that are not their home and frequently tokenize the communities being studying. In the course, we were asked to critique papers assigned in the class and look for ways of integrating different types of knowing. We focused on how land conservation and policy development typically ignore indigenous communities or other communities without much social capital who really on the land.

An example of this is among indigenous communities and small-scale farming communities in the Amazon Basin who have worked with and learned about the landscape over generations. Because these observations are not documented in the same way that scientific research is other forms of knowledge are consistently disregarded. I believe that a major part of researching forest hydrology is in using access to the scientific community to communicate the knowledge that some people have developed over generations to a group of people who demand a sort of quantitative documentation.

After this course, which gave me tools to critique the actions of others, I wanted to focus on how I can dismantle systems of power in scientific research within myself. I worked with the Compassionate Knowledge Project, a student group at Hampshire College, which focused on the personal and cultural impacts of science. This group attempted to integrate new ways of knowing and sharing science through art or other, accessible, forms of expression. I helped in facilitating discussion on how knowledge is created, power within sciences, and the difference between objectivity and subjectivity and if anything is truly objective (which I do not believe it is). The group was rooted in mindfulness and self-reflection. My experience with the program allowed me to ground myself in my research interests and reflect on my positionality.

Self-reflection and self-critique are critical to my success in forest hydrology. I am beginning to learn more about feminist scientific theory and how I can continue to work within the sciences without succumbing to the unequal distribution of power and impact of my research. Before my Division III, I balanced scientific courses with classes focusing on the influences of humans on the environment and the development of scientific knowledge on policies and communities. Holding these two perspectives on the function of science was critical to my education, informing my Division III work, and understanding the world of science. One of my driving interests for researching under the field of forest hydrology is the concern of water availability. Lack of access to potable water has been more prevalent in regions with less access to scientific resources. I combined my education on the impacts of environmental science and the larger problematic structures within the natural sciences to add consciousness to how I develop questions and implement the scientific method into my Division III research practices.

Chapter 2: Forest Water Literature Review

This literature review provides a detailed description of the water cycle and the importance of understanding water yields and fluxes. I contextualize the water cycle within forested systems and explain how forest systems change the way water is stored and moves. Then, I complicate the forest water nexus further by discussing variation in water demand by forests by geographic location and biome. After explaining the basic relationship between the water cycle and forest systems and with how they change globally, I shift into discussing changes in understanding forests water interactions are interpreted based on the scale of study. Methods of studying forests vary depending on the scale. I detail different methods used to measure water stocks and fluxes on forested systems. After providing background on forest water interactions, variations in these interactions based on forest structure, and the different spatial scales and methods to study these interactions, I combine knowledge from each topic and focus on the impacts of changes in land use (deforestation, reforestation, and afforestation) and climate change on ecosystem water use and availability. All of these aspects of forest water interactions are critical to developing a comprehensive understanding of the field of forest hydrology. The goal of this review is to create a narrative of how forests and changes in forest systems influence the water cycle along with how these interactions are likely to transition due to climate change.

1. Importance of the water cycle:

The expansion of cities, demand for more food and clean water, and rise in industrial production has led to the rapid deforestation of some of the world's most valuable and diverse forests[1]. Rapidly increasing rates of deforestation and conversion to agriculture or other human benefits has had many influences on our climate: more natural disasters, increased temperature, ocean acidification, and melting ice caps[1–3]. Forests are one of the great stabilizers of global shifts in climate by sequestering carbon and cooling the local air through an established relationship with the water cycle. Historically, climate research has focused on how changes in forest land use have impacted atmospheric carbon sequestration by storing it in the soil and biomass, but it seems like the discussion is excluding a focus on how deforestation is impacting precipitation and the hydrological cycle[4,5]. Climate science began by focusing on carbon research in response to climate observations and increased annual average temperature due to the industrial revolution. Why is water not included in conversations of climate change?

Climate change has already begun to show more radical natural disasters combined with a decrease in precipitation over time within small watersheds parallel to decreases in cover[4]. Scholars have used these shifts in abiotic and biotic conditions across ecosystems to question how variations in forest use play a role in climate change[1,2,4,14,]. Within the past decade, research has shifted to investigating how climate change is influencing the water cycle. One of the main drivers for the increase in forest-water research is because of the realization that water resources will influence human survival at a much faster rate than global warming. There is an international concern regarding water access for small communities in arid regions (and this does not include the added variable of access to clean/ potable water). Water is critical for life and is a basic human right, but how does that change when there is not enough water or too much water available due to climate changes and shifts in ecosystems influencing how the natural world stores and regulates water.

The necessity of water for production (both economic and ecological), biodiversity, carbon sequestration, and human survival create a compelling argument for the research of how forests change the water cycle; hence the increase in forest water research. Through understanding the fundamentals of the hydrological feedback loop and the different variables that play a role in precipitation, we can begin to understand how trees and water relate to each other. Current research indicates a clear relationship between deforestation and decreased annual precipitation[1]. However there is a call for a deeper understanding of how changes in forest land use impact local, regional, and global precipitation patterns. Literature of forest-water dynamic theories have shown contradictions in research from data collection causing confusion in the influences of vegetation of water cycling. For example, some theoretical models describe forest-water interactions by simply stating that forests increase rainfall and therefore the removal of forests decreases rainfall[6]. However, the addition of forest systems increases transpiration.

2. <u>Basics of the water cycle:</u>

The ratios of available water and water use present differently in all forested ecosystems, but at its core there are six different variables of the systems water budget where precipitation (P) is calculated by finding the sum of streamflow (Q), evapotranspiration (ET) (the water that either evaporates from surfaces or transpires from leaves back into the atmosphere), runoff (R) (water that does not evaporate or go into the soil, but rather flows on the surface out of the area being studied and exiting the system), infiltration (I) (the water that is absorbed by the soil), and the change in storage in the aquifer (S) (which varies due to well pumping and infiltration)(Equation 1). On a local scale, water enters a watershed through precipitation and exits through groundwater flow, ET, or Q.

$$P = Q + ET + R + I \pm S \qquad (1)$$

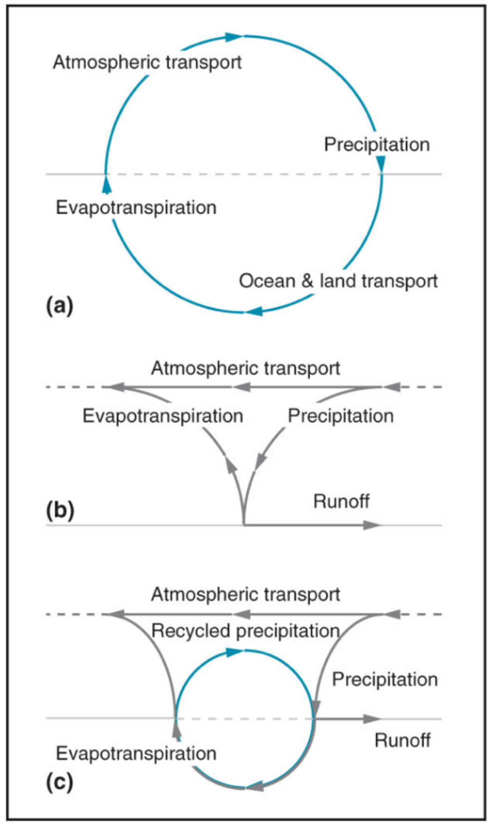

Figure 1 The hydrological cycle represented on three different scales. a. the global hydrological cycle, b. the local hydrological cycle, and c. the regional hydrological cycle. Each scale is simplified to show the basic components of the water budget.[7]

There are many ways to complicate the water cycle. The precipitation entering a watershed is likely derived from evapotranspired water which regionally transported from other systems, but a small portion of precipitation is recycled into the same region. Precipitation recycling is a fraction of water that is released from a system as ET which stays within the same system. The majority of water deposited as precipitation is from regional water transfer. Once in the atmosphere, water remains in the atmosphere for approximately 8 days. [8] Mapping water transportation and cycling across larger regions becomes challenging. Current research typically investigate water cycling with perspectives of different spatial scales: local, regional, or global. Global water cycling typically focuses on P, ET, and atmospheric water transport via wind over both terrestrial and oceanic systems (Figure 1).[7] The local hydrological cycle shows more of a resemblance to a simplified water budget. Local hydrological cycling has water entering a system through precipitation, some from locations upwind and a fraction from local precipitation recycling, which is then distributed across the terrestrial system (Figure 1). Regional cycles attempt to use information from local precipitation recycling and add a spatial dimension to understand how different landscapes are altering the hydrological cycle through S, ET, or Q.

More simply put, analyzing the hydrological cycle from a global perspective looks at where precipitation goes and where water vapor comes from. Analyzing the hydrological cycle from a local level is mapping where water goes within a system once it is introduced through precipitation before it leaves (mainly by ET).

Regional hydrological cycles are the middle ground between local and global precipitation cycling where it accounts for water fluxes on a small scale, but also where water is transported and redeposited in other regions.

ET is arguably the most influential to changes in local precipitation recycling[4]. 70-90% of water deposited in a basin leaves as ET[9]. In areas with large quantities of water availability, only approximately 30% of the water that is evapotranspired returns to a given basin[10]. Within forested systems, transpiration is the main driver of water loss. Not only is ET the most influential to local water cycling and water recycling, but it is also the most challenging to quantify. Transpiration rates are dependent on water availability, humidity, temperature, solar radiation, atmospheric pressure, vapor pressure deficit (VPD), and species.

3. <u>Methods of studying evapotranspiration:</u>

Quantifying and tracking evapotranspiration are dependent on the scale of the study. On a local level, ways of quantifying ET typically involve field work. Studies of transpiration rates on a single tree scale typically use thermal dissipation probes to measure sap flow within the xylem to estimate water transport through the trunk of a single tree[11,12]. This measure is representative of transpiration for a single species stand, but does not account for evaporation[13]. Using the sap flow method for a mixed stand would mean that each species needs to have sap flow meters to measure each specie's water use along with methods of measuring evaporation of throughfall and evaporation from the canopy.

A second option for measuring local ET, which is more feasible when attempting to scale local water cycling to a regional scale, is through meteorological data to estimate water release through transpiration and combined ET. Potential evapotranspiration (PET) can be estimated with data on temperature, solar radiation, latent heat, maximum atmospheric moisture concentration, atmospheric pressure, air conductivity, leaf surface conductivity (conductivity of stoma), and VPD[14]. VPD is the difference between the maximum amount of moisture that could be in the atmosphere and the actual concentration of water in the atmosphere. VPD is highly influential to ET. VPD represents how much more water could enter the atmosphere through ET. PET assumes that the vegetation has excess water. Actual evapotranspiration (AET) is the rate of ET within a current atmospheric moisture concentration and water limitations within the system.

Eddy covariance towers are an example of a method of collecting a variety of different meteorological variables to estimate PET and AET over a given forest. The flaw with the eddy covariance method is that it generalizes ET over an area. However, calculated ET from meteorological data provides a more informed estimation from an ecosystem scale rather than a plant physiology level. Eddy covariance towers also, potentially, measure with speed and direction which is helpful in tracing regional atmospheric water.

Global estimations of ET, along with other meteorological variables, are typically modeled using satellite data and remote sensing. These models have the highest degrees of error and generalize areas into single values (pixels), but are useful for looking at larger regional trends in water cycling and areas with greater precipitation and ET rates. Global models also typically project weather patterns which, in combination with regional or global land use change data can inform how changes in ecosystems or landscape will influence ET and the complete hydrological cycle locally and regionally.

4. **Forest land change and the water cycle:**

Forest systems interact with the water cycle differently than grasslands, deserts, agricultural fields, or non-forested systems because of one thing: transpiration. Although all vegetation transpires, and there for grasslands transpire, other ecosystems are more equally effected by evaporation and transpiration[3,15,16]. Forests provide more shade for infiltration after a precipitation event minimizing instant evaporation, but rather a more regulated release of water over time[9]. This allows for water to distribute into regulated stream flow and ground water recharge.

Within forest systems, forest age is influential to the percent of precipitation released as ET. Imagine a theoretical watershed which is completely covered by dense primary forest with a stream through the middle. This forest is currently at a steady state of the water cycle. ET rates are fairly consistent depending on water availability and groundwater storage is also consistent and stream flow is regulated by increased infiltration and delayed runoff. During times of water scarcity, trees with deep root systems access water and transport it to the subsurface as a form of plant resistance to drought.

If this area were to be completely deforested by clear cutting, transpiration rates approach zero and evaporation rates become more variable.[17] Because evaporation is dependent on solar radiation the present water on the surface or in the soil has the potential to be evaporated. After a rain event, there is an immediate spike in evaporation, but there are limits to the amount of evaporation that can happen before water begins to transport across the landscape towards the stream. This may happen through runoff or subsurface flow. Some studies indicate peak flow events which accounts for 99% of the water from the corresponding precipitation event.[18] This means that precipitation is the major driver of stream flow and flow regulation. A lack of vegetation prevents the slowing of overland flow to allow time for infiltration, so stream volume becomes less stable[19]. Deforestation increases the probability of flooding after heavy rain events.

Over time, this land regenerates. First with short grasses, then short plants with woody tissue, then young secondary forests also known as pioneer species which represent the first stage of forest succession (Figure 2). Forest regeneration minimizes overland flow and rapid discharge of water mediating flooding events improving water preservation within the system[20]. First succession forests are typically composed of many fast growing, light demanding, species. Young secondary forests or regenerating forests are often dense with thin saplings with their energy focused on competing for light rather than developing a foundation. The quick growth of these trees means that they rapidly acquire carbon and in response rapidly release water creating increased transpiration. Reforestation frequently show decreased water availability during the initial establishment of forested systems due to the increased release through transpiration[20–22].

Over time forests begin to stabilize into secondary forests (Figure 2)[15]. Secondary forests are less dense due to natural thinning from competition, more diverse, and have a more complex forest structure (variations in root depth, leaf area, shade tolerance, growth rates, life spans, water demand, etc.). As forest growth and water demand becomes more stabilized, the local water cycle also has time to adapt to the new vegetation. The theoretical watershed begins to reach a new hydraulic steady state.

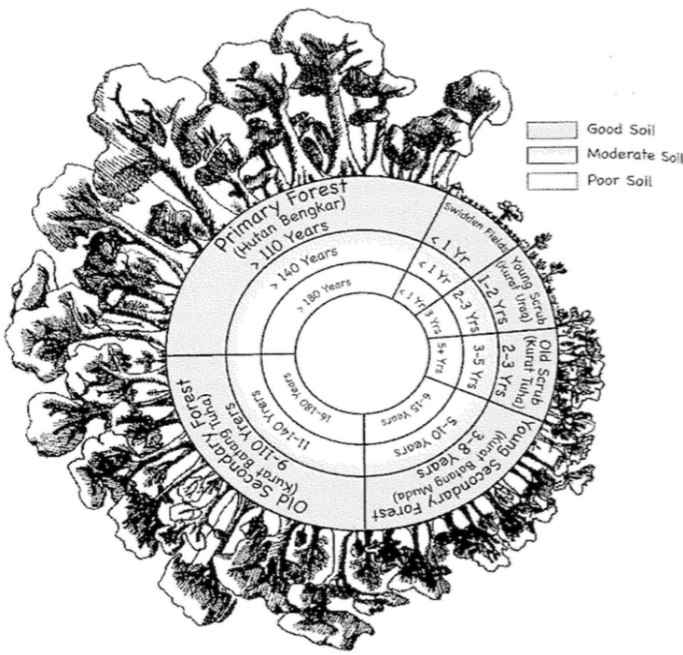

Figure 2 Timeline of forest regrowth and forest succession depending on soil quality based off of a tropical forest[15]

This theoretical exercise was tested at the Hubbard Brook Experimental Forest in New Hampshire, United States. One small watershed was clear cut in close proximity to another, similar, intact watershed[23]. The results were similar to what was just described. Deforestation in 1966 showed immediate increases in daily stream flow in comparison to reestablished forests in 2008. Deforestation showed other impacts than water volume. There was also increased particulates, turbidity, and conductivity in the streams indicating nutrient and soil runoff with the increased volume of surface flow.

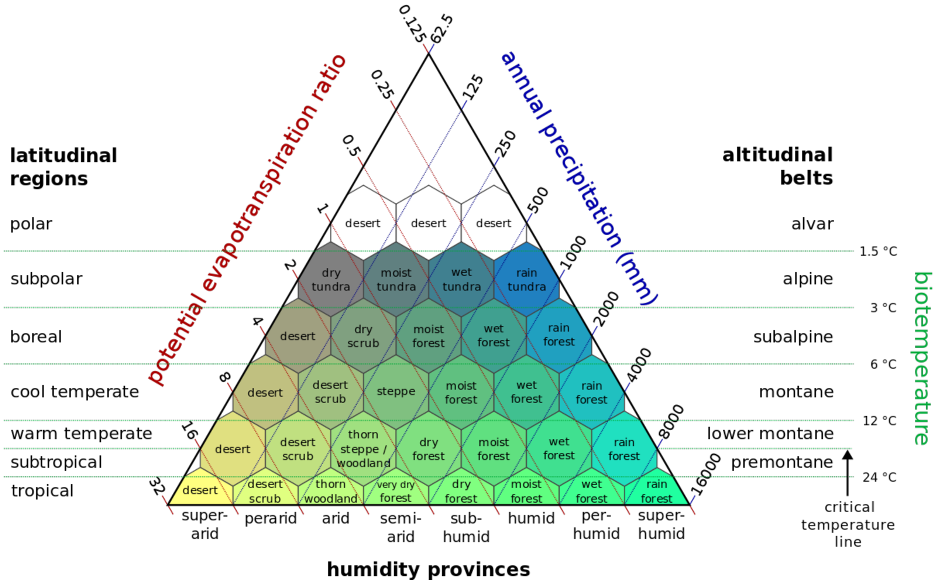

Figure 3 Life Zone characteristics based on latitude, potential evapotranspiration ratios, precipitation, temperature, and humidity province

5. Global variation in forest water demand:

Water accessibility varies by geographic location. Some biomes have high annual precipitation and evapotranspiration rates while others experience low precipitation no matter the increased variability of climate change. Tropical and subtropical biomes have the most complex relationships with water due to the high evapotranspiration rates and typically high annual precipitation (Figure 3). Biomes can be differentiated by intersections between different meteorological and geographic locations: latitudinal regions, annual precipitation, the potential evapotranspiration ratio, humidity, altitude, and temperature (Figure 3).

Latitudinal regions create distinctions in biomes due to terrestrial locations in different Hadley cells controlling wind direction[24,25]. Wind direction influences the transpiration of oceanic water transport and continental moisture deposition[4,9,25].

Precipitation varies with geographic location latitudinally, but is also dependent on temperature and moisture transpiration. For example, the northern region of the Andes

Mountains in South America have higher rates of precipitation on the eastern side because it is located in the southeasterly trade winds (meaning wind moves northwest)[26,27]. The west side of this mountain range is characterized as, predominantly, tropical humid moist forests [27]. East of the mountain range, due to precipitation deposition on the eastern side, regions are classified as tropical desert scrub[27,28].

In defining life zones, PET is an indicator of the vegetation present to evapotranspire in an area. PET is connected to atmospheric moisture deficit, solar radiation, vegetation presence, and temperature[14]. Humidity influences actual ET and condensation. Humidity provinces are regions classified by the relationship between precipitation and evaporation along with a moisture index which considers water availability (excess and deficits) relative to ecosystem water demand[29,30].

Changes in altitude shift factors which build the foundation for ecosystem development: soil type, atmospheric temperature, solar radiation, and species competition and specialization[31,32].

The 7 variables included in mapping out life zones as a form of classifying biomes shows the interconnectedness between geographic, hydraulic, orographic, and atmospheric temperature. Each biome has a different connection to the water cycle. Variations among these systems emphasize the importance of understanding how vegetated ecosystems different roles in regional water cycling. They also highlight the challenges of applying information from one ecosystem type to another.

Each biome is also impacted by climate change differently. Air pollutants are an example of an unequally distributed influence of climate change across geographic locations and elevation shifting ecosystems which otherwise may be classified under the same life zone. Increase in temperature has allowed for tree species to migrate northward colonizing ecosystems classified under different biomes[33]. Vegetation shifts over landscapes also change evapotranspiration rates and therefor the water budget.

6. Conclusions:

Water is critical to the conversation of climate change, land use change, and the future of ecosystem stability across the globe. Anthropogenic influences on the natural world have begun to shift global hydrological patterns. Creating ways of regulating water cycling to preserve water availability is necessary to preserving ecological and human function. One of the most impactful and variable aspects of the water budget is ET.

ET, while being an important part of water regulation, is also incredibly challenging to measure in comparison to other aspects of the water budget. There are different methods for measuring ET depending on scale; measurements can happen from a leaf to a continental level. However, due to variability between vegetation and the influences of weather and atmospheric traits, transpiration is always changing, so most methods of measuring, especially on a larger scale, are only estimations.

The intricate connection between forests and water allow for forested systems to stabilize and regulate water in the atmosphere and keep it accessible for terrestrial demand. ET from developed forest systems, along with other climate regulating aspects, aids in mitigating water use and optimizing water storage and stream flow.

Just as forests play a role in regulating the water cycle, water availability plays a role in forests. Humidity, precipitation, and ET all influence the climate and therefore what plant can thrive within a geographic location. How water availability acts as a limitation for plant life which feeds back into plant regulation of the water cycle. The interconnectedness of forests and the water cycle create an equilibrium where each one positively plays into the other. The major impacts of climate change -- increased temperature, more frequent weather events, prolonged droughts, and flooding -- are influencing forest structure and function along with global water cycling[3,19,34,35].

Changes in forested landscapes through deforestation, development, agriculture, and forest restoration have changed the way water is cycled and regulated on a local scale. However these land use changes have greater regional implications as to how water is cycled on a regional level. However, changes in land use and the meteorological responses to greenhouse gas emissions throw the two out of sync. Restoration has been referenced with looking at how to regulate changes in climate, but the forested systems also have to respond and adapt to regulate water processes and preserve water availability.

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Chapter 3 Forest cover, windspeed, and precipitation: A global analysis of the impacts of forest systems on wind and weather patterns

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Abstract

Gaps persist in our comprehension of forest-water interactions and how forest cover potentially alters and sustains precipitation at continental scales. We analyze high-resolution, remote sensing data on forest cover, annual average wind speed and total annual precipitation amounts in order to better understand how forest cover impacts windspeed, and how the forest impact on windspeed can influence the transport and potential re-deposition of atmospheric moisture as downwind rainfall. Our global analysis of these interactions indicates forests slow wind speeds, providing more opportunity for the accumulation and aggregation of both incoming atmospheric moisture and local evapotranspiration, thereby contributing to its increased potential re-deposition as rainfall. Our findings indicate rainfall is greater where forest cover has the effect of slowing windspeeds. Moreover, by slowing windspeeds, greater forest cover intensifies the hydrologic cycle, providing more opportunities for atmospheric moisture and evapotranspiration to condense, precipitate, re-evaporate and re-transpire back to the atmosphere, thereby potentially increasing terrestrial rainfall and water availability across continental surfaces. We are hopeful improved understanding of how forest, wind, and water interact can help motivate further study and promote the development of a more rigorous approach to preservation of the hydrologic cycle through forest landscape restoration.

Keywords: precipitation-recycling, forest-water interactions, windspeed, hydrologic cycle, reforestation, deforestation

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1. Introduction:

The impacts of forested ecosystems on wind speed, water vapor transport, rainfall and the potential for precipitation recycling remains at the forefront of recent research.[1–3] The concept of moisture- or precipitation-recycling describes the process whereby trees, forest and other forms of vegetation cover evapotranspire moisture back into the atmosphere where it becomes available once again for downwind rainfall.[1,4–6] Evapotranspiration (ET) – the confluence of *transpiration* by trees and *evaporation* from leaf and soil surfaces – represents the principal process and mechanism whereby water is returned to the atmosphere to be transferred to other locations across terrestrial, regional and continental surfaces. Atmospheric moisture originating from oceans can be carried far inland from upwind shores and even back out over the ocean.[5–7] ET provides a significant source of additional moisture and contributes importantly to downwind rainfall.

Were it not for the phenomenon of precipitation recycling, it would be impossible to understand what explains the occurrence of some 112,000 km^3 of rainfall on terrestrial surfaces when the net oceanic contribution is only about 40,000 km^3? Though one can quarrel with the absolute amounts of the oceanic contribution on upwind coasts, as well as the amount of rainfall of terrestrial origin that lands over oceans.[6,8] a relatively large share of precipitation over land is explained by the phenomenon of precipitation recycling. Thus, adding more forest cover to terrestrial surfaces, as long as this goal is strategically pursued, should positively influence total amounts of terrestrial rainfall.

For this reason, much work suggests the total amount of water that falls on terrestrial surfaces as rain is in fact a variable quantity that can be influenced by human action and anthropogenic modification of the terrestrial landscape.[1,9–11] An increasing number of studies suggest the principal factor affecting this relationship is the relative share of forest cover on terrestrial surfaces, since relative shares of forest cover presumably impact the number of times water is recycled across terrestrial surfaces, presumably impacting downwind rainfall and water availability.[1,5,9] However, the residence times of atmospheric moisture are considered a second factor in this relationship, potentially affecting how much recycled moisture is likely to return as precipitation over land surfaces, as opposed to how much might land over oceans.[6,12]

There is, however, another possibility that has not been frequently investigated. This third possibility resides in the potential for forest cover to affect land-atmosphere interactions. On an ad hoc basis, it is frequently recognized that trees have the effect of slowing wind speeds (and add multiple REFs). But, to the best of our knowledge, this relationship, as well as how or why it might happen, has never really been consistently investigated. Moreover, an obvious corollary is that changing windspeeds may also have the knock-on effect of altering rainfall patterns and relative quantities. For our research then, the key question is whether forest cover can affect things like windspeed and rainfall? A simple glance at virtual, global windspeed maps (see, for example, windy.com), should be sufficient to assure even visually windspeed is typically highest over oceans and that, as winds begin to move across land surfaces, they slow down considerably. Moreover, observing the movement of winds over land surfaces rapidly leads to the suggestion that windspeeds are slowest over larger and more heavily forested areas.

The precipitation-recycling view ultimately suggests the total amount of terrestrial rainfall is essentially determined by the total number of times rainfall can be recycled between land and the atmosphere as it moves across terrestrial surfaces.[6,11] We postulate therefore that in addition to the forest impact on the total amount of rainfall returned to the atmosphere as evapotranspiration, we likewise hypothesize that forest cover can potentially impact things like windspeed and rainfall through the mechanism of land-atmosphere interactions. Our findings suggest relative shares of forest cover do in fact have relatively strong impacts on wind speed and total annual amounts of rainfall. Although this relationship appears to be stronger in the tropics and somewhat less pronounced toward the outer latitudes, generally speaking, winds slow significantly when they come into contact with forest cover. And, since greater amounts of rainfall occur together with this phenomenon, the impact of forest cover also appears to be linked with a greater likelihood of rainfall.

Our goal is to report these relationships and contribute to an improved understanding of how water is recycled, transported and returned as rainfall over terrestrial surfaces. To investigate this question, we provide a global analysis of the impacts of forest cover on windspeed and precipitation and test our hypothesis that relative shares of forest cover can affect windspeed and rainfall potential through the mechanism of land-atmosphere interactions, we study the relationships between forest cover, windspeed and rainfall on a global scale. The analysis is broken up into the following parts. We first describe the phenomenon of local precipitation recycling and the impact of variation in forest cover on rainfall in local basins. Second, we investigate and quantify patterns between forest cover, wind speed, and precipitation.

2.a. Variation in Continental and Local Precipitation Recycling:

Discussion of the factors that can affect the total amount of water recycled over terrestrial surfaces frequently stumbles over analyses that take the catchment as their basic unit of analysis. Generally studied at the level of the catchment, the addition of more forest cover has been repeatedly demonstrated to lead to losses in surface runoff. Though such analyses have repeatedly been used to argue the addition of forests at the catchment level has no positive impact on downstream water availability and therefore on rainfall, the extension of this argument to the larger scale forest impact on rainfall is not strictly true. In fact, many observers find forests can even have positive impacts on rainfall at the local level, though the addition of forest cover is likely to flush larger amounts of water out of individual basins.[13]

As it turns out, we know comparatively little about what factors explain variation in the rates of precipitation recycling across terrestrial surfaces. Though the continental scale has been increasingly studied, local level precipitation recycling has been almost entirely neglected. As early as 1994, Eltahir and Bras, can be credited with distinguishing between local and regional precipitation recycling.[7] At the time, clarifying that the occurrence of precipitation recycling did not mean most of the recycled moisture returned to the same basin from which it originated as rainfall represented an important contribution to the literature. This recognition shifted attention to the upwind contributions to local rainfall provided by the much larger magnitude *continental* precipitation recycling.[6,9,14] The unintended downside of this shift, however, was the missed opportunity to better explain and understand variation in rates of local precipitation recycling.

Evidence from moisture-tracking models suggests very little locally produced ET returns to the same basin as rainfall.[6,11,15] Rather, most local rainfall in a given basin can be explained in terms of upwind moisture sources, i.e. a mix of oceanic and upwind terrestrial sources. On average, only about 8-12% of the precipitation deposited in individual basins can be traced back to local ET.[4] The majority of this local ET will be transported on toward other downwind basins and will only return as rainfall at much greater distances from the local basin. Thus, the dominant impact of forests and rainfall occurs through the mechanism of the much larger scale continental precipitation recycling.[4,6]

There are however many reasons to want to know more about the factors that can explain and help us better understand precipitation recycling at the local scale. For one, from location to location there is considerable variation in rates of local precipitation recycling that has largely gone unexplained in the literature. Ellison et al.,[9] for example, note in passing that local precipitation recycling rates in the Amazon are comparatively high. Around 30% of the local ET is estimated to be recycled as local rainfall.[4] And this finding is supported by other work on precipitation recycling in the Amazon and the Congo suggesting local precipitation recycling can explain anywhere from about 25% to as much as 50% of local rainfall.[6,16–20]

There is likewise considerable seasonal variation in local recycling ratios across the board. Generally speaking, summertime local recycling ratios increase significantly. In the Amazon, for example, wet season local precipitation recycling is approximately twice the size of dry season recycling. In the MacKenzie basin, summertime precipitation recycling is as much 4.5 times higher than winter-time recycling.[9] While it is not surprising that precipitation recycling more generally should increase during summer or wet season months, when more transpiration is generally produced by trees and forests adding to ET, the fact that local precipitation recycling also changes creates a call to question.

The possibility that variation across forest biomes might be the driving force behind such phenomena is potentially contradicted, however, by the fact that there are clearly pockets of rainforest-like landscapes closer to the poles, where rainfall is exceptionally high, producing rainforest like ecosystems. The fact that rainforests, for example, are found in several parts of the world, both further away from the equator and closer to the outer latitudes is curious, since we tend to associate rainforests with the exceptionally wet conditions that arise primarily in vary humid places in the world. On the other hand, the presence of rainforest pockets in latitudes further toward the poles that are surrounded by other kinds of forest may suggest that unusual land and atmospheric-based conditions operate in and over these pockets.

One possible explanation is that higher local recycling ratios are primarily a function of the forest biome, with the Amazon as perhaps the principal tropical region exhibiting higher rates of local precipitation recycling. In particular in the Amazon, it is difficult to understand why this might happen on the basis of things like orographic features. There are few mountains in the Amazon region (apart from those in the western interior that have the effect of containing and directing atmospheric flows toward the southern part of South America, while the Peruvian side of South America remains very dry). In this regard, higher local precipitation recycling may have something to do with the specific land-atmosphere interactions that occur in more tropical systems.

Though it is possible such phenomena can be explained by higher local recycling ratios, this begs the question of why these ratios might be higher in such regions in the first place. In at least two areas where such rainforest or near-rainforest pockets occur (Olympic rainforest, Washington, US; and the temperate, coastal spruce rainforests in Trøndelag and Nordland, Norway), mountains are also a part of the local terrain. Thus, orographic features presumably provide a part of the explanation. The degree to which the share of local partitioning might potentially interact with and potentially drive up local precipitation recycling is an importantly under-researched phenomenon. To the extent that such interactive effects are possible, the role of orographic features and the presence of mountains are likely to provide inadequate explanations.

Further, it is likewise difficult to explain the case of comparatively small islands like Borneo, where deforestation and land conversion to palm oil production has resulted in dramatic changes to the natural landscape—one of the most important of which has been declining rates of rainfall.[21] Given that the ET produced by local forest cover should, for the most part, be swept off to other locations, in these small island cases, it is difficult to explain why more forest cover could potentially lead to more rainfall.

There are in fact many indications throughout the literature that suggest change in forest cover impacts the relative share of ET that gets flushed out of individual basins. Filoso et al, through analyzing the impact of reforestation on catchment-based runoff, arrive at the peculiar finding that both larger basins and basins with older forests tend to witness lower rates of rainfall partitioning toward the atmosphere and favor local runoff. Mercado-Bettin et al, further support the general view that larger expanses of forests have the effect of partitioning less water toward the atmosphere and having higher relative shares of runoff.[22]

Thus, it makes good sense to further develop our understanding of the parameters affecting the extent of local precipitation recycling. For the sake of argument, we might assume the phenomenon of local precipitation recycling is primarily driven by local weather patterns, and that as long as these weather patterns do not change, the relative share of local precipitation recycling should remain the same, regardless of the extent of local forest cover and the relative share of ET in P. In this sense then, increases in local forest cover will almost always increase the total amount of water leaving an individual basin by more than it increases locally recycled ET. And this increased ET must of course come at the expense of reductions in locally available runoff.

Though additional forest cover should produce additional ET from local basins, anywhere from 70-90% or more of this ET will be transported out of the basin to other locations (Figure I). The relative ratio of recycled to outgoing ET remains relatively stable, regardless of change in the total amount of forest cover. This means that the addition of local forest cover will almost certainly initially remove additional water from the local basin—above and beyond the increase in the local contribution to rainfall—and transfer it to other locations as ET. Additional local forest cover will, almost never, have the effect of raising the total amount of available water in the local basin and, in most cases, will reduce the locally available water supply. Though additional forest cover should generally mean more ET will be returned to the local basin in the form of rainfall, this amount will generally be significantly smaller than the additional amount of ET flushed out of the basin to other downwind locations.

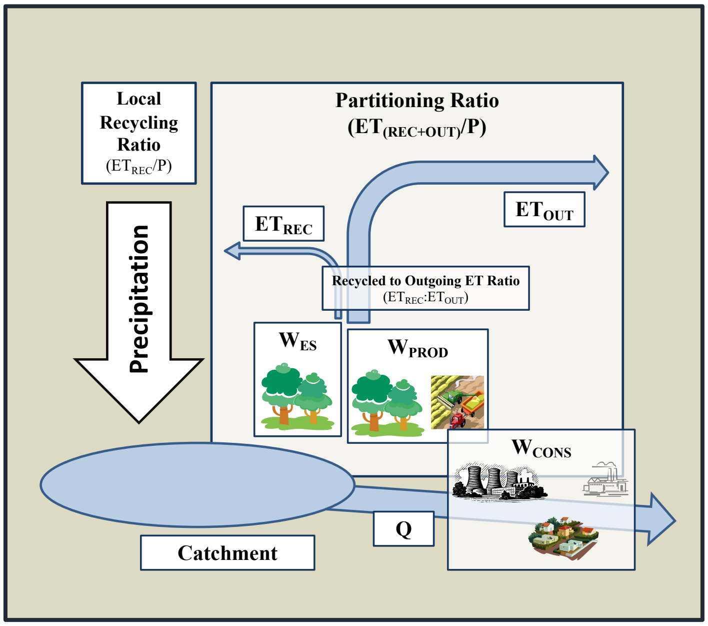

Figure 1. Illustration of the Partitioning Ratio, Local Recycling Ratio and the Recycled-to-Outgoing ET Ratio. Recycled ET (ET_{REC}), ET leaving the catchment (ET_{OUT}), water for ecosystem use (W_{ES}), water for agriculture use (W_{PROD}), water consumed for industry(W_{CONS}), stream flow (Q)

This can be more clearly expressed in numbers. Assuming 100 mm of rainfall, on average, somewhere around 60 mm will be turned into locally produced ET (based on global hydrological estimates).[23–25] If we assume that approximately 10% of local rainfall is sourced from the local ET contribution, this means that 10 mm of locally produced ET must return as rainfall, while the remaining 50 mm of locally produced ET will exit the basin in the form of atmospheric moisture. Since increases in local ET production (whether through increases in local forest cover or climate change) will contribute less to local precipitation recycling than to outgoing ET (in our calculations, at a ratio of about 1:5), greater ET production simply means that more water will be flushed out of the basin.

The impact of change in forest cover can again be expressed more clearly in numbers. If we assume a 50% increase in forest cover, this should mean that locally produced ET will increase to about 90 mm. Assuming this ET continues to be distributed in the same way, this would mean an increase in locally recycled ET of +5 mm (and a total local recycling contribution of 15 mm), and thus an increase in local precipitation to 105 mm. However, this also means an increase of +25 mm to outgoing ET, or a total outgoing ET of 75 mm. Since previously the basin lost 50 mm of rainfall to downwind locations, the increase in forest cover in this case has led to a greater increase in outgoing ET relative to the increase in incoming precipitation (25:5). This represents a total marginal loss to the basin water balance of -25 mm (given previous runoff was 40 mm, new runoff can be calculated as the remainder of P – ET, or 105 – 90 = 15).

In order for increases in forest cover to have a positive impact on the local water balance, the ratio of local to outgoing precipitation recycling would have to be greater than 50%. In order for this to happen, local precipitation recycling must be equal to or greater than 30%. However, even with one of the highest local precipitation recycling ratios in the world, the Amazon frequently does not approach these levels. With a wet season, local precipitation recycling ratio estimated at approximately 28-29%,[9] the Amazon generally may not be able to improve upon the local water balance by increasing forest cover. Even in this case, locally recycled precipitation amounts should still be marginally smaller than outgoing ET (in this case 28-29 mm: 31-32 mm).

On the other hand, given the difficulties in estimating local precipitation recycling rates, positive contributions to the local water balance cannot be ruled out.

On the one hand, the seemingly persistent failure to recognize these relationships is potentially the result of a tendency to conflate two distinct hydrologic processes: 1) the *partitioning* of hydrologic resources across downstream flows (Q/P, or the share of rainfall *appropriated* for local use where these quantities have been anthropogenically manipulated) and atmospheric moisture supply (ET/P, or the relative share of rainfall redistributed to downwind locations), and 2) the *local recycling ratio*, (ET_{LOC}/P, i.e. the relative share of precipitation originating from the share of local ET returning to the same basin as rainfall). The demand-side literature has consistently pointed to the phenomenon of *partitioning*, while either ignoring or denying the *recycling* phenomenon, regardless of whether this occurs at the level of the basin or beyond.

Conflating or confusing the *partitioning ratio* with the *recycling ratio* may well be what leads many to believe that increasing forest cover should, ultimately, benefit local rainfall. The local *recycling ratio* is, however, largely independent of the total amount of, and change in, local forest and vegetation cover. Instead, this partitioning of rainfall into ET and runoff depends primarily on local weather patterns and, for the most part, does not principally affect, local precipitation *recycling ratios*. These are two more or less independent processes. The local *recycling ratio* is primarily influenced by climatic conditions such as local wind and weather patterns, orographic features such as the presence or absence of surrounding mountains, and other factors such as surface roughness. The partitioning ratio, on the other hand, is primarily affected by the relative share of local forest or other forms of vegetation cover.

2.b. Land-atmosphere interactions as a means of understanding variation in local precipitation recycling:

Discussion of the factors that can affect total amounts of water recycled over terrestrial surfaces occasionally stumbles over the problem of residence times for water in the atmosphere. Due, in particular, to the long residence times of atmospheric moisture, much of the locally produced ET will return as rainfall only in more distant locations, and an important share will return as rainfall over oceans. Thus, some precipitation-recycling skeptics suggest very little of the atmospheric moisture produced by forest-based ET will even return as rainfall over land, and thus that increasing forest cover or engaging in extensive forest landscape restoration cannot affect rainfall.[26,27] Residence times for water in the atmosphere are in fact quite long, averaging approximately 8-10 days[12,28] and thus represent one of the most important features limiting the potential for precipitation recycling to have a positive impact on total terrestrial rainfall.

Being able to calculate where and when additional ET, together with the remaining atmospheric moisture from oceanic evaporation, will return as rainfall, as well as to determine the factors likely to influence this general relationship, remain important questions. Precisely because so much of ET is ultimately transported on to other basins, better understanding factors that can affect how far ET is likely to travel before becoming rainfall is ultimately key to understanding how much of an impact increasing forest cover can potentially have on total amounts of terrestrial rainfall. Estimates of local precipitation recycling suggest there is considerable variation from basin to basin.

As suggested in the introduction, the role of forest cover in triggering land-atmosphere interactions may begin to provide a pathway for better understanding the consequences of increased forest cover on variation in local (and thus also continental) precipitation recycling. Different types of vegetated ecosystems interact with land-atmosphere fluxes, weather, and local climate in different ways.[29–31] The shifting fluxes associated with increased tree and vegetation cover drive energy flows from vegetation surfaces to the atmosphere. *Latent energy flows* in the form of *increased humidity* describe changing land-atmosphere interactions that may also drive increased rainfall potential by their potential ability to affect windspeed. More can likewise be learned about how forest-based aerosols are transported into to the atmosphere and the impact these have, both on convection and cloud formation, and thus also on the interaction with incoming oceanic molecules and the winds that carry them.[32–35] The cloud formation and rainfall-triggering literature, for example, suggests forests, their relative share, as well as the aerosols and relative humidity they produce, play an important role in explaining the occurrence, frequency and abundance of rainfall.[32–37] This literature, however, again stops short of asking whether these phenomena have any potential impact on windspeed, though it clearly suggests an impact on rainfall.

Surface roughness, a principal outcome of increased forest cover, further creates the potential for friction between incoming winds and the terrestrial surface.[29,38] Likewise, forest cover has powerful and important effects on the temperature fluxes in land surface-atmosphere interactions due to relatively dramatic albedo effects.[29] The surface darkness of forests further causes solar radiation to be used for the production of latent heat, in this case evapotranspiration. The biotic pump theory (BPT) in particular, developed by Makarieva and Gorshkov,[39,40] and popularized by Sheil and Murdiyarso,[41] relies on the principle that forest ET production propels atmospheric interactions that drive the formation of vertical air columns and trigger condensation. The BPT claims that low-level winds move from areas with less ET to areas with increased ET creating a pull of water vapor across a landscape influencing the direction and speed of atmospheric water transport.

Moreover, these fluxes can presumably affect incoming wind patterns, shifting incoming horizontal wind flows to match the formation of rising vertical air column patterns triggered by biotic pump-like latent heat fluxes. As condensation triggering aerosols increasingly add mass and density to forming cloud cover, gravity is also likely to have an increasing impact on their formation and may serve to further slow the movement of air and vertical cloud columns, in particular as these interact with additional surface (forest) roughness. It has even been suggested that total amounts of forest cover influence features such as cloud cover height, yet another indication that gravity likely plays an important role in slowing wind speeds,[42,43] and that both of these factors can likewise interact with orographic features.

The fact that local precipitation recycling is so variable should perhaps ultimately be seen as an indicator for the likelihood that increasing forest cover and growing season leaf area index (LAI) are likely indicators of the possible impact of important but as yet undefined land-atmosphere interactions that can further impact windspeed and rainfall. The land-atmosphere interactions triggered by changing amounts of tree and forest cover should therefore be expected to influence the rate of local precipitation recycling. However, despite considerable variation in local precipitation recycling rates, surprisingly little literature has attempted to find adequate explanations for why such variation might reasonably be said to occur.

We thus turn our attention to this specific problem. In order to do this, we analyze associations between forest cover, windspeed and rainfall at the global scale.

3. Methods:

In an attempt to analyze and quantify the relationships between forest density, wind speed, and precipitation, we map 2010 forest density, wind speed, and precipitation on a global scale. The year 2010 was selected since it falls in the beginning of a time period of having documentation in newer generations of meteorological models and is included in all of the different modeling datasets used for this study. We do not claim that these results act as a standard, applicable, model of predicting precipitation based on forest cover, wind speed, and geographic location.

We used 2010 data from a variety of meteorological datasets to confirm trends across meteorological models with varying methods in order to uncover major trends in forest, wind and water relationships. Meteorological data was extracted from three different forecasting model sets Global Land Data Assimilation System (GLDAS-2) and Modern-Era Retrospective Analysis for Research and Application (MERRA-2). GLDAS-2 and MERRA-2 were used for modeled surface wind speed (10m) and precipitation (kg m^{-2} s^{-1}) data. We averaged monthly data maps of wind speed and precipitation for each of the data sets.

3.1 Forest Cover Model:

We examined the Hansen et al. forest cover within an area to understand the impact of forest presence on wind speed, as well as precipitation, globally[44] This forest cover data presents global forest density on a 30 m^2 global scale. Forests were classified as areas with vegetation with a height greater than 5m and forest cover is ranked on a scale of 0-100.[44] Despite criticisms of the datasets documentation of forest regeneration, this data is documented as one of the most accurate sources for depicting forest cover.

Table 1: Meteorological model characteristics

Model	**Resolution**	**Modeling Method**	**Time Resolution**
GLDAS[45]	.25x.25°	Meteorological Forcing	3-Hourly
MERRA-2[46]	30km2	Integrated Forecasting System (IFS)	Hourly

3.2. Meteorological Data

3.2.1. GLDAS-2 Meteorological Data[47]

The Land Data Assimilation System's GLDAS Noah Land Surface model is a meteorological dataset developed through forcing data, land surface states, and flux data[45](Figure 2). Forcing data is a form of spatial modeling and evaluating values at a given pixel relative to surrounding and then cross-checking the outputs with recorded data from other sources.[47] This database is composed of both spatial and temporal datasets beginning in 1979.[47] Data is available, and used for this analysis, in 0.25° pixels for a refined structure with data modeled from continental data in 3-hour intervals which are then upscaled to develop a broader image of monthly data (Table 1). To evaluative the meteorological forcing model estimations of precipitation in GLDAS-1 and GLDAS-2, the precipitation results from GLADS-1 were reported to overpredict precipitation.[47] However, improvements and updates to the modeling software made GLDAS-2 a more accurate predictor of land-surface flux simulations.[45]

Along with a global analysis, we also used the GLDAS-2 data to analyze spatial and seasonal interactions in South America (Figure 3). We classified the continent into a dry (May-November) and wet (December-April) season.

3.2.2. Modern-Era Retrospective Analysis for Research and Applications V.2 (MERRA-2)

MERRA-2 is an updated generation of the MERRA models with hourly resolution incorporating the newest sources of satellite data and interprets GEOS-5 general circulation modeling[46,48](Figure 4). The data is recorded hourly temporal resolution from 1980 to preset with and 30km^2 spatial resolution[46] (Table 1).

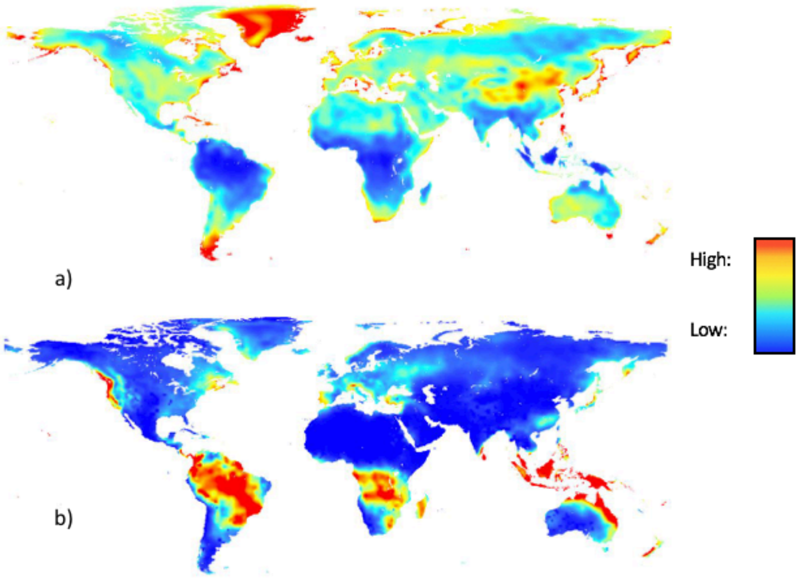

Figure 2. Averaged annual GLDAS-2 global a) windspeed ms-1 and b) precipitation (kg $m^{-2}s^{-1}$)

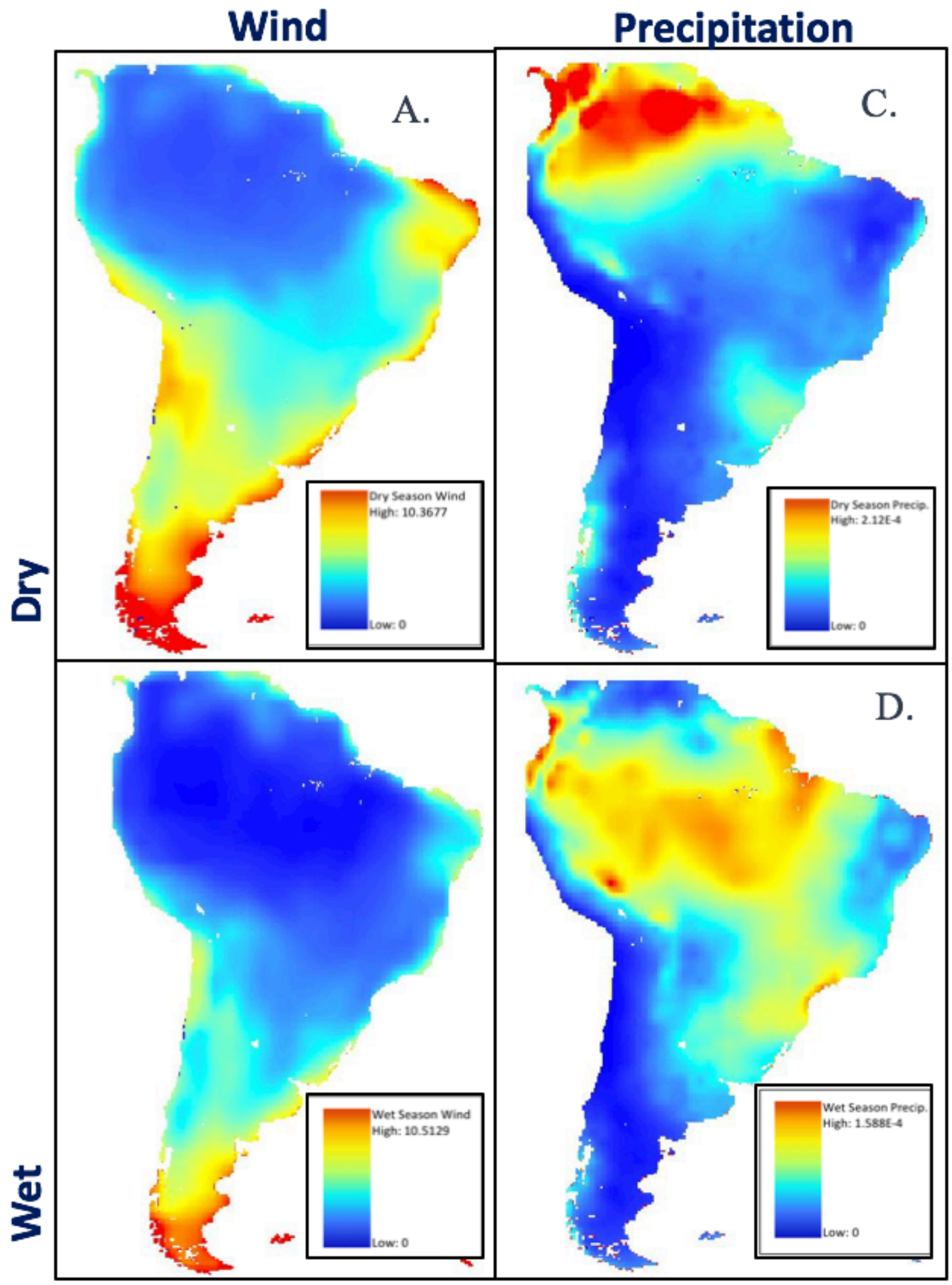

Figure 3. GLDAS seasonal averages of precipitation ($kgm^{-2}s^{-1}$) and wind speed (ms^{-1})over South America (10N90W,50S30W)

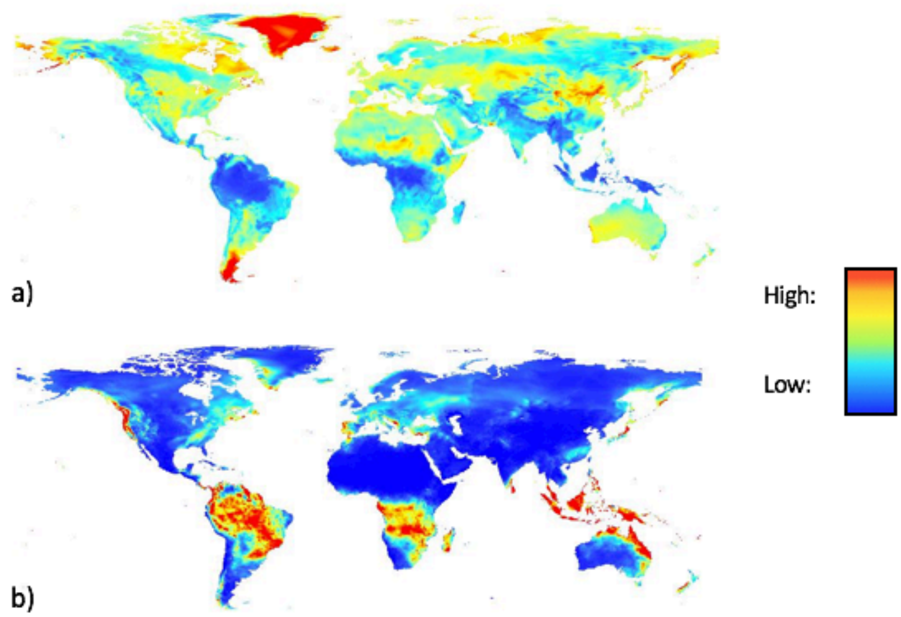

Figure 4. Annual Averaged MERRA-2 global a) windspeed ms^{-1} and b) precipitation ($kg\ m^{-2}s^{-1}$)

3.1 Data Analysis:

Modeled data collected was analyzed and interpolated in ArcGIS (ArcMap 10.4, ESRI location). Two different types of analysis -- general trends and spatial analysis -- were overlaid on each meteorological dataset of to the forest density data and annual means of wind speed and precipitation.

We divided the global dataset into five subregions by latitude every 30 degrees to represent the dimensions of Hadley cells (band 1: 90-60N, band 2: 60-30N, band 3: 30N-0, band 4: 0-30S, and band 5: 30-60S). Dividing the maps into subregions allowed for a closer analysis of the other potential influences which vary with proximity to the equator or poles. The region of 60-90S was excluded from the analysis because of a lack of vegetation data and terrestrial meteorological data. The dataset for South America was analyzed using the same methods over the two seasons.

A non-spatial analysis was used to see general trends without the indicated influences of forest cover on wind speed, forest cover on precipitation, and wind speed on precipitation using bivariate analysis. We also developed a multivariable linear model to represent how both forest cover and wind speed influence precipitation in a given region. Precipitation data was converted into a larger until (mm s-1) to properly assess the coefficient for the explanatory variables.

The Moran's I report informed our spatial analysis. Each map was analyzed for spatial autocorrelation comparing wind speed and precipitation to neighboring pixels within each band. We conducted a Moran's I spatial autocorrelation to find any significant patterns within the datasets.

We conducted an ordinary least squares regression (OLS) where forest cover and wind speed are explanatory variables for precipitation within a pixel. The OLS model does not account for geographic location. It is a regression of all pixels within the individual bands as individual datasets, irrespective of geographic location.

The Moran's I and OLS outputs then inform our spatial analysis searching for concentrated areas with consistent deviation within subregions of the bands.

In regions resulting in a low likelihood of clusters being randomly distributed, Cluster and Outlier analysis (Anselin Local Moran's I) indicates concentrations pixels that are overpredicted or underpredicted precipitation relative to the linear model along with anomalies. The clusters and outliers are indicated as high-high (HH) representing areas with statistically significant and high z-score values and low-low (LL) for areas with statistically significant and low z-score values. More specifically, HH regions support the hypothesis of forest cover influencing both windspeed and precipitation patterns with values that are overpredicted by the mean of the whole region under analysis. LL clusters are the opposite and are underpredicted by the total mean. Other results include high-low (HL) and low-high (LH) pixel outputs. HL signifies a pixel with a higher z-score than the neighboring pixels, and LH indicates the opposite. Visualizing the geographic location of clustered trends allows for a qualitative understanding of how forest cover increases or decreases wind speed and therefore precipitation while also indicating the influences of other unaccounted for variables.

4. Results:

To compare the relationships between forest cover, wind speed, and precipitation, we first compared each variable to see general trends excluding spatial relationships and find variation in coloration by latitudinal region. Figures 5 and 6 display the linear relationships between forest cover and wind speed, forest cover and precipitation, and wind speed and precipitation across the five latitudinal bands. In figure 5, the bands with the closest proximity to the equator have the highest correlations as represented by the R^2. Bands 3 and 4 indicate the strongest regression between forest cover and wind speed with R^2s of 0.82 and 0.28 (Figure 5G,J). Both plots of wind speed over forest cover also show a negative trend line signifying that, within those regions wind is likely to be slower over highly forested regions. However, as the bands move away from the equator, the strength of the correlation decreases. Higher wind speeds indicate less precipitation across in bands 2,3, and 4. The most northern and southern regions show the reverse trend where the linear regression predicts more precipitation in areas with high wind speed.

Figure 6 shows the same bivariate combinations of our three variables using the MERRA-2 dataset. The pixel density is higher because of the finer resolution of the model. The MERRA-2 comparison of forest density and wind speed has the smallest correlations in band 4 south of the equator, where the variables were strongly related in the GLDAS results. The correlation between forest cover and wind speed is strongest between 0 and 60N where there is a positive linear regression (Figure 6D,G). This contradicts the findings from the analysis of forest cover with the GLDAS-2 model. Like the GLDAS-2 output, forest cover and precipitation have a weak correlation and show little indications of the impacts of forest cover on precipitation. The relationship between wind speed and precipitation remain consistent across latitudinal degrees with varying strength of the correlation, but the strongest relationships are, again, around the equator (Figure 6I,L). These locations also have the most distinctly plotted shape in comparison to the other plots for both models. This raises questions about other variables which could cause a more rapid decrease in precipitation in differences of wind speeds with a lower magnitude.

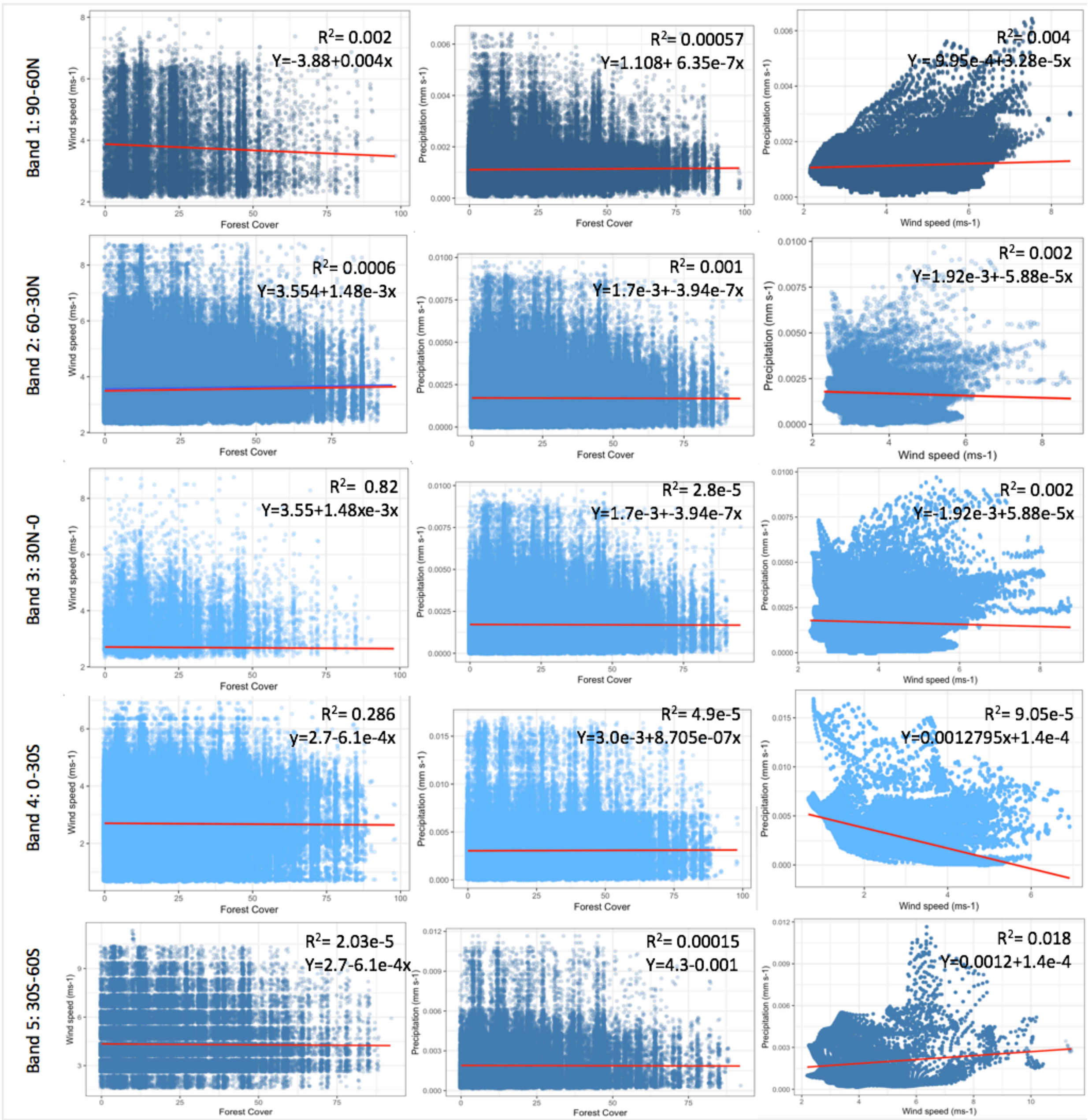

FIGURE 5. Comparison between forest cover and GLDAS-2 wind speed and precipitation data divided by explanatory variables (left to right) and latitudinal bands (top to bottom). Points are slightly transparent to show pixel density within each plot.

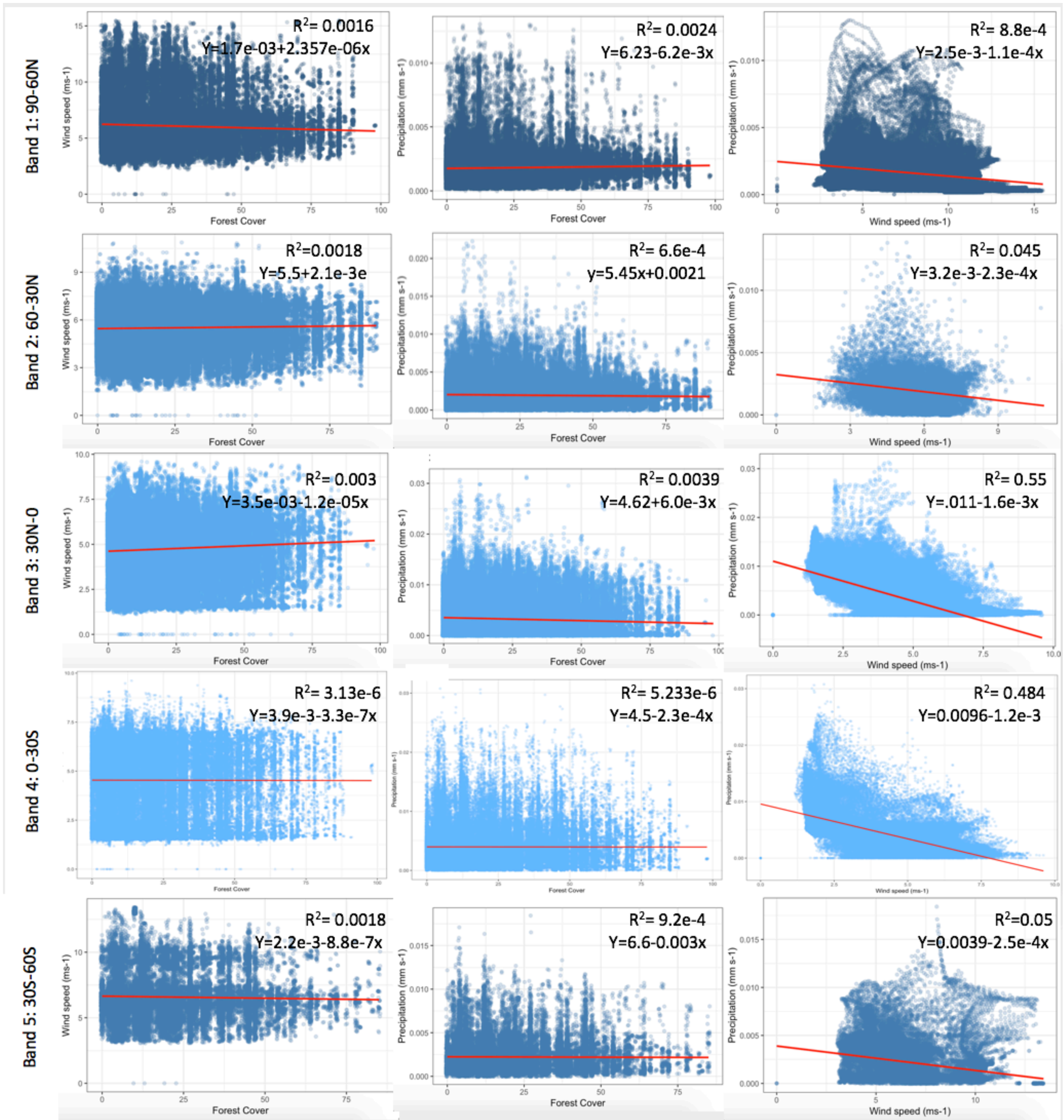

FIGURE 6. Comparison between forest cover and MERRA-2 wind speed and precipitation data divided by explanatory variables (left to right) and latitudinal bands (top to bottom). Points are slightly transparent to show pixel density within each plot.

The impact of forest cover and windspeed on precipitation was analyzed in an OLS in order to determine their relative independent influence. The coefficient for wind speed has a consistently greater magnitude than forest cover across both models and all geographic regions indicating that wind speed is more influential on the modeled precipitation at any given location (Table 2). The OLS results indicate that there is consistently high probability that the influences of forest cover and wind speed on precipitation are significant. In the most northern and southern regions of the OLS models with the GLDAS data, the wind speed coefficient indicates that increased wind speed increases precipitation in that area. That observation is consistent with the linear regression between wind speed and precipitation in. Between 90-60N, forest cover has a positive coefficient indicating that areas with greater forest cover have more precipitation (Table 2). 90-60N also has a positive wind speed coefficient, so the areas with the highest precipitation values will also have high wind speeds and minimal forest cover. Regions with negative forest cover coefficients signify that, independent of location, increased forest cover is predicted to decreases precipitation.

Table 2. OLS results for each geographic location and both meteorological data sets

Database	**Region**	**Forest Cover Coefficient**	**Wind Speed Coefficient**	**Intercept**	**OLS R^2**	**Statistical Significance from OLS**
GLDAS	90N-60N	**1.0e-6**	**3.3e-5**	9.8e-4	0.0047	***
	60N-30N	<-1.0e-6	-5.9e-6	0.0019	0.002	***
	30N-0	-3.0e-6	-1.5e-3	0.0073	0.33	***

	0-30S	**2.4e-7**	-1.0e-3	0.0058	0.28	***
	30S-60S	-2.8e-7	**1.4**	0.0012	0.018	***
MERRA	90N-60N	**2.0e-6**	-1.1e-4	0.0024	0.055	***
	60N-30N	-2.0e-6	-2.3e-4	0.0033	0.046	***
	30N-0	-2.0e-6	-1.6e-3	0.011	.55	***
	0-30S	-1.0e-6	-1.2e-3	0.0096	.48	***
	30S-60S	-1.6e-7	-2.6e-4	0.0034	0.05	***

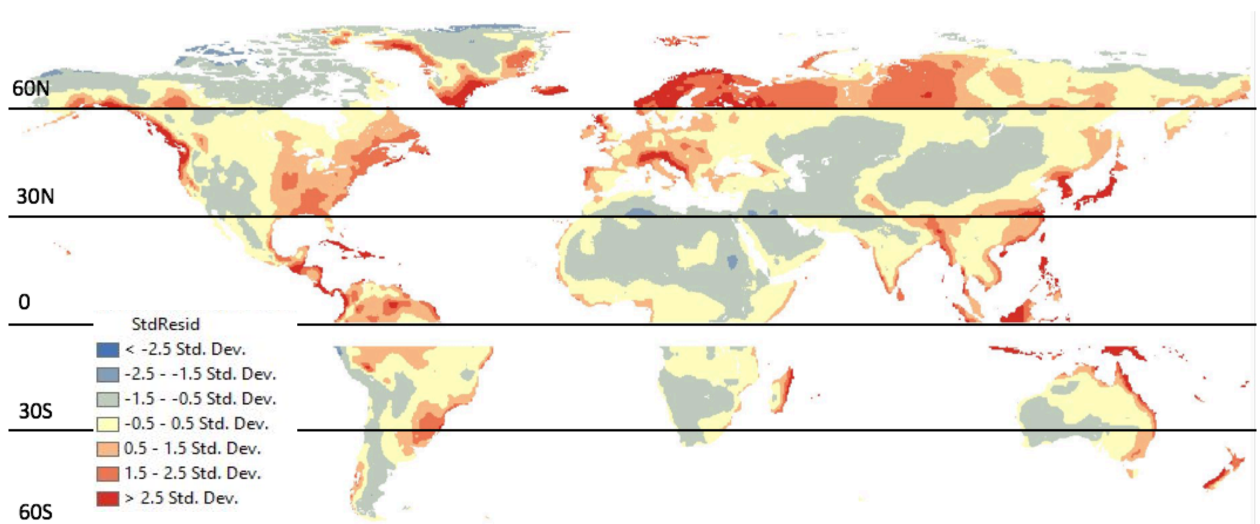

Figure 7. Standard deviations of precipitation from the ordinary least squares regression results of forest cover and wind speed as independent variables on precipitation using the GLDAS-2 meteorological data. Each latitudinal region was modeled separately.

However, the spatial context is critical to understanding the results of the linear model. The majority of the results have low correlations between forest cover, wind speed, and precipitation within each dataset due to high variability and a high sample volume. The regions of over and under predicted precipitation falls consistently with our knowledge of large scale global forested systems. Each subsection shows cluster patterns.

4.1. Spatial Analysis

Both data sets showed high probability of clustered spatial autocorrelation according to the Moran's I statistical autocorrelation meaning that the linear regression of the OLS is not capturing the influence of neighboring pixels on each other. And although it indicates that forest cover and wind speed influence predicting precipitation, a single linear fit does not account for the spatial variability and influence of neighboring areas. Figures 7 and 8 show the OLS standard deviations from the mean over space for each band. Areas are overpredicted or underpredicted relative to other regions within the same latitudinal region. Areas distinguished by positive standard deviations are under predicted by the linear regression model meaning that the actual precipitation in those regions is greater than what would be expected. Areas over predicted with negative standard deviation values have actual precipitation values less than what the model predicts. Areas of overprediction are consistent with large tropical, temperate, and boreal forests around the globe.

GLDAS-2 provides a more generalized map of trends because it has a larger pixel size because of the larger pixel size. Even still, there are still large areas of over prediction on the east coast of North America, around the equator in South America and into Central America, Madagascar, along the east coast of Australia, along the east and south east coasts of Asia, and above 60N in Russia and northern Europe. Coastal areas are also distinguished for being greater than the mean. The latitudinal divides make it challenging to compare results between different regions because they are based on models with different magnitudes and influences of forest cover and/or wind speed.

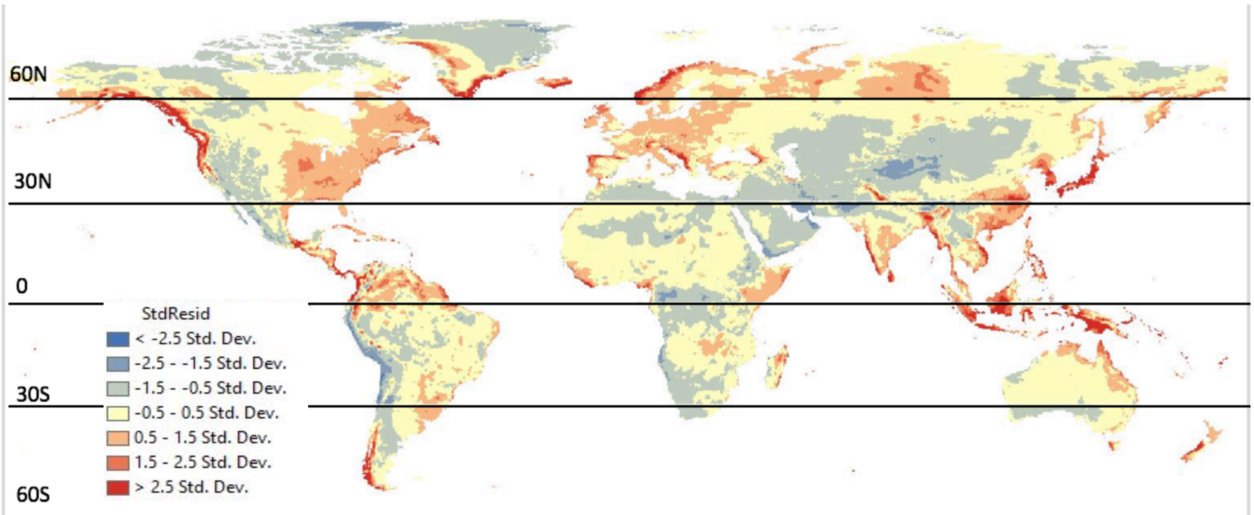

Figure 8 Standard deviations from the ordinary least squares regression results of forest cover and wind speed on precipitation using the MERRA-2 meteorological data.

The MERRA-2 OLS map shows a more intricate depiction of variation from the mean and shows smaller areas that stand out as anomalies or show unexpected patterns. Figure 8 documents a larger section of the Sahara Desert as close to the mean rather than being <-1.5 standard deviations away like in the GLDAS results. Band 3 (30N-0) has an R2 of 0.55 in this model but shows less of a correlation in the GLDAS model with an R2 of 0.33. The refined scale allows for a more detailed representation of the relationships between forest cover, wind speed, and precipitation, but makes it more challenging to distinguish regional and global patterns. Even with the smaller pixel size, there is still a clear pattern of clustering with over predictions in areas with little forest cover and underpredictions in areas with high percentages of forest cover.

Clusters signify areas with similar forest cover and wind speed values. For example: high forest cover and slower wind speeds; areas with low forest cover and higher wind speeds. These are both represented by the distance from the mean in the OLS analysis. Analyzing for clusters and outliers explains the magnitudes of the explanatory variables and explains patterns in locations of the groupings. Analyzing the spatial patterns between forest cover, wind speed, and precipitation also contributes to understanding where and to what degree forest cover and wind speed are influencing water cycling. Both the GLDAS-2 and MERRA-2 cluster outlier analyses distinguishes statistically significant cluster which are under predicted by the mean and are represented as H-H regions (Figure 9). Many of the high high (H-H) regions overlap with heavily forested areas. The majority of low-low (L-L) regions are in areas with little forest cover and high wind speed. These areas are also shown as being over predicted by the OLS.

Eastern Australia shows a large concentration of H-L pixels in an area with little forest, slightly high wind speeds, and high precipitation. The H-L pixels signify that although they may be underpredicted by the mean, they are not similar to each other or similar enough to have significance, but the values are still in close proximity to the mean.

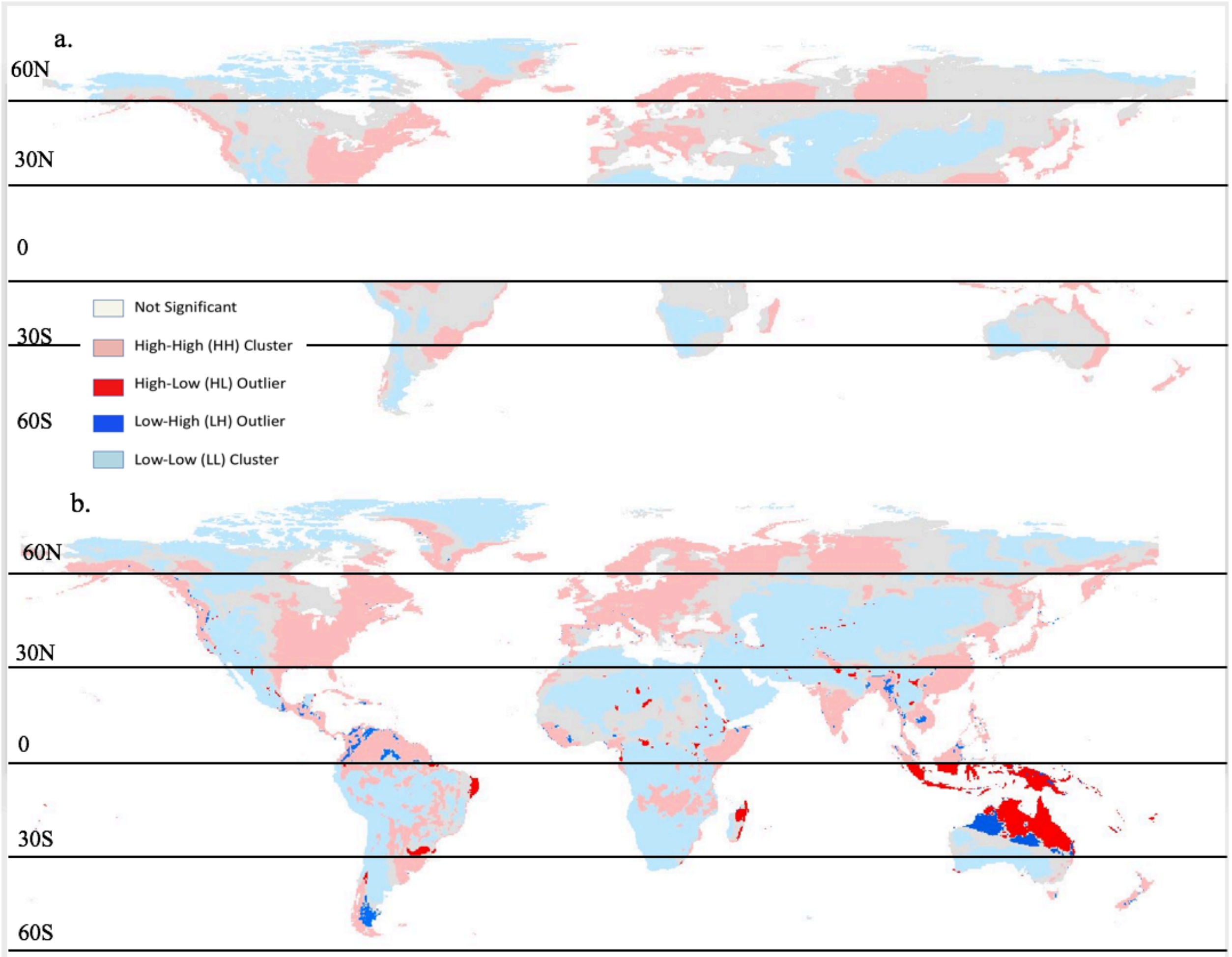

Figure 9. Cluster Outlier Analysis of a. GLDAS-2 and b. MERRA-2 OLS residuals

General trend of forest cover, wind speed, and precipitation relationship

4.2 Geographic Location Example: South America

Results of the global analysis of forest cover, wind speed, and precipitation allow for an overview of how the three variables are interacting within and between larger regions. The analysis across latitudinal bands simplifies forest-atmosphere interactions and dilutes the influences of other variables. South America is an interesting continent to analyze because of the high rates of precipitation recycling in the Amazon and the Andes Mountains to discuss the potential influence of orographic features.

Relationships among the three variables are clearer within the smaller dataset. Forest cover has a stronger correlation to wind speed during the wet season and the trend shows that wind speed changes more based on forest cover during the wet season (Figure 10A). The connection between these variables provide evidence that forest cover may influence, and slow wind speeds, especially during the wet season, allowing more time for precipitation recycling.

Forest cover also has a stronger correlation to precipitation than most of the global analyses, and there is evidence that increased forest cover also increases precipitation independent from wind speed (Figure 10B). However, the strongest correlation is between wind speed and precipitation showing that high wind speeds indicate low precipitation (Figure10C). However, precipitation rates increase with some of the highest wind speeds. This may be mainly along coastal areas when wind speeds and precipitation are high due to water transport from the oceans across the continent.

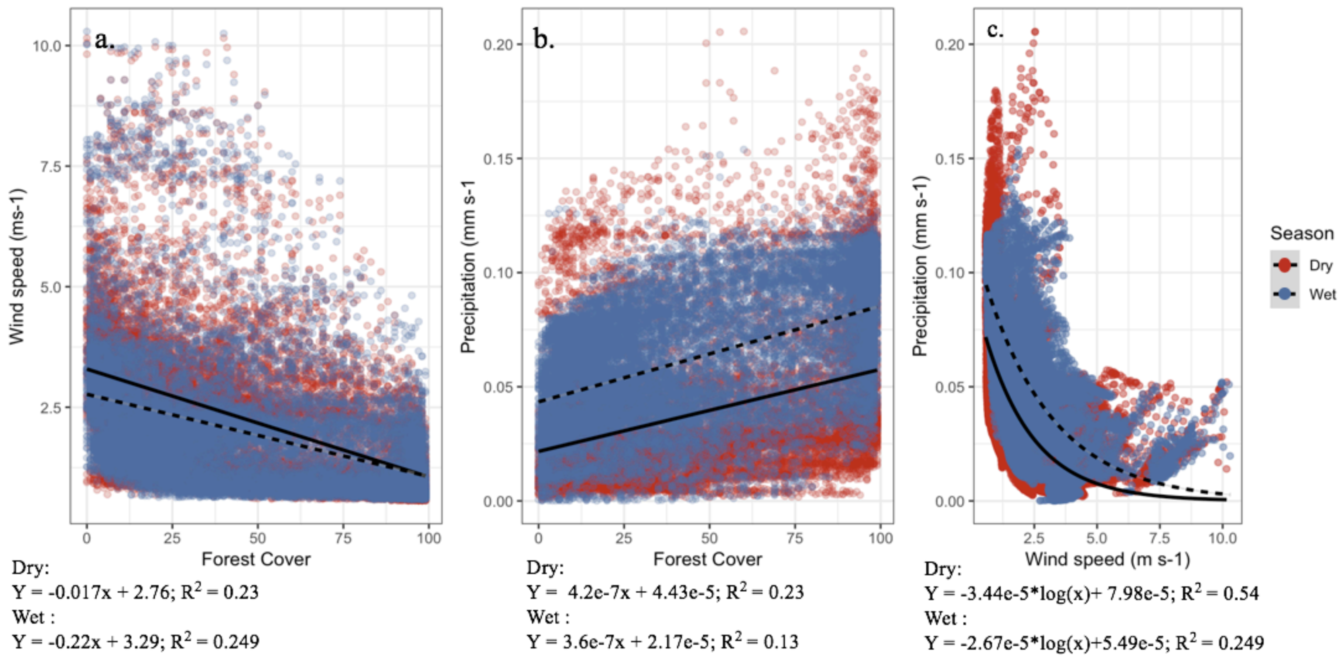

Figure 10. Forest cover, wind speed, and precipitation non-spatial analysis by dry and wet season in South America.

There are distinct differences in the spatial patterns of linear models between the dry and wet season. There is more variation during the dry season. The Amazon Basin is also highly over predicted during the dry season, while during the wet season the actual precipitation is more than the modeled. This may be due to the change in magnitude of water added back into the water cycle of the impact of a dry period on a dense tropical forest relative

There are seasonal changes in precipitation rates across the continent, but the Amazon basin and the region further down the wind currents (south west) see much greater changes in precipitation (Figure 11). These heavily forested areas also have much higher rates of ET indicating increased water vapor added to the feedback loop. The highly forested areas like in the Amazon basin over predicted during the dry season and under predicted during the wet season. The Andes remain consistently over predicted during both seasons indicating that, relative to the rest of the continent, the mountains are consistently receiving less precipitation than what a model would suggest.

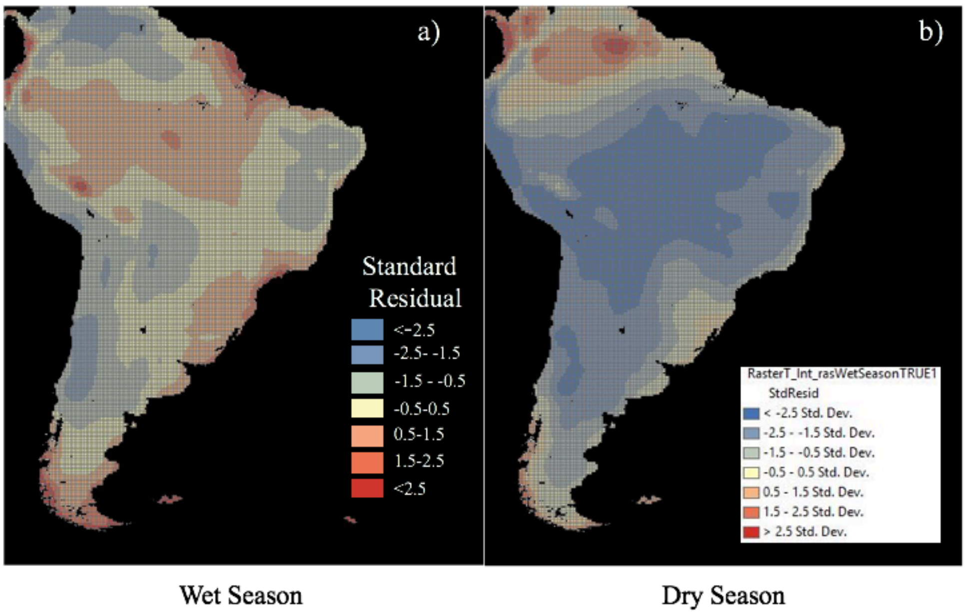

Figure 11. OLS of the dry and wet seasons in South America using the GLDAS

The cluster outlier analysis of South America shows concentrations of pixels that have higher forest cover, lower wind speed, higher precipitation, and are underpredicted by the OLS regression forming H-H clusters (Figure 12). The mountain range and into the desert show the opposite pattern represented by L-L clusters. The majority of the rest of the continent if filled with pixels that are not close to the mean but are not similar to their surrounding pixels.

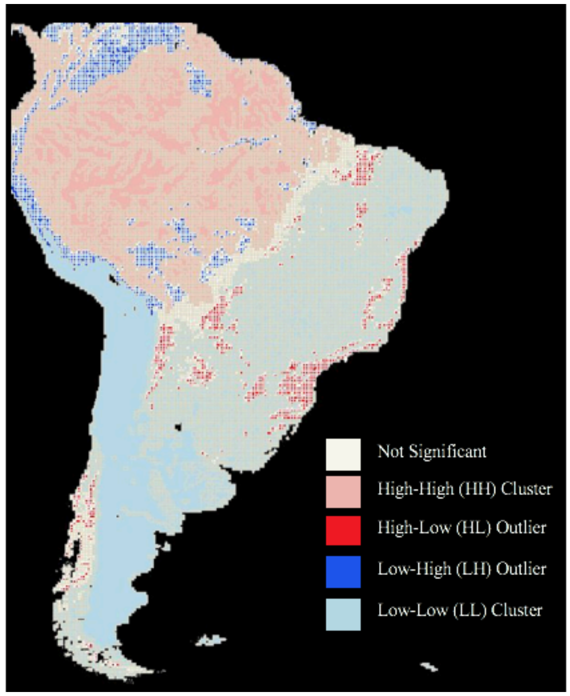

Figure 12 Cluster outlier analysis results of South America

5. Discussion:

We find direct evidence that larger shares of forest cover are associated with the slowing of windspeed and the increased likelihood of precipitation within the same pixel. Increased forest cover may thus lead to greater total amounts of precipitation occurring over the same territory. Windspeed is generally greatest over oceans, and then over land surfaces with no or limited vegetation cover (such as deserts and grasslands).

As the molecules from the oceanic evaporation system begin to move over land masses, they begin to interact with the land-atmosphere fluxes caused by vegetation along with other factors of terrestrial systems which vary from the over ocean atmosphere (i.e. aerosols, ET, etc.), they appear to have a moderating impact on windspeed. The relative extent (and potentially density) of forest cover are thus linked to both local and downwind weather patterns, and thus most likely to variation in local recycling ratios. This suggests that the interaction effects between these phenomena may well be an important factor in helping us better understand potential variation in local precipitation recycling, and thereby the potential influence of local level factors in explaining the likelihood of local rainfall.

We have shown that on a global scale, forest cover does not have as strong of a direct influence on precipitation patterns. However forest cover shows a stronger influence on precipitation. This signifies that forests are interacting with the atmosphere changing the way water is transported and the distance water vapor travels before precipitating. Within each latitudinal region, large areas of heavily forested areas are underpredicted by the linear models which indicates that there is more precipitation than would be expected in less densely forested regions.

The tropical forests in South America and southeastern Asia, the temperate forests on the east coast of North America and the eastern coast of China, and the boreal forests of northern Europe and Russia and the east coast of Australia are all highly forested areas that are underpredicted by the linear model of forest cover and wind speed. Areas across the globe with a known lack of forested systems like the Atacama Desert in South America, Sahara Desert in Africa , and Great Basin in North America are all underpredicted by the model.

Forested systems interact with atmospheric wind currents through a variety of methods, slowing wind speeds, allowing more time for water vapor to enter the atmosphere and for precipitation to deposit within that location. Water travels smaller distance over the atmosphere within a vapor resonance time maximizing the amount of time water is cycled across an area.

Correspondingly, large areas of non-forested landscapes have significantly less precipitation than modeled meaning that over these regions, wind speeds have the ability to increase and transport water further minimizing the amount of water cycling and precipitation recycling within a specific location and along the wind currents. Large open regions like grasslands and deserts allow for wind speed to increase across the region similarly to over oceans, but evaporation rates are significantly lower therefore precipitation decreases.

Clusters of forested or non-forested areas also influence water transport in regions down wind. As wind travels across a continent, forested systems slow wind speeds and allow for more precipitation recycling down wind. Large forested areas over wind currents allow for a continuous decrease in wind speed.

Along with influences of clustered patterns on the areas around them, latitude influences the strength of forest and wind speed's influence on precipitation. Our results show that proximity to the equator influences the strength of the relationship between forest cover, wind speed, and precipitation. More northern regions are less influenced by forest cover and wind speed. This is potentially due to forest type. The majority of forests between 60-30N and 30-60S are temperate and have the weakest weight on predicting precipitation. Regions with boreal forests are more influenced by forest cover than temperate forests although still not as influential as wind speed. The association between forest cover and wind speed and precipitation is also much stronger in those regions. Tropical forests and forests closest to the equator (30N-30S) have the strongest influence on precipitation relative to the other forest types and regions. This is likely due to the forest structure and how different forest biomes interact with the water cycle and atmosphere.

Since areas with little or no forest cover are associated with higher windspeeds and smaller amounts of total annual precipitation, increasing deforestation and forest degradation will presumably have similar effects. Moreover, changing land cover is thus presumably strongly linked to change in local and regional wind and weather patterns, suggesting there are powerful land-atmosphere interactions at play that have important implications for total amounts of rainfall and available freshwater.

Because these findings suggest the influence of the land-atmosphere interactions driven by increasing forest cover has important consequences on things total annual rainfall amounts, we likewise expect this phenomenon to have important implications also for the relative rate of local precipitation recycling. As forest cover increases, we should expect the rate of local precipitation recycling also to increase. On the other hand, we cannot definitively say anything quantitative about the rates at which changing forest cover will affect changing rates of local precipitation recycling. However, per latitudinal region, we can theorize the impact of additional forest and create a broader model of how increased forest cover and the range of developed forests may alter wind speed.

We are also not able to say much that is meaningful about the potential likelihood of crossing the 30% threshold we have highlighted as crucial for shifting the catchment-level balance of the forest contribution to water availability in the positive direction. This point, in particular, remains an open question we hope will excite significant future research. We do, however, expect this phenomenon to occur in some regions or pockets where local dynamics are particularly propitious. Thus, for example, we expect that certain locations, such as those outlined above that produce unusually high amounts of rainfall and lead to the formation of rainforest-like conditions in locations where we would not otherwise expect them, are likely to exist also in other places, but may not be revealed without increasing average hydrological intensity across larger landscapes. At the same time, however, we still expect crossing this 30% will remain the exception rather than the rule in most locations, especially in regions with lower total amounts of evapotranspiration and rainfall.

Biome effects (PET=>AET)

Our results may suggest that the type of interactive relationships we have described between forest cover, windspeed and rainfall are more or less consistent depending on the specific biome in which they occur. This may not be that surprising, since warmer, wetter and more tropical biomes are more likely to produce significantly larger amounts of evapotranspiration. Thus, we might expect these land-atmosphere interactions to be significantly stronger across the tropics, and these interactions may themselves be one factor helping to describe the formation of the tropics as a forest biome in the first place.

Further, we highlight the fact that both the Amazon and the Congo have uniquely high rates of precipitation recycling, without having any significant elevation. Thus, though we might expect land elevation to have an important lifting effect that promotes both condensation and rainfall, it is clear from these two tropical cases that orography is not the sole determining feature in this regard.

Residence Times (Role of forest cover)

Water vapor residence times in the atmosphere are occasionally seen as a barrier to significant and more extensive precipitation recycling. However, our results suggest increased forest cover is likely to profoundly affect the impact of water vapor residence times on the likelihood of rainfall. Increased forest cover essentially means that atmospheric water vapor will travel shorter distances before it is likely to return as rainfall over terrestrial surfaces. Tuinenburg and van der Ent, on the other hand, find that residence times over land surfaces are marginally longer than over oceans,[49] a point we find difficult to support based on the data we assess.

Deforestation and Reforestation

Though we do not explicitly analyze *change in forest cover over time*, these findings raise important questions about the role both de- and reforestation might play in disrupting or increasing the frequency of regional precipitation recycling and hydrologic cycling across terrestrial surfaces. The key message is that reducing forest cover will raise windspeeds and thus the rapidity with which atmospheric moisture that could become rainfall will move across denuded or degraded land surfaces. Likewise, without the contribution from this forest cover to the formation of vertical columns, the aggregation of atmospheric moisture over land surfaces, as well as its potential condensation and re-deposition, is less likely to occur. Thus, we expect that with extensive reforestation, much of this cycle can be improved upon, thereby contributing to the re-intensification of the hydrologic cycle across land surfaces. By intensification we explicitly mean the increasing frequency and amount of precipitation recycling across land surfaces.

Important Caveats

There are important limits to the work we have undertaken here. Our analysis does not explicitly cover a number of important points, despite the fact we hope to provide some insight on the likelihood of certain effects. We do not, for example, test questions that would help us determine how the slowing of windspeed occurs. Our analysis only notes that windspeed, as measured at various elevations, is either slower or faster.

For another, since we do not in any way measure or assess ET, we can in no way assess the direct effects of change in forest cover and ET on the likelihood of slowing wind speeds and the occurrence of rainfall. Though we expect increases in forest cover to correspond with increases in evapotranspiration amounts (we expect the relative share of ET production to stay constant, while the relative distribution of ET across local precipitation recycling and outgoing ET should presumably change), we are not able to demonstrate that it is the increasing amounts of ET that have an effect on windspeed. While this explanation seems the most likely, cannot adequately demonstrate this phenomenon.

We do not directly assess the fact of precipitation recycling itself. Since we only include precipitation in our analysis, we do not have any way of assessing either increases in the total amount of ET over time, nor the likelihood that the relative hydrologic intensity across the landscape will change. Again, this seems like a reasonable outcome. But we do not directly assess this phenomenon.

Finally, since we have not in any way assessed recycling, we also have no way of assessing the number of times recycling can occur across land surfaces. This of course would provide yet another indication of the fact that increasing forest cover has an effect on relative hydrologic intensity. Thus, the need for a satisfying methodology for resolving questions about the relative number of times moisture recycles between land and the atmosphere before returning to the ocean, remains to be fulfilled.

Implications for Biotic Pump Theory

Our analysis appears to contrast somewhat sharply with some of the existing literature on the impact of forested ecosystems on land-atmosphere interactions(citations). One variant of this work, in particular, stands out as being at least partially out of sync with our findings. The "biotic pump" literature makes a series of claims about the impact of forests on the formation of weather systems that contrast with the view that forests slow windspeeds and increase the likelihood of rainfall through this particular mechanism (Citations).

BPT points to the creation of atmospheric currents caused by the production of ET. By drawing oceanic moisture in over land, the BP reportedly initiates and drives a cycle that propels atmospheric moisture further inland and thereby adds to the total amounts of water precipitating over land, thereby driving a cycle of moisture accumulation and transport to more distant downwind locations.[5] It has even been argued the biotic pump drives atmospheric pressure dynamics and potentially helps to explain the origin of winds.[50] Thus, these authors have claimed forest evapotranspiration, in particular in the tropics, is the principal force behind global atmospheric circulation patterns.[50]

From our perspective, however, the BPT authors seem to ignore the fact that windspeeds over oceans, presumably due to the lack of topography and vegetation, are considerably higher than over terrestrial ecosystems. And as winds begin to move over forested surfaces, they become progressively slower. This can happen presumably because the extent of forest cover has the impact of slowing relative windspeed, in particular by creating increased amounts of surface friction, and by encouraging the formation of overland cloud systems through the interaction of forests and aerosols with incoming atmospheric moisture circulation patterns. We suggest that any theory purporting to explain phenomena caused by vegetation such as windspeed and rainfall must adequately take these phenomena into consideration.

On the other hand, there are specific elements of the biotic pump theory with which we are inclined to agree. The BPT argues, for example, that forests interrupt Hadley cell air cycling by pulling air in from the surrounding forests, pushing it up, and thereby creating a shift in direction through evapotranspiration. However, while the BPT authors argue this motion drives winds toward continental interiors, we are inclined to think that the BP essentially drives moisture upwards, thereby slowing winds coming in from oceanic surfaces. In fact, if any shift in wind direction occurs, it is primarily likely to be due to the horizontal wind path arriving from the oceans colliding with the vertical wind path created by the BP.

A further complexity of the BPT does not seem to handle well is the question of directionality. The theory itself suggests it is the formation of vertical columns closer to the coasts that somehow drives these systems in the direction of continental interiors. Yet, the mechanism of their formation is not explicitly directional. If such vertical columns draw air in from the surrounding areas, there is no reason they cannot do this from multiple directions (even from the side closer to continental interiors). Thus, the only explicit directionality such systems might initially have is upward rather than away from coastal regions. Such systems may, on the other hand, draw in moist air from ocean surfaces. However, low-level wind current and direction shows consistent directional pulls from oceans over land masses.

Instead, we imagine directionality is likely to be driven by other factors, in particular the interaction of winds coming in from ocean surfaces as they mix with terrestrial winds building out of the interaction between rapid cooling effects at the base of these vertical columns and the rapidly rising warmer air higher up. Temperature mixing between oceanic and terrestrial winds has further interactions between the increasing mass of these building systems with gravitational forces.

Beyond these basic descriptive relationships, we remain undecided about the direction winds will develop after the formation of such vertical columns and the implications of the increased energy potential they contain.

6. Conclusions:

Though much work has repeatedly insisted increased forest cover leads to the increased loss of water in individual basins, this very basic and general proposition does not appear, at least on deeper investigation, to be strictly true. While studies of forest cover show an immediate decrease in stream flow after reforestation, our work suggests increasing forest cover is likely to shift local wind and weather patterns in the direction of increasing rainfall. Thereby, over time, will increase the rate at which local precipitation is recycled back into the same basin. The shift in wind and weather patterns is further presumed to have a positive impact on regional or continental scale precipitation recycling, and thus on the larger scale intensity of hydrologic cycling.

Though compelling in its own right, the central finding is that variations in forest cover have significant impacts on wind and precipitation patterns. The observation that these interaction effects can have important impacts on total annual rainfall, will, we hope, provide an both an exciting foundation, as well as intense motivation, for future research. As we have really only begun questioning and researching the interconnectedness of forest cover, wind speed, and precipitation, much important and potentially compelling work remains to be done.

Therefore, in closing, we highlight a few possible pathways for future study:

1) Perfecting techniques for analyzing and monitoring the number of times precipitation physically recycles across terrestrial surfaces: such measurements could of course assist in better understanding and estimating the relative intensity of local and regional precipitation

recycling and would further make it possible to improve estimates of the impact of increased forest cover. Recent work by Weng et al, may begin to point in the right direction.[16] At the same time, it would be preferable to develop direct and precise, as opposed to inferred, measures of precipitation recycling.

2) We likewise require better methodologies for assessing actual amounts of ET production over different types of vegetated surfaces and ecosystems. Estimates of potential and actual ET amounts vary significantly from technology to technology (remote sensing, eddy flux, sap flow, etc.), and thus comparatively little is known about the relative impact of change in forest cover on relative wind and weather patterns, as well as actual rainfall amounts. While we can importantly estimate the relative tendency and direction of these relationships, it is difficult to provide more precise results without significantly better data on the actual amounts of evapotranspiration promoted by different vegetation types. One pathway may be suggested by recent publications.[51,52]

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Chapter 4 Impacts of the hemlock woolly adelgid on old-growth forest water use

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Abstract:

Higher annual temperatures and fewer hard freezes have allowed the hemlock woolly adelgid (Adelges *tsuge*) (HWA) to migrate north on the east coast of the United States. The addition of this invasive species has caused the decline of the foundation species of old-growth forests in the northeast United States causing space for forest dominance by black birch (Betula *lenta*) changing the hydrology of the landscape. The shift from needle leaf foliage with annual transpiration to the seasonal water use of broadleaf trees changes the seasonal demand and overall volume of water use via transpiration. I want to explore eastern hemlock transpiration rates and investigate how the rate of predation by the HWA will change the hydrology of the forest landscape. I will use thermal dissipation probes to measure sap flow as a representative of tree transpiration to compare water use between infested hemlocks and black birches. These measurements will be combined with historical transpiration and meteorological data to see changes in water cycling over time within these old-growth stands. The rapid transition of forests from slow growing needle leaf coniferous forests to fast growing broad leaf species with high water use during the growing season raises concern for future water availability, stocks, and fluxes. Quick alterations in transpiration influences evaporation rates, ground water recharge, aquifer storage, stream volume and ecology, and water access. The importance of my research is to document how transpiration and water cycling has changed due to the HWA, and to understand the impacts of forest on stream ecology and water accessibility. This overall study attempts to answer the question: has hemlock transpiration decreased with the severity of infestation, and how is the growth of birch changing seasonal water use? .

Understanding how invasive species are changing forest-water interactions is critical to understanding the future of water demand and storage within the presence of climate change. By

proposing to research hemlock and black birch transpiration, I hope to gain an understanding of how the HWA will influence old-growth forest transpiration rates. I hypothesize that birches will have greater transpiration over the growing season than hemlocks and hemlock transpiration will decrease with decreased percent foliage. Quantifying changes in hemlock stand transpiration can provide a better understanding of water flow and fluxes, stream ecology, and water stability within New England forests.

1. Introduction:

Anthropogenic impacts on climate and water flow have increased average temperature, decreased the likelihood of water availability, increased the frequency of natural disasters, and provided space for the success of more invasive species. In temperate forests, foundation tree species such as the eastern hemlock (Tsuga *canadensis*), create dense canopy cover which regulate understory temperature, have unique nutrient cycling and defoliation which influences soil quality, and provides habitats which increase species diversity[1]. The projection of future rapid forest structure change and species dynamics play a critical role in understanding the resilience of ecosystems.

On the east coast of the United States, the introduction and migration of the hemlock woolly adelgid (Adelges *tsuge*) (HWA) are decreasing eastern hemlock (Tsuga *canadinsis*) populations. Decrease of hemlocks stands due to the HWA has begun to show influences on the ecosystem structure raising the concern for the health and stability of these old-growth forests. Changes in vegetative structures, especially foundation species (hemlocks), have significant influences on the hydrological fluxes of those ecosystems.

The hemlock woolly adelgid is a non-native species introduced from Japan and has migrated north with decreased hard freezes over the winter. The HWA is present as north as New England and Canada and as west as the Mississippi River[2]. Hemlocks have a lifespan of 4-15 years after initial infestation[3]. The HWA defoliates hemlocks through feeding on sap from the base of hemlock needles causing the needles to dry out[4]. The degree of infestation of an individual hemlock can be assessed by a percentage of defoliation or hemlock infestation index (HII):1 (76-100%), 2 (51-75%), 3 (26-50%), 4 (1-25%), 5 (no foliage)[3]. Eastern hemlocks have shown no resilience to HWA predation and there are no indications of preferences in physical characteristics: age, size, or location of branches[1,3,5].

Increased canopy gaps allow for early successional species to intrude old-growth stands due to the light availability.[5–7] As hemlocks death creates gaps in the canopy due to predation or selective logging, deciduous species like black birch (Betula *lenta*.), red maple (Acer *rubrum*), and oak (Quercus *rubra*) saplings begin to develop[3,5–8]. Black birch have been observed as the dominant successor of hemlocks[4,8]. The succession of old-growth coniferous species with continuous annual water use and dense leaf area to fast-growing deciduous species with seasonal water use and less dense canopies with seasonal variation raises questions for the future of carbon, water, and nutrient cycling of the landscape[9,10].

Hemlock stands at the Harvard Forest (Petersham, Massachusetts) either have single species hemlock stands or hemlock-white pine stands which have created ecosystems with high leaf area, acidic soils, and slow nitrogen cycling creating biotic and abiotic variations within the canopy, understory, and soil ecology over the large northeastern temperate forests and riparian zones[1,8,10,11]. The cool damp microclimate and shift in soil composition due to biomass deposition developed by old-growth hemlock stands allow for increased species diversity[1]. Furthermore, hemlock prevalence along riparian zones create shaded regions over stream systems, provide bank stability, and stabilize annual stream flow through regulating water fluxes and demand from surface and groundwater for the ecosystem.[1,7,12].

The more general influences of rapid forest transition from hemlock to black birch alter the hydrological cycle. Forest turnover will likely increase throughfall, evaporation, and transpiration; flooding is predicted to become more frequent, severe, and less predictable; changing transpiration will also decrease water available as runoff and stream flow likely decreasing stream velocity and variations in seasonal water use and canopy cover will increase seasonal variability; groundwater uptake will likely shift to relying more on surface water[9,11,13–15].

In this study, I attempt to quantify the impacts of the HWA on hemlock water use over the growing season in comparison to black birch. By measuring transpiration rates of the two species in comparison to historical data of pre-infested hemlock transpiration, I hope to gain and present an understanding of how the HWA is changing hemlock stand hydrological fluxes in transpiration which can then be connected back to the other changes in the water budget of the hemlock stands and New England temperate forest watersheds.

My research addresses the consequences of the HWA on transpiration water use in New England old-growth forests by asking three major questions: 1) How does the decline of canopy cover due to HWA predation impact eastern hemlock transpiration rates? 2) How do hemlocks, both infested and non-infested, and black birches vary in transpiration rates? 3) How have hemlock transpiration rates shifted due to defoliation caused by the introduction of the HWA over the past two decades?

2. Methods :

To investigate hemlock and black birch transpiration rates, I plan to use thermal dissipation sap flow sensors to quantify transpiration rates between black birches, healthy hemlocks, and hemlocks with a range of degrees of defoliation at the Harvard Forest in Petersham, MA. I will connect my collected data with eddy flux data from the hemlock stand and neighboring deciduous stands. I will also use historic sap flux data of growing season transpiration rates of black birches and hemlocks at the same site location before the introduction of the HWA to New England. The influence of transpiration on water storage is critical to understanding future changes in hydrological dynamics with forest succession.

2.1. Site Location

All samples are located in the Prospect Hill tract of the Harvard Forest Long-Term Ecological Research (LTER) site in Petersham, Massachusetts with an elevation of 340 m (Figure 1). At the Harvard Forest, all trees are located in the 35-hectare site of mapped and monitored aboveground biomass observing for species growth and transition since 2010 . Average temperature and precipitation during the growing season of 2019 (June-September) were 17.5°C and 98.4 mm with a regional average total annual precipitation of 1149mm. The site elevation was 340m.

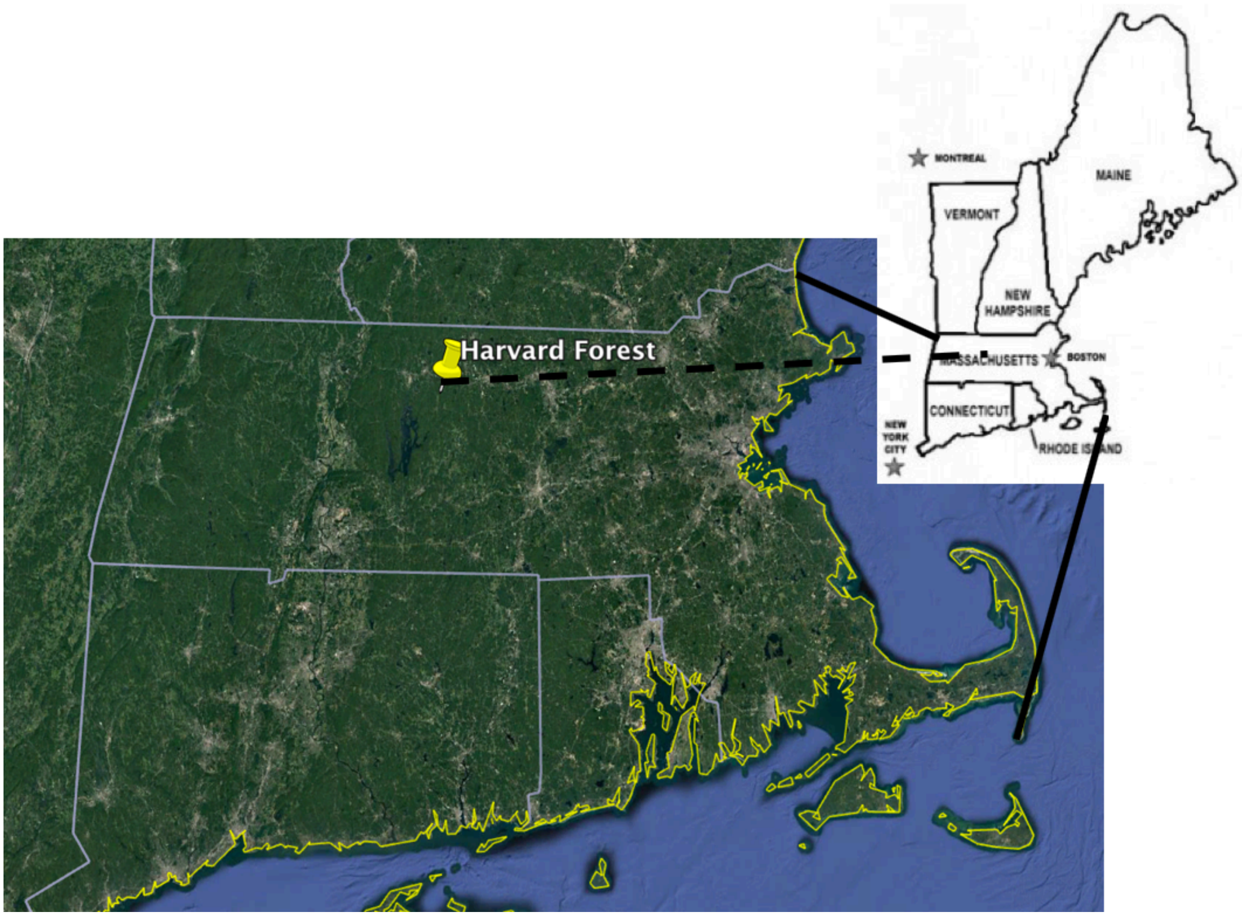


Figure 1. Map of Harvard Forest location in Petersham, Massachusetts in the northeast region of the united states

2.2.Sample Selection

Sampling will occur between the end of May to the beginning of October. Sap flow sensors were installed in the spring of 2019 to allow a healing period before taking measurements. Each tree contains one sensor installed northward in mid-April (2019) to allow for a healing period. Trees were selected in comparison with historical data of birch and hemlock[54]. Hemlock and birch samples were selected within approximately .6 km of the hemlock meteorological tower (Figure 2). Hemlocks were taken from an infected hemlock dominated old-growth stand and average DBH of 16.6 cm (Table 1)[55]. Birch samples were taken from an adjacent predominantly birch stand with an average DHB of 16.0 cm (Table 2). Hemlocks selected for sap flow measurements were taken from trees that were clearly infected by the HWA. Samples with minimal visible trunk scaring and straight vertical growth were selected to minimize unequal distribution of sapwood around the tree.

Table 1 Physical characteristics and measurements for hemlock samples

ID_Number	Species	DBH (cm)	Height (cm)	HII
1	Hemlock	66	20.4	3
2	Hemlock	78.8	14.15	4
3	Hemlock	65	12.4	2
4	Hemlock	70.3	12.95	4
5	Hemlock	80.3	16.8	4
6	Hemlock	75.8	11.8	2
7	Hemlock	95.9	16	1
8	Hemlock	63	17.8	1
9	Hemlock	77.8	20.4	3
10	Hemlock	78.2	16.8	4
11	Hemlock	90.4	22.5	2
12	Hemlock	80.6	16.75	3
13	Hemlock	117.5	12.05	3

Table 2 Physical characteristics and measurements for birch samples

ID Number	Species	DBH (cm)	Height (cm)
0	Black Birch	75.7	15.6
1	Black Birch	94.4	22.95
2	Black Birch	54.6	16
3	Black Birch	58.2	17.7
4	Black Birch	72.5	16.95
5	Black Birch	53.1	14.2
6	Black Birch	53.4	12.55
7	Black Birch	41.6	14.05
8	Black Birch	46.5	13.4
9	Black Birch	42.3	15.6
10	Black Birch	55.9	14.15
11	Black Birch	57.6	23.1
12	Black Birch	49.5	15.95
13	Black Birch	67.8	15.1
14	Black Birch	50.5	12.05

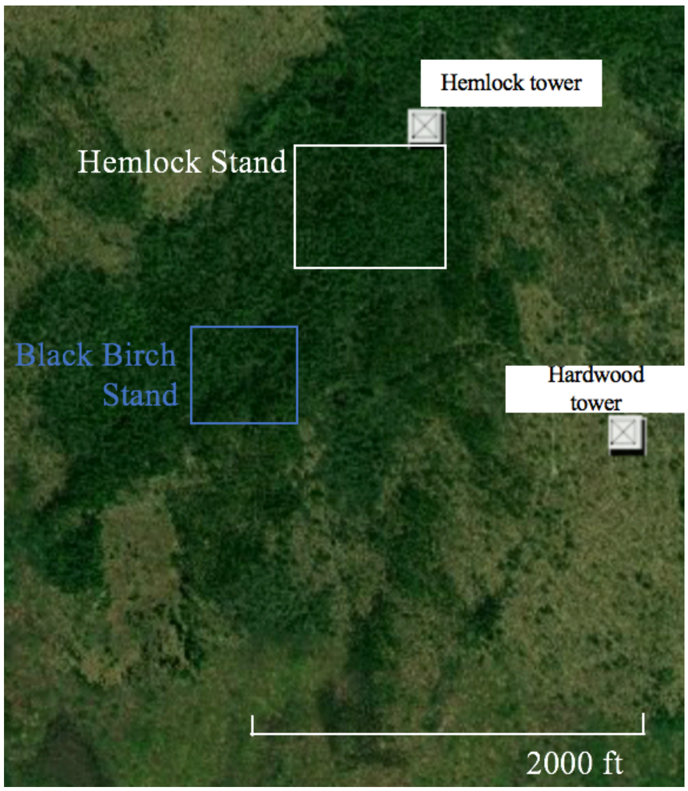
2.3. Species characteristics:

2.3.1. Eastern Hemlock

Hemlocks are coniferous species which transpire year round [54,56,57]. Hemlock forests thrive along stream banks and wetlands, and play a major role in stream bank structure[54]. Hemlocks have a high shade tolerance and dense layered canopy structures with low throughfall rates[58,59]. Late successional hemlock stands have very little understory growth due to a high, annually consistent, leaf area index (LAI). Hemlocks have higher stomatal sensitivity and control over xylem water transport, through their coniferous woody tissue, depending on water availability relative to other species in New England forests[60]. Mature hemlock stands are typically comprised of trees approximately 200-350 years old[61]. Mature hemlocks are traditionally trees greater than 160 years old[61]. The infestation of the HWA increases canopy gaps and throughfall and decreases LAI allowing for more light penetration [58,62]. Hemlock stand

LAI has declined with the introduction of the HWA (Figure 3). Infestation by the HWA leads to death of trees within 4-17 years[63].-Hemlocks were assessed and classified under the HII to compare water use between hemlocks with varying canopy cover [64].

Figure 2 Hemlock and black birch sample locations and hemlock (42.539N 72.180W)



and hardwood (42.535N 72.174W) eddy flux towers at the Harvard Forest

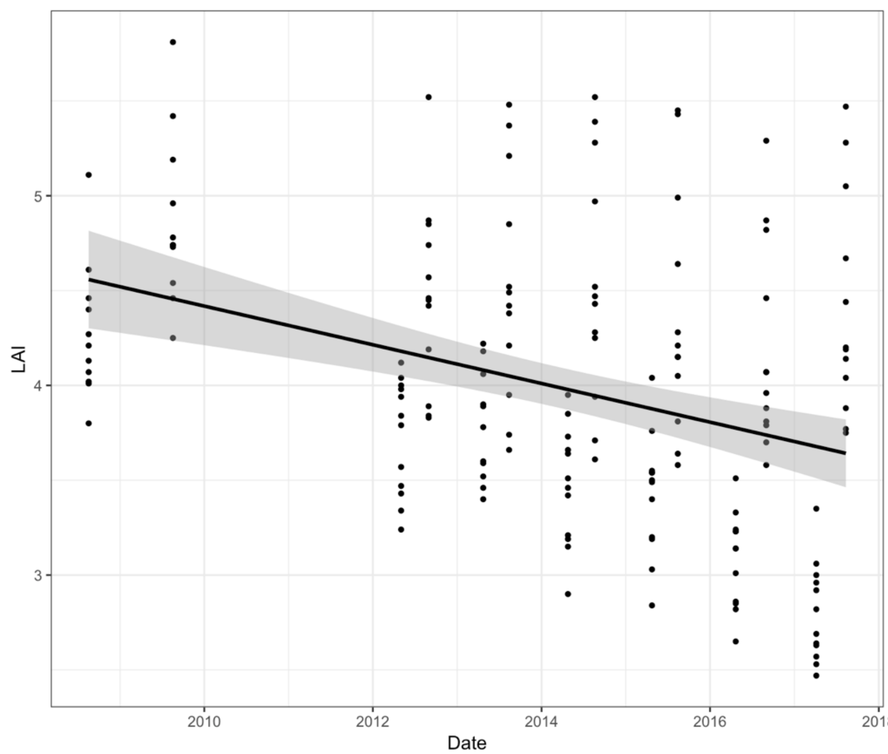


Figure 3. LAI data collected along four cardinal locations on transects out from the hemlock eddy flux tower with annual seasonal variation between the dormant and growing seasons.

2.3.2. Black Birch

Stand succession is leading to increased dominance of black birch. Birch have dense seeding and growth patterns dominating canopy gaps from fallen hemlocks[65]. Birches thrive in well drained soils, but are frequently dominated in forests with excessively dry soils[66]. They can grow successfully at a variety of elevations[66]. Birch are classified as a pioneer species because of their rapid growth, high light demand, and small life span relative to other New England species of 40-200 years, but in unmanaged systems lose dominance after 40 to 50 years [62,66–68]. Birches have diffuse-porous woody tissue and higher hydraulic conductivity allowing for trees to use more water throughout the growing season without as much influence from meteorological factors (VPD, soil moisture, temperature)[54,60,69]. Differences in stomatal conductivity and physical parameters of the different woody tissues are potential explanations for the differences in water use during the growing season to optimize productivity before senescence [54,60,70]. Birches, like other broad-leaf species have increased water demand and atmospheric release, as indicated through sap flow, from May to September during the bud out and growing seasons, and minimal water use during the dormant season[56]. During the growing season, birch still have a smaller LAI than hemlocks. This combined with the annual leaf loss causes significant seasonal changes in LAI giving light and space for denser understory vegetation[57,58].

2.4. Sap Flow Measurements

Sap flow measurements will be conducted using a constant heating method to measure water velocity conducted through sap wood xylem[71,72]. Heat dissipation methods allow for the scaling up of tree water use to represent whole canopy transpiration values[73]. I constructed sap flow probes designed by Oregon State University OPEnS Lab with Arduino datalogging system and custom probe sensors that use the thermal dissipation method (TDM) to measure sap flow velocity (Figure 4)[72,74]. Each probe consists of a 3 mm diameter custom printed PCB board coated in thermal epoxy for an even measurement across the probe and a thermistor; the lower probe had a resistor providing the 3.3V heat pulse which was measured by both probes. Probes have been installed 30 mm deep in the sapwood. The probes were fastened 10 mm apart vertically in the tree and installed northward to avoid sun interferance[71]. Via the Granier method of TDP, sap flow rates will be collected by continuous heat release over a 10 second period every 30 minutes to estimate diurnal and seasonal variation between species.

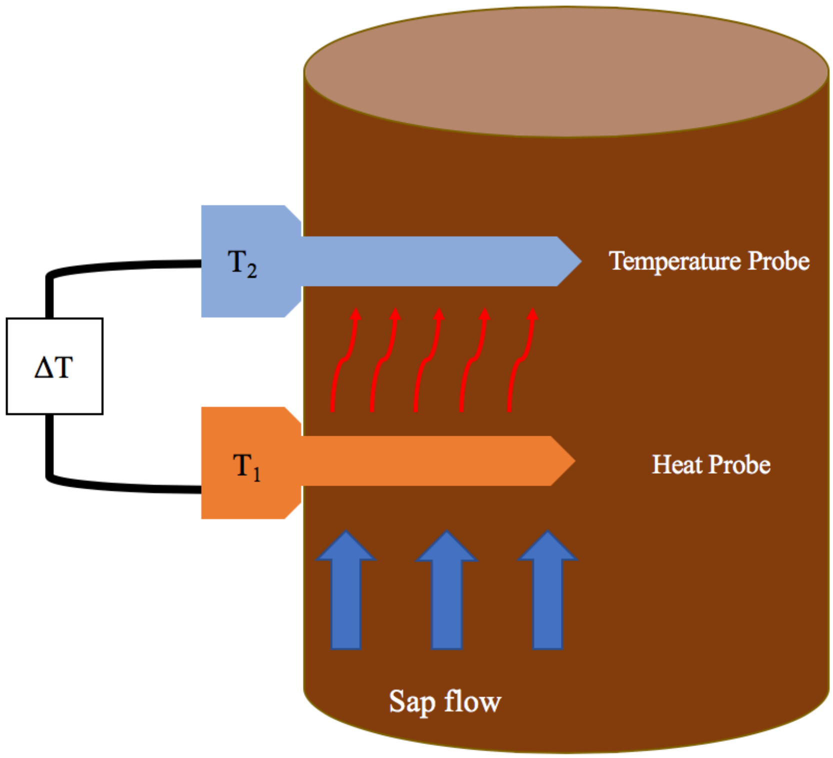


Figure 4. Thermal dissipation probe schematic

Each probe set is connected to a Adafruit feather circuit board data logger composed of a Adafruit Basic M0, an Adalogger featherwing datalogger with a real time clock (RTC) (Adafruit Industries), 8-GB storage card, and an individual battery source allowing for more space between samples. Data will be collected from May through October or until senescence.

The maximum temperature (T_m) (K) was measured when xylem water potential was highest and vapor pressure was lowest to calibrate sap flow to account for wood characteristics. Sap flow was calculated using the specific heat capacity of water C_w (4186.8 J K-1kg-1), sap wood area, and temperature maximum, the measured difference in temperature (ΔT) for each measurement (Equation 1).

$$F = 0.4284\, S_a \left(\frac{T_m - \Delta T)}{\Delta T}\right)^{1.231}$$

Equation 1. Calculation for measuring sap flow (F).

I did not account for inactive xylem or uneven distribution of water uptake around the diameter causing two potential sources of error[75]. Using a medium length probe allows for a depth falling between standard Black Birch and Eastern Hemlock sapwood depths while also minimizing error caused by not using longer probes than necessary[76] Errors in TDP deployment have the potential to create the more predominant sources of error leading to the under estimation of high flux rates relative to eddy covariance predictions using latent heat fluxes due to failure to account for non-zero nocturnal water uptake, failure to scale measurements for the region of study, and failing to account for other and all components of evapotranspiration rather than solely transpiration through sap flow[77].

2.5.Historic Data Collection Methods

The sampling location was selected to follow up on two studies; the first of which was conducted in 1999 and the second in 2005[54,56]. Both used sap flow sensors on species in the Harvard Forest Prospect Hill Tract which includes uninfected hemlocks and developed birches. The study conducted in this area in 1999 compared hemlock sap flow to deciduous species[57]. They measured sap flow using the TDM. The documented water use by hemlock allows for a baseline visualization of water fluxes due to transpiration at the Harvard Forest.

The 2005 sampling also used TDM collected data from 8 healthy hemlocks (DBH average of 54.1cm and sapwood depth of 6.8 cm) and 8 developed birches (average DBH of 26.4 cm and sapwood depth of 8.1 cm). In this study, all trees were located less than 20m from the hemlock stand eddy flux tower. Circumferential differences were accounted for by installing at least two sensors in each tree to avoid errors in overestimations caused by scaling assumptions in the sap wood and protected from direct solar heat. They recorded continuous heat supply using the Grainer method.

2.6.Meteorological Data

All hemlock samples are within a 50m radius of the eddy flux tower within the hemlock stand containing historical meteorological changes in the nearby landscape -- 30m in height, recording temperature, precipitation, humidity, CO_2 fluxes, photosynthetically active radiation (PAR), latent heat flux, windspeed, and soil temperature[78]. The comparison between eddy flux modeled evaporation and transpiration rates to measured sap flow provides a general reference to the errors of stand water loss as vapor[77].

Meteorological data will be compared to the historical data measurements which coincided with previous sap flow measurements. The eddy flux measurements of canopy conductance and vapor pressure deficit (VPD) were also compared to a nearby, eddy flux tower within a deciduous canopy. This allows for a comparative analysis of differences in water use at the same time between the two tree species. I will also use meteorological data from the eddy flux towers to determine potential evapotranspiration (PET) using the Penman-Monteith equation (Equation 2)[79]**.** Estimating PET using dew point, relative humidity, solar radiation, and wind speed will be used to compare maximum water loss through transpiration between the systems.

$$ET_o = \frac{\Delta(R_n - G) + \rho_\alpha c_p(\delta e)g_\alpha}{\left(\Delta + \gamma\left(1 + \frac{g_\alpha}{g_s}\right)\right)L_v}$$

Equation 2. Penman-Monteith equation for PET (variable definitions in Appendix A)

Precipitation, soil moisture, VPD, air temperature, and canopy conductance between 2005 and 2019 will be used to account for differences in water use of both hemlocks and deciduous forests based of due to water availability and potential evapotranspiration rates allowing for a more precise representation of the differences in sap flow over the different measurement periods. Transpiration is one variable of the local water cycle, but including other meteorological data allows for developing a complete water budget between the measurement periods. Completing a whole budget allows for a more complete narrative of tree water demand and accurately depicts the difference in hemlock water use and canopy conductance due to the HWA.

2.7.Data analysis

Three different forms of comparative analysis will be conducted: hemlocks by HII, hemlocks and birches, and hemlock sap flow from the three time periods. The first will analyze the impact of HWA on hemlock transpiration as indicated by collected sap flow data. The second analytical comparison will be between hemlock and black birch sap flow over the growing season. The third form of analysis that I would like to compare my measured hemlock sap flow to the hemlock transpiration measurements from 1999 and 2005.

I will compare the greater weather data trends over the period of data collection. Figures of air temperature, soil temperature, precipitation, and soil moisture all provide a visual understanding of the climate trends of the Harvard forest and an ability to comment on any weather anomalies like droughts or especially dry seasons, wet seasons, floods, or other potential climatic impacts on transpiration rates.

2.8.Comparing hemlock transpiration by HII

The goal of comparing hemlock water use by different degrees of infestation is to investigate if defoliation changes water use in hemlocks. If hemlocks change water demand with defoliation, then as HWA predation persists, transpiration begins to shift as the stand regenerates with new, deciduous species. The reason for differentiating interspecies hemlock sap flow by each of the HII classifications is to determine if there is a significant difference among groups with varying defoliation. Plotting sap flow by HII over time in comparison to precipitation and cumulative sap flow over time will show not only if there is a difference between hemlocks based on percent defoliation, but also any potential variations over time and the total seasonal differences between HII.

2.9. Hemlock versus birch sap flow rates

The methods for quantitatively and visually comparing hemlock to birch will be similar to how I plan to analyze hemlock by HII. However, I will only compare two things unless there are significant differences in hemlock sap flow between HII groups. If this is true, in I would compare slightly defoliates (<50%) hemlocks, very defoliated (>50%) hemlocks, and black birches. Through statistical analysis and data visualization of transpiration rates and cumulative transpiration over time will show any potential difference in water use between the two species over the growing season.

Along with comparing sap flow measurements, I will also use modeled transpiration rates from the hemlock and deciduous eddy flux towers to determine any differences between the two forest types. Birch transpiration on a tree level is more representative of the birch communities. However, hemlock turnover will create space for birch along with other deciduous species. Estimated whole deciduous transpiration is another accurate representation of how hemlock and birch dominated deciduous forests will differ in water use.

2.10 Historical analysis of hemlock transpiration and water fluxes

Comparing my measured hemlock and black birch transpiration rates to measurements from 2005 and 1999 is more complex than solely investigating two species. This would include a comparison of the three sap flow measurements, but also calculated PET, VPD, temperature, and humidity. All sap flow measurements will need to be corrected by water availability over the season to prevent any limitations of water or other meteorological variables that would cause limitations on overall water release. Meteorological variables such as temperature, precipitation and water availability, humidity, latent heat energy, PAR, etc. all influence the physical parameters that influence transpiration. Comparing VPD, and other meteorological variables, over the tree years can act as an explanation for variations in transpiration. Using VPD to determine atmospheric moisture is used as an indicator of plant water use and will also be a critical variable in making data between the different years comparable. PET, in comparison to actual transpiration or evapotranspiration, also accounts for potential interannual variations.

Analyzing differences in hemlock and birch transpiration between the years along with temperature, precipitation, hemlock and deciduous eddy flux tower evapotranspiration, VPD, and

PET allows for the most complete depiction of hemlock water use has changed due to the HWA. Comparing birch also provides two growing season measurements of birch to compare birch and hemlock water use.

Table 3 A breakdown of data sources and how they will be integrated into my analysis

Data Available for Analysis	Data access location	Which analysis it is used for
HII	Collected in the field through visual assessment of canopy health	Hemlock by HII
Hemlock sap flow	Collected in the field with sap flow sensors	Hemlock by HII; Hemlock v birch; Historical water use
Birch sap flow	Collected in the field with sap flow sensors	Hemlock v birch; Historical water use
2005 hemlock transpiration	Harvard Forest data archive	Historical water use
2005 birch transpiration	Harvard Forest data archive	Historical water use
1999 hemlock transpiration	Harvard Forest data archive	Historical water use
Air temperature	Hemlock tower	Hemlock v birch; Historical water use
Precipitation	Hemlock & deciduous tower	Hemlock v birch; Historical water use
VPD	Hemlock & deciduous tower	Historical water use
Soil Moisture	Hemlock & deciduous tower	Historical water use
PET	Calculated hemlock and deciduous	Historical water use

3. Predicted Outcomes:

The input of water into the system through precipitation has a major effect on the transpiration. A comparison of ET to PET depicts the system water yield signifying water available for groundwater recharge and stream flow[79]. ET is lower than PET, but a greater difference in PET to ET also indicates less ET due to other biotic factors: primarily foliage loss. The data collected from this study will show how the HWA has changed transpiration rates of old-growth hemlock stands. More broadly, these results will help us document how the water budget of these forests will be altered by climate change, and more specifically how the potential increase in invasive pests due to climate change with create more dramatic changes in forest structure and water cycling.

Although I have not collected sap flow results to compare hemlocks by HII, hemlocks and birches, and sap flow data from both species to measurements in 1999 and 2005, I still have information on the species selected for my study, historical meteorological data, changes HWA populations and the impacts on hemlock, and changes in hemlock LAI (Table 3).

3.1. Current Data

Currently, I have collected physical characteristics of the hemlock and birch which will be used in this study including DBH, HII, and height. I have also analyzed publicly accessible data on the increased presence of the HWA, hemlock LAI decline, and meteorological data since 1999.

Predation because of the HWA has led to decreased foliar coverage on both a canopy and tree level in hemlock dominant stands. A survey conducted by Foster and Barker-Plotkin randomly selected hemlocks within the stand in 1999 showed over 300 trees with a HII of 1, but a repeated study of those trees in 2016 showed less than 50 with a HII of 1 and over 200 with a HII of 5[64,80]. Decreased foliage cover of hemlocks is indicative of decreased water use by hemlocks with increased impacts of HWA infestation.

3.2. Meteorological and Hydrological Data

An overview of the general meteorological data shows changes in air temperature, humidity, VPD, deciduous measured transpiration, hemlock transpiration, and precipitation. Plotting data from weather towers also allows for a comment on any anomalies during the growing season that may influence the transpiration measurements.

3.3. Foliage decline and hemlock transpiration

The goal of comparing hemlocks by HII is to determine if defoliation impacts hemlock water use and if there are changes in water transpiration with increased HWA infestation. Assuming that foliage is directly connected to water demand and transpiration, I would expect to find decreased transpiration by hemlocks based on their HII classification of percent defoliation. If the results support my hypothesis, I would expect that analyzing differences in mean sap flow by HII classification will show how predation by the HWA has decreased hemlock water use. To visualize this data once collected, I will plot sap flow over time with the mean sap flow of each HII subgroup (1-4). I will also compare cumulative transpiration over the growing season for each subgroup.

After visualizing the data, I will conduct a statistical comparison of the multiple subgroups looking for differences. However, because there are few samples for each of the subgroups from the overall sample size (1: n=2, 2: n= 3, 3: n=3, 4:n=4), I would also run a t-test to compare species with less than 50% foliar loss and species with greater than 50% foliar loss. The benefit of this is that I am more likely to find differences between the two HII groups if there is one because of a larger sample size. Even still, characterizing subgroups by HII allows for understanding how the HWA is impacting hemlock water use.

3.4. Hemlock and black birch seasonal water use

Hemlocks and birches have different transpiration during the growing season because of their leaf structure and physiological shifts during the growing season. Birch develops hard wood and produces the majority of its new growth during the growing season and does not transpire or grow during the dormant season. Hemlock, although more active during the growing season due to increased sunlight, has fairly consistent water use year round because of its coniferous nature[54,54,56].

The sap flow data I plan to collect will be plot both sap flow over time and cumulative sap flow over the growing season between the two species with hemlock sap flow between all samples. This data would also be compared to precipitation and temperature data to look at see if there are connections between weather events and transpiration rates to eliminate potential meteorological anomalies relative historical trends (drought, heavy rain events, high or low temperature periods) in the sap flow data.

To compare hemlock water use to black birch statistically, I plan to conduct a comparative statistical analysis to quantify the difference between the two species. I also plan to conduct a multi-variate analysis of severely infested hemlocks, healthy hemlocks, and black birch in my study. The differences between the two characterized hemlocks and black birch signify how water yield may vary based off of increased water vapor leaving the system during the growing season. The growing season is also a time of increased evaporation while precipitation patterns stay fairly constant in region annual.

Field measurements of transpiration on a tree scale estimate single species transpiration rates while modeled evapotranspiration from meteorological data show whole canopy water use. With this, I also hope to compare hemlock and birch sap flow means to evapotranspiration rates measured from eddy flux towers in the hemlock and a neighboring deciduous stand. The dense canopy cover of hemlocks minimizes evaporation, but gaps in the canopy of birch forests indicate greater evaporation rates while transpiration rates have high seasonal variation and, as published by previous studies, have greater annual water demand. Presenting results of tree level transpiration and canopy transpiration show two different ways of measuring transpiration and allows for two potential ways that hemlock and birch or deciduous forests differ in water use.

In answering my questions on potential differences and magnitudes of water use between species provides information on how forest transition will influence the hydrological cycle of these stands.

3.5. Historical data comparison of stand water use

The historical data available on the Harvard Forest's public data archive has transpiration rates from sap flow from sensors installed in the four cardinal directions of hemlock samples from December 1997 through September 1998. Catovsky et al.'s results state that water loss via transpiration was approximately 18.8 mol $m^{-2}d^{-1}$.[9] However, there was not set mean water transpired over the growing season. Hemlocks did show significantly less water loss, photosynthesis, and overall production than the other species (red oaks and red maples). These species are not equivalent to black birch, but do show that deciduous species have higher water use over the growing season.

Data from the Daley et al. study compared hemlocks and black birches more closely, and found that the water use by black birches is significantly greater than that of hemlocks over the growing season (which is documented at approximately Julian Day 179-290).[13] The recorded black birch group mean transpiration was 2.23 mm. Hemlock mean sap flow over the growing season transpiration was 1.25mm. The cumulative transpiration on black birches was recorded to be 77 mm higher than hemlocks. I will also compare the historic sap flow data with historical meteorological data including air temperature, precipitation, VPD, canopy conductance, and evapotranspiration rates. [9,13]

Once I have collected sap flow data over the growing season with my sensors, I hope to compare and present potential variations over the three years. I will use meteorological data from the two historical datasets and the year which I collect sap flow data to compare water availability and potential variables that influence transpiration. I will also use the meteorological data to approximate PET of the hemlock stand which has been consistently used across the three studies as another form of comparing hemlock transpiration rates.

Based on my hypothesis that the water use in trees would decrease at a factor of LAI due to decreased foliage (higher HII) from the HWA. Because the two historical studies were conducted before the HWA was found at the Harvard Forest, variations in sap flow rates, once accounting for other influences on tree water use, could potentially be connected to the HWA's infestation of hemlock stands.

4. **Implications:**

The succession of old-growth hemlock forests to stands being dominated with black birch has the potential to rapidly change the hydrologic structure of the forest. This study focuses on the importance of any hydrological on hemlock stand caused by the introduction of the HWA. And, in connection to my hypothesis and the literature, how the increased population in black birch will continue to influence water use.

As forests transition from hemlock to birch, water use may potentially decline due to the HWA. And, theoretically the addition of birches will increase overall water over the growing season and use no water during the dormant season.

In New England, total precipitation remains constant over a year. However, longer days, increased temperature, and increased PAR implies that more water is lost to evapotranspiration during the summer. Before the ecosystem adjusts to a deciduous dominant forest, birches theoretically have the potential to have a net loss of water within the stand over the growing season, exporting more water through transpiration than in entering the system. Significant differences in the overall volume of water use and temporal variability over the growing season would mean that less water would be available for stream discharge and ground water recharge. The combination of changes in transpiration and meteorological changes in summer months enhance the importance of understanding how these two species are interacting with the forest water budget.

Modeling out patterns of transpiration in combination with meteorological data can predict changes on other aspects of the water cycle within a theoretical stand. Combining my collected data with historical transpiration rates allow two time steps of transpiration: pre- and post- HWA infestation. Literature has modeled temporal changes in species composition as the presence of the HWA persists. Combining species composition models with transpiration measurements and eddy flux towers may allow an accurate portrayal of how and at what speed the hydrological change.

Understanding how water moves and is stored within an infested hemlock stand is critical to comprehending the future of water availability. The rate that water demand changes may also have permanent implications on ecosystem services: flood prevention, erosion control, terrestrial and aquatic diversity and biogeochemical cycling.

Changes from hemlock to birch stands will likely impact flood mitigation, stream ecology, and transportation of water to the atmosphere. The impacts of the HWA may have permanent impact on water use within forested systems through changing runoff, groundwater recharge, understory temperature and light availability, and stream ecology. Looking forward, as hemlock populations decline, it is important to include changes in the hydrologic cycle in management plans and assessments of ecosystem services.

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Appendix A: Penman-Monteith Equation Variables:

Definitions of variables used in the Penman-Monteith Equation.[34]

Abbreviation	Variable	Constant Value/ Unit
λ_v	Latent heat of vaporization	Jg^{-1}
L_v	Volumetric latent heat of vaporization	2453MJ m^{-3}
E	Mass of water evapotranspiration rate	g s^{-1} m^{-2}
ET_o	Water volume evapotranspired	mm s^{-1}
Δ	Rate of change of saturation specific humidity with air temperature	PaK^{-1}
R_n	Net irradiance	W m^{-2}
G	Ground heat flux	W m^{-2}
c_p	Specific heat capacity of air	J kg^{-1} K^{-1}
ρ_a	Dry air density	Kg m^{-3}
δe	Vapor pressure deficit (VPD)	Pa
g_a	Atmospheric conductance	m s^{-1}
g_s	Surface conductivity	m s^{-1}
γ	Psychrometric constant	$\approx$ 66 Pa K^{-1}
PET	Potential evapotranspiration	mm s^{-1}

Chapter 5 Conclusion

1. Summary of DIV III Research Projects:

I hold a lot of pride in the work I have produced and the knowledge I have gained throughout my Division III. I developed two advanced research questions that add to the literature in their respective sub-fields of forest hydrology and contribute to the greater understanding of forest-water interactions on both a global and local scale. I integrated knowledge that I developed over my time at Hampshire College: developing research questions, scientific communication, and writing, group work, developing boundaries between my work and non-work time.

1.1. Global forest cover, wind speed, and precipitation

I have gone through the complete scientific research process through my investigations of global forest cover, wind speed, and precipitation interactions on a global level. This has allowed me to learn a variety of skills so that I can start to build a career in scientific research. Starting with being able to reach out to other experts in my field and getting to dive into a plentiful research topic, I followed this research project from start to finish. My co-author, David Ellison, and I are hoping to submit our manuscript to a peer-reviewed journal in the spring.

Our major question driving this research was: how does forest cover impact wind speed, and what does that mean for water cycling on a global scale? We hypothesize that areas, especially continuous areas of forest cover slow windspeed increasing precipitation over an area.

To test this, I conducted a spatial analysis of global forest cover and meteorological data of wind speed and precipitation divided into latitudinal subsections by Hadley cells. Of these three variables, regions of high forest cover that neighbor other areas of high forest cover have similar relationships between forest cover, wind speed, and precipitation indicating that larger intact forest areas slow wind speed and influence on precipitation recycling (potentially maximizing precipitation recycling within regions with high forest cover and slow wind speed).

Our results support our hypothesis that forest cover slows winds allowing more time for precipitation recycling within a given pixel, watershed, or local area. We found that areas with high forest cover correlate with slower wind speeds and higher precipitation rates on an annual base within a single area. Therefore, less forest cover indicates decreased rainfall. Some literature theorizes that transpiration and water use create a vacuum, increasing wind speed, and pulling in more water from ocean systems over a landscape increasing precipitation, this is known as the biotic pump theory (BPT). The results of our work show that the water vapor provided by forest systems slow winds allowing for more precipitation contradicting the BPT. This could be for a variety of variables: forest canopy topography increased air weight from water vapor (caused by ET), or potentially other biotic or abiotic factors.

1.3. Hemlock, Black Birch, and Sap Flow

My work with David Ellison pushed me to develop a greater understanding of the global relationships among forest-water interactions. However, I also wanted to learn about local water cycling. Rather than using computer work and mapping, I designed a second project that included learning methods of measuring transpiration rates on an individual tree level, building sap flow sensors and doing a comparative analysis of historical data.

Literature on hemlock, black birch, and transpiration has informed that my hypothesis that hemlocks, when defoliated by the hemlock woolly adelgid, decrease their transpiration, allow gaps in the canopy for increased evaporation, and give space for new species in forest succession from old-growth forests to first successional species: black birch. A study published in 2007 quantified significant differences in water use by healthy hemlocks and black birches in the same region of the Harvard Forest.[1] I hope that the results from my research add to the understanding of the differences of water use by healthy hemlocks, severely infested hemlocks, and regrowth black birches indicating that as hemlock stands decline, water demand will change and the growth of black birches may potentially be more impactful to the greater water yield of the system. This could influence groundwater recharge and streamflow. This in combination with other literature's indications of changes in soil chemistry, stream ecology and stand species composition raises apprehension for the overall impacts of the hemlock woolly adelgid on New England forest systems.[2–5]

Because I was unable to execute my fieldwork due to technical difficulties, I relearned the age-old lesson that science does not work on the timeline that one initially anticipates. Even still, I was able to gain practice in analyzing some data and discussing the implications of my results I would have collected data. Even still, I hope to continue this work after my time at Hampshire. I have communicated with people at the Harvard Forest, where I planned to do this research, and they all expressed the need for information about infected hemlock water use and changes in old-growth stand forest water dynamics. The greater impacts of these potential findings may raise concern for the future of water availability and changes in ecosystem functions. Changes in water access influence both terrestrial and aquatic ecosystems and human communities by changing well water access in neighboring areas.

Building knowledge on water fluxes due to changes in forest structure on a local and global level have allowed me to develop different perspective in the field of forest hydrology. Individually, both of these projects have significance when contextualized in the larger unease of how climate change and shifts in land use will influence water availability for ecosystems and human use. Combining the knowledge, skills, and results from each of these studies to my greater interests have also shaped the overarching question of my Division III: how do climate change and land-use change shift water in forested ecosystems?

2. **Skills Gained During DIV III:**

My Division III experience was about more than completing research projects. I selected projects and other academic and extracurricular activities that would further expand upon the topic of forest hydrology. My Division II focused on building a foundation of knowledge in biogeochemistry, ecology, hydrology, and mathematical modeling. I also attempted to incorporate a personal education of the problematic nature of the sciences to better further my practices through anthropology and journalism and working with the Compassionate Knowledge Project.

During my Division III, to connect my previous academic experiences with my independent research projects, I took a graduate course at the University of Massachusetts, Amherst and I was a teaching assistant for an introductory ecology course at Hampshire College. I gave a class lecture for the ecology class that I was a teaching assistant for on plant physiology loosely based on my sap flow research along with other research conducted at the Harvard Forest. I presented my research on global forest, wind, water interactions at a Hampshire College School of Natural Science Fantastic Friday, the IUFRO World Congress in Curitiba, Brazil, and the Intact Forests in the 21st Century conference in Oxford, England[1].

In the courses I took during my year in Division III, I focused on building a deeper understanding of ecosystem-water interactions and exploring ways of educating about ecological function. In the first semester, the spring semester, of my thesis, I took GeoSci 691: Ecohydrology at UMass with Christine Hatch. The goal of this course was to examine the impact of plants on water storage and fluxes and then apply that to different ecosystems. We talked about methods for measuring surface and groundwater fluxes, how water moves throughout the critical zone, impacts of restoration on water flow, and current political conversations about water availability. I was able to get fieldwork experience in studying invertebrates and water chemistry in different ecosystems. We also gave student lead discussions. My discussion focused on evapotranspiration, methods for measuring, and ambiguities in current theories of plant water transport. This discussion pushed me to understand the history of sap flow measurements and sources of error. The class overall taught me about ways of calculating changes in water storage over space and time. I have learned a range of equations and methods for approximating water use that I have found useful in my own research an in interpreting primary literature.

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[1] See **Appendix A** or a summary of Division III Work: Conferences, talks, and guest lectures, collaborations, work locations, skills developed, grants, budgets, extracurriculars.

Being a teaching assistant for Blair McLaughlin's NS207: Ecology course at Hampshire College -- fall of 2019 -- allowed me to think about ecology from a perspective of educating rather than learning, similar to my work in facilitating a student lead discussion. I revisited my knowledge on the broad topic of ecology and I was able to critically look at class readings. Having the opportunity to rethink and expand upon the basics of my academic interests was well-timed and helped me solidify my skills in literary analysis. I prepared datasets for class lessons on statistical analysis and I played a role in teaching R Studio to students testing my own knowledge of R. Outside of R and digging deeper into my knowledge of ecology as a larger subject, the major skills I learned from this was how to explain topics in ecology to students and prompt them to discover the answers to their confusions about course work themselves. I have found a lot of joy and passion for being a teaching assistant and facilitating group discussions. Learning and building my skills in engaging students in conversations about course materials showed me how much I enjoy the education process and working with learners.

Leading discussions on forest-water interactions are one skill that I was able to work on over the past year, but I also practiced professional academic presentation. I gave an in-depth presentation of the background, methods, and results of my GIS research of forest cover, wind speed, and precipitation patterns at an NS Fantastic Friday. I simplified much of my work to make it more accessible to a larger audience of friends, professors, and peers. Because I had quite a lot of time to give this presentation, I was able to work on explaining the background and making my work accessible in order to present more complex interactions. I presented a much more refined summary of my work at the XXV IUFRO World Congress: Forest Research and Cooperation for Sustainable Development annual meeting in Curitiba, Brazil (fall of 2019). At the conference, I was limited to 15 minutes including time for questions. The brevity of this talk, a more formal setting, and an audience with an advanced understanding of this topic pushed me to show my experience in my research rather than focusing on making my presentation accessible to a wider audience. This conference was composed of academics, policymakers, activists, and community representatives from around the globe with the intention of sharing knowledge on the challenges and importance of understanding the importance of forests in the face of climate change. While at the conference, I made many connections to potential graduate programs and discussed scientific knowledge formally and in casual conversations.

Technical Skills developed:

- ArcGIS
- R Studio
- Statistical Analysis
- Literature Review
- Electronics construction/ Arduino
- Data Analysis
- Scientific Writing
- Presenting Scientific Research

This experience was similar to a conference I presented a poster at in the summer of 2018 as a part of my Division II research. At the Intact Forests in the 21st Century conference in Oxford, England I presented a preliminary study of forest cover, wind speed, and precipitation interactions. This conference was much smaller but allowed me to add and refine the questions driving my research. I began developing skills in a professional environment and worked on my scientific communication to an audience with advanced knowledge in forest functions.

3. **Personal Impacts of DIV III:**

Beginning my Division III, I had experience with field work, mapping research, data analysis, scientific communication, and working with scientists. The semester before I began my thesis, I was working at the Semester in Environmental Science at the Marine Biological

Laboratory. That experience was a lot of intense interactions with older climate scientists with more conservative/ less informed social views (specifically about gender in the field of ecology), and the majority of the education was from lectures and labs. The curriculum lacked space for the sort of critical thinking that Hampshire College had given me. I went into the 2019 spring semester with enthusiasm and drive to make the most of my academic independence. I was able to apply many of the skills developed throughout my Division II into my Division III work.

My research and experiences during the past year of my undergraduate education working on independent research, challenging myself with advanced classroom positions, presenting at conferences, and engaging with the Hampshire community as a leader (a resident advisor, signer and club leader, active leader for the student co-operative, and engaging in campus programming) has allowed me to see a clear career trajectory. I have learned that I love primary research, specifically fieldwork, and education. The challenges of asking and attempting to answer complex questions about the natural world are fascinating. I find joy and passion in that work, and see forest hydrology research as a constant puzzle. Water transportation is a challenge to map. Variables change over time depending on an overabundance of variables. The complexities and constant change of water in forest systems fascinates me and keeps me engaged in the subject. I want to play a role in discovering and mapping that dynamic puzzle. I also think the knowledge I learned through my research should be shared. Between having passionate and supportive faculty throughout my education and finding satisfaction and energy when supporting students in understanding topics of environmental science, I believe that I want a career in science education. Most likely forest hydrology, ecology, or plant physiology. I would also like to continue doing scientific research, predominantly based in field work which can then be applied to models and projecting changes in water fluxes over time.

My plan after Hampshire, which I have begun, is to find graduate programs in forest hydrology. I have been fortunate to develop a specific field of study at Hampshire that exists for masters and doctorate programs. Because I narrowed my field quickly during my time at Hampshire College, I have developed proficiencies in mathematical modeling and natural science that provide me with a knowledge of a variety of topics and skills developing methodologies and communicating results. I am currently searching for doctorate programs in my field in hopes of pursuing a lifeline career in scientific research and education. My research projects for my division III work, which some have referred to as a "mini masters" has given me the tools to execute my research and has shown me the challenges, benefits, and satisfaction of ecological research. I look forward to applying my education at Hampshire College to my future in forest hydrology.

I have not finished my research projects from my Division III. As I apply for graduate programs, I am planning on finishing my two projects. I hope to continue with my research on hemlocks and black birches by getting my data loggers to work and collect data over the growing season in 2020. I also plan on continuing my work with forest, wind, and water interactions by incorporating a few more meteorological models of windspeeds over oceans, potential evapotranspiration (PET), and terrestrial wind speed at 100m to our analysis to better defend our findings. David Ellison and I will also be moving forward with our manuscript in hopes of submitting it to a peer-review journal in 2020. I hope to continue developing skills in data collection and analysis along with completing the process of publishing an article.

Appendix A: Summary of DIV III Work

Conferences, Talks, & Guest Lectures:

- Intact Forests in the 21st Century; Oxford, England (Summer 2018)
- Fantastic Friday presentation of wind, forest, water nexus (Spring 2019)
- IUFRO World Congress; Curitiba, Brazil (Fall 2019)
- Guest Lecture: Plant Physiology and the Harvard Forest (Fall 2019)
- Winter Graduation Division III symposium (Fall 2019)

Collaborations:

- David Ellison (Swedish University of Agricultural Science)
- David Owing (Harvard Forest)
- Tim Rademacher (Harvard Forest, Harvard University, and University of Arizona)
- OpenSensing Lab (Oregon State University)

Work Locations:

- Hampshire College
  - Jerome Lemelson Center for Design: Electronics
  - Cole Science Center: Collaborative Modeling Center
- Harvard Forest (field and office work)

Skills developed:

- ArcGIS
  - Spatial Statistical Analysis

- R Studio
- Statistical Analysis
- Annotated Bib. / Lit review
- Electronics construction
    - Soldering
    - Arduino Programming

Grants:

- Dr. Lucy Fund (2018)
    - Sap flow sensor materials
- Samuel Morris Sustainability Endowment Fund (2018)
    - Sap flow sensor materials
- Ray and Lorna Coppinger Endowment Grant (2019)
    - Sap flow sensor materials
- Presidents Grant (2019)
    - Sap flow sensor materials
- Hampshire College School of Natural Science Endowed Funds (2019)
    - Sap flow sensor materials
- Roddenberry Grant (2019)
    - Summer Housing at the Harvard Forest
- Sherman Fairchild Grant (2017)
    - Initially for summer research on reforestation, but also used for **conference travel** funding

Budgets:

- **Funding Schedule and Use**

Date Ordered	Money Spent	Vendor	Funding Source	Total Funding Remaining
Fall 2018	1600		NS Endowed	1600
28-Feb	-262.15	Digikey	Dr. Lucy	1337.85
28-Feb	-538.8	Adafruit	Dr. Lucy & Sam Morris	799.05
28-Feb	-120.87	Pololu	Sam Morris	678.18
6-Mar	-214.8	Adafruit	Sam Morris	463.38
6-Mar	-52.23	Sparkfun	Sam Morris	411.15
5-Mar	-217.5	OSH Park	Presidents	193.65
29-Mar	-229.5	Adafruit	Coppinger	-35.85
8-Apr	-81.53	Amazon	Coppinger	-117.38
8-Apr	-101.5	OSH Park	Presidents	-218.88
9-Apr	-319.87	DigiKey	Coppinger	-538.75
9-Apr	3060		Coppinger	2521.25
10-Apr	300		NS Endowed	2821.25
22-Apr	-1395	Amazon	Coppinger	1426.25
22-Apr	-1048.5	Adafruit	Coppinger	377.75
22-Apr	-7.99	Amazon	Presidents	369.76
24-Apr	3000		Roddenbery	3369.76
11-Jun	-19.08	Amazon	NS Endowed	3350.68
11-Jun	-4.99	Amazon	NS Endowed	3345.69

11-Jun	-24.79	Amazon	NS Endowed	3320.9
17-Jun	-20.71	Adafruilt	Coppinger	3300.19
Jun-Aug	-1750	Harvard Forest	Roddenbery	1550.19
Jun-Aug	-455	Food	Roddenbery	1095.19
Jun-Aug	-1200	Travel	Roddenbery	-104.81

- **Sensor Budget**

ITEM	Vendor	Quantity (per Sensor)	Estimated Cost (per sensor)	Estimated Cost (per sensor)	Total Quantity (30 sensors)	Estimated Cost (30 Sensors)	Actual Cost (30 sensors)
Resistor	Digikey	2	$ 0.46	$ 0.92	60	$ 55.20	$ 65.54
Thermistor	Digikey	4	$ 0.37	$ 1.48	120	$ 177.60	$ 65.54
Heater Resistor	Digikey	3	$ 2.29	$ 6.87	90	$ 206.10	$ 65.54
Encapsulating Epoxy	Digikey	0.1	$ 16.80	$ 1.68	3	$ 5.04	$ 65.54
Probe PCB boards	OSHPARK	1	$ 10.90	$ 10.90	60	$ 654.00	$ 203.00
8-pin connector	Sparkfun	1	$ 1.50	$ 1.50	30	$ 45.00	$ 52.23
Ethernet Waterproof Connector	Adafruit	1	$ 7.95	$ 7.95	30	$ 238.50	$ 214.80

Adafruit Feather Basic M0	Adafruit	1	$ 19.99	$ 19.99	30	$ 599.70	$ 538.80
Adafruit M0 Wifi	Adafruit	1	$ 34.95	$ 34.95	30	$ 1,048.50	$ 1,048.50
Voltage Regulator	Pololu	1	$ 3.75	$ 3.75	30	$ 112.50	$ 120.87
PCB for 8-pin connector	OSHPARK	1	$ 6.00	$ 6.00	30	$ 109.00	$ 109.50
Female 90 Headers	Pololu		$ 0.50	$ 1.00	60	$ 30.00	$ 27.84
Enclosure	Amazon	1	$ 12.13	$ 12.13	30	$ 363.90	$ 363.90
Adalogger FeatherWing	Digikey	1	$ 8.95	$ 8.95	30	$ 268.50	$ 268.50
TalenCell Rechargeable Battery	Amazon	1	$ 33.99	$ 31.00	45	$ 1,395.00	$ 1,395.00
FeatherWing Tripler	Adafruit	1	$ 8.50	$ 8.50	30	$ 255.00	$ 229.50
SD Card	Amazon	1	$ 0.73	$ 0.73	30	$ 21.90	$ 21.90
Lithium 3VBattery	Amazon	1	$ 0.40	$ 7.99	20	$ 7.99	$ 7.99

Total Cost				$ 157.57		$ 5,593.43	$ 4,834.59

Extracurriculars:

- Residential Advisors (Greenwich Spring 2019, Prescott Fall 2019)
- Signer: Collage Club (Spring 2019)
- Signer: Design Conspiracy (Fall 2019)
- Mixed Nuts Member (2019)
    - Social Justice Committee (2019)
    - Events Committee (Spring 2019)

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