Mid-scale RI-1 (M1:IP): A High-Fidelity Forest Observatory to Improve Prediction of Future Forests

We propose a Mid-Scale RI-1 Implementation Project to establish a High-Fidelity Forest Observatory (HFFO) at the Hubbard Brook Experimental Forest (HBEF). We recommend this pre-proposal be jointly reviewed by the Biological Sciences and Geosciences Directorates (Division of Environmental Biology and Division of Earth Sciences). The tower and power line installation in this project are subject to environmental permitting.

Response to Review of Previous Pre-Proposal

We received encouraging comments on our previously submitted pre-proposal to build the HFFO highlighting the strategic importance of gaining higher resolution understanding of forest processes. Suggestions for improvement included: 1) state more specific hypotheses that could be tested with the data produced by the HFFO, and 2) better integrate broader impacts into the project. In response, we have sharpened our hypotheses and clarified how data from the HFFO will be used to test them. We have also built more robust broader impacts around how new knowledge can be extrapolated to forests generally through modeling. We further outline how a new generation of natural scientists and engineers will be trained in a collaborative approach for establishing complex infrastructure to advance scientific knowledge of forest ecosystems.

Intellectual Merit

Forest ecosystems are critical to climate regulation, carbon sequestration, drinking water supply, water and air quality, biodiversity, forest products, aesthetics and recreation, and human health (Sugden 2008). Monitoring and understanding the range of ecosystem services provided by forests is a fundamental scientific and infrastructure challenge (Beier et al. 2015) and at the center of multiple enduring Grand Challenges in Environmental Science (National Research Council 2001). Particularly as climate change continues to emerge as a major threat to the U.S. economy and society (USGCRP, 2018), slowing deforestation, encouraging reforestation, and improving forest management are gaining attention as effective climate mitigation strategies (National Academies of Sciences, Engineering, and Medicine, 2018). To do this, we need a thorough, mechanistic understanding of how forests store and process water, energy, carbon, and nutrients to present land managers and policy makers with accurate forecasts of the ecosystem services future forests will provide.

The HBEF is one of the most studied forests in the world. Hundreds of scientists have spent significant portions of their careers at the HBEF since its establishment in 1955, gathering data and generating knowledge about how forests develop and interact with the Earth system, provide feedbacks that sustain the forest (e.g., mineral weathering, forest nutrition) and affect climate, biota, water quality and quantity. Their findings have advanced basic understanding of forested ecosystems and how they respond to disturbances (Bormann and Likens 1979) and have been seminal to national policy such as the 1990 Clean Air Act Amendments (Likens 2010, Driscoll et al. 2011). Similar to other parts of the U.S., the HBEF climate is changing while simultaneously recovering from decades of high acid deposition (Fig. 1). Long-term climate data collected at the HBEF over the past six decades indicate mean annual air temperatures have increased by 1.5˚C, mean annual precipitation has increased by 25 cm, the growing season has lengthened by 18 days, and snowpack depth and duration have been reduced by 35% and 17%, respectively (Campbell et al. 2010; Hamburg et al. 2013). Long-term chemical data indicate atmospheric deposition of sulfur and nitrogen (key constituents of "acid rain") increased during the earlier part of the 60+ year record and then plummeted by 80% and 66% (Likens et al. 2020), respectively, in response to the Clean Air Act and its 1990 Amendments. These changes in the physical and chemical environment have had profound and cascading impacts on forest function, many of which we are just beginning to unravel. Investigations at the HBEF of forest function in response to environmental change have produced general knowledge that has informed forest management around the world, demonstrating the value and broad applicability of deep study at a specific ecosystem (Driscoll et al. 2011). The intensive studies at the HBEF provide perhaps one of the most comprehensive foundations of knowledge for posing increasingly sophisticated questions about how forests function and their potential future benefits to society (Deidl et al. 2016). Additionally, the HBEF has been a leader in technological advances in forest monitoring, wireless communications and data processing, and is poised to continue that role in the deployment of cutting-edge monitoring technologies to track forest function (Campbell et al. 2020).

Emerging technologies are empowering new scientific advances and high resolution data (e.g., Farley et al. 2018). For example, forests with high resolution data on soil CO_2 emissions show how temperature and moisture control ecosystem carbon dynamics (Jassal et al. 2005). Similarly, LiDAR data provide detailed analyses of forest canopy architecture and snow depth (Sullivan et al. 2017, Jacobs et al. 2021) and have allowed us to discern previously undetected spatial patterns in soil development and groundwater fluctuations (Bailey et al. 2014; Gillin et al. 2105). There are many examples of detailed sensing of single aspects of a forest. ***However, the simultaneous, comprehensive sensing of an entire well-constrained forested watershed has yet to happen.*** We propose a HFFO at the HBEF to gain new, multi-dimensional insights into how forests respond to climate variation and the legacy of high acid deposition at fine spatiotemporal scales. This project will: advance our understanding of how forests function in a changing world; make novel data openly available; and increase our ability to predict forest ecosystem dynamics for improved forest management and environmental policy development.

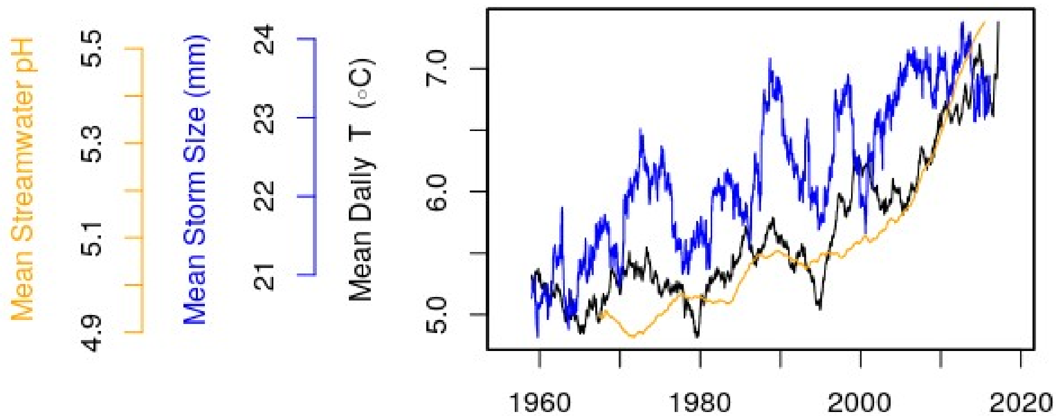

Figure 1. Long-term data from the HBEF reveal the changes that northeastern U.S. forests are facing: recovering pH as acid deposition decreases, increasing storm intensity, and climate warming.

Research Goal and Hypotheses

Our overarching goal is to improve mechanistic understanding of forest functions related to the transfer and distribution of water, energy, and matter that underlie multiple ecosystem services. Changes in temperature, precipitation, and biogeochemistry cascade through forested ecosystems with major consequences for forest productivity, water resources, and climate regulation. We will address our goal by testing these hypotheses:

1. The interactions among water, energy, carbon, nitrogen, and geogenic element cycles regulate the forest response to climate variability. More specifically, we hypothesize that increases in carbon flow in soils mute the response of nitrogen and geogenic elements to disturbance. This flow is driven by elevated levels of atmospheric CO_2 that increase the movement of carbon into trees and then into soil, and by deacidification, which stimulates decomposition and the supply of labile carbon to soil microbial communities. This muting will be especially obvious in short-term extreme events such as high precipitation events, rewetting of dry soils, and rain on snow events that can only be monitored with high frequency sensors or automated event-based sampling.
2. The depletion of soil base cations from acid rain has depressed forest productivity, which increases the variability of water, energy, and solute cycling, making the forest more sensitive to climate variability. We hypothesize reduced temporal variability in soil and stream chemistry in a catchment amended with $CaSiO_2$.
3. There is systematic spatial variation of ecosystem processes related to soil development, patterns creating system leverage points that disproportionately impact the ecosystem response to climate variability and extreme weather events. We expect that areas with soils that tend to produce shallow lateral hydrologic flow have a disproportionate impact on the streamwater fluxes of solutes and dissolved gases in streamwater.
4. The impacts of winter snow depth on soil freezing, springtime runoff and groundwater recharge, and springtime surface albedo play a major role in controlling the subsurface environment (e.g., soil moisture, soil temperature, groundwater storage) during the growing season which influences annual soil carbon balance, nitrogen availability, and forest growth.

We will address these hypotheses by building multivariate empirical and mechanistic models using data from the HFFO. **Hypothesis 1** will be tested by measuring streamwater solute and soil CO_2 fluxes during pulse events (e.g., precipitation or snowmelt) across multiple years while also monitoring interannual variability in the carbon stored in the forest canopy and the forest nitrogen status. **Hypothesis 2** will be tested by comparing the temporal variability of sensed energy, water, and biogeochemical variables in a reference catchment and one experimentally treated with $CaSiO_2$ in 1999 (Battles et al. 2013). **Hypothesis 3** will be tested by assessing the correspondence of streamwater discharge, solute concentrations, and trace gas concentrations with different landscape units. **Hypothesis 4** will be tested by analyzing the relationship between seasonal snowpack dynamics and forest ecosystem functional dynamics (e.g., forest canopy characteristics, soil CO_2 fluxes, streamwater fluxes). Testing each hypothesis will require constructing empirical and mechanistic models. Empirical models will range in complexity from multiple regression (e.g., mixed effects models) to machine learning algorithms (e.g., boosted regression trees). Multiple deterministic models will be used that vary in their representation of spatial and temporal variability. The HFFO data set will be the best available for testing spatially distributed catchment models. We will participate in the NSF funded Research Coordination Network (RCN) called the Ecological Forecasting Initiative by contributing a new modeling challenge for the ecological and hydrological science communities. The RCN, which is at Virginia Tech, has developed a scalable cyberinfrastructure that is deployable for other challenges using near real-time data streams to benchmark models and evaluate ecological forecasting performance. Currently, the RCN is focused on an ecological forecasting challenge that is leveraging data streaming products from the National Ecological Observatory Network and we will work with that team to build a forecasting challenge for the HFFO.

<u>Scientific Justification</u>

Long term records of water, energy, and solutes entering and leaving small watersheds have provided a backbone of knowledge related to ecosystem functions. This small watershed approach to tracking forest ecosystem budgets was pioneered in the watersheds at the HBEF (Bormann and Likens 1967; Likens 2020), and has resulted in fundamental understanding of forest water, carbon, nitrogen, calcium, phosphorus, potassium, chlorine, and sodium budgets (Likens 2013), making these watersheds hallmark case studies in many ecology textbooks. These forest ecosystem energy and material budgets are changing as atmospheric CO_2 concentration increases, air temperature increases, soils recover from decades of acid rain, winter snowpacks become less persistent, and precipitation patterns change (Fig. 1, Groffman et al. 2018, Campbell et al. 2020). The suite of rapid changes at the HBEF are similar to the changes occurring in forests around the world. We lack an understanding of internal spatial structure, linkages, and mechanism that combine to produce the signal measured at the catchment outlet. The advanced understanding of the HBEF forests make them ideal for examining processes and spatiotemporal linkages that control watershed behavior by bringing the small watershed approach into high resolution by deploying intensive modern sensing capabilities.

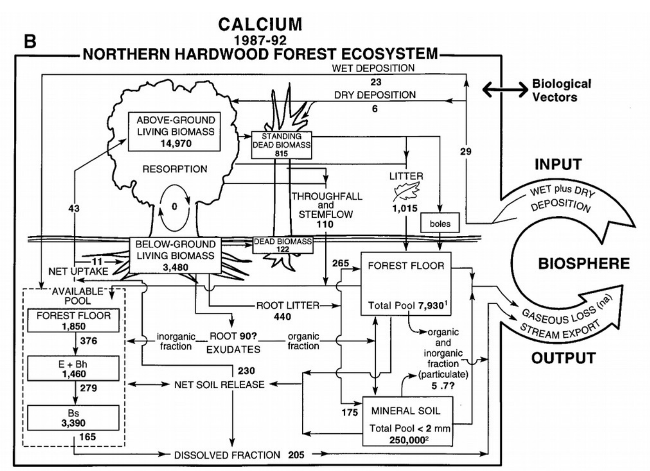

Figure 2. The small watershed concept, pioneered at the HBEF, quantifies watershed ecosystems processing of energy, water, carbon, nitrogen, and geogenic solutes by tracking ecosystem inputs and outputs. Studies of long-term datasets have produced detailed understanding of forest element cycles (calcium shown as an example; Likens et al. 1998). These budgets suffer from using watershed averages to describe internal stores and fluxes, which obfuscate the role of spatial and temporal patterns in catchment properties that mechanistically control the watershed response.

The processes that control forest ecosystem behavior operate at fine temporal and spatial scales.

Simultaneous measurements at small (cm or smaller) and whole-ecosystem scales (100 m or larger) are necessary to gain insight into emergent behaviors in ecosystems. For example, stomata are microscopic pores on leaves that regulate the uptake of CO_2 and transpiration by plants, whose behavior in sum impacts global carbon cycling and river basin hydrology (Gedney et al. 2006). Soil pores between silt particles hold water and solutes during dry periods creating a stable environment for bacterial colonization (Or et al. 2007) and having major implications for carbon sequestration and many other ecosystem functions. The emergent behavior of individual watershed budgets and their coupling is driven by an amalgam of these small-scale structures and their processes, spread heterogeneously across the landscape. Modern drone sensing allows us to characterize spatial variability in fine detail (Fig. 3). Data like these can simplify the scaling of processes to whole ecosystems through classification of functional landscape units. Units with similar topography, soil, vegetation, and canopy structure help bridge small and large scales, illuminating emergent behavior. For example, catchment scientists have sought to identify the “hot spots and hot moments” or control points in ecosystem behavior (McClain et al. 2003) that influence emergent behavior at different scales. ***An intensive observatory, like the HFFO we propose, would create an opportunity to identify which small-scale processes and which parts of the landscape drive major ecosystem behaviors.***

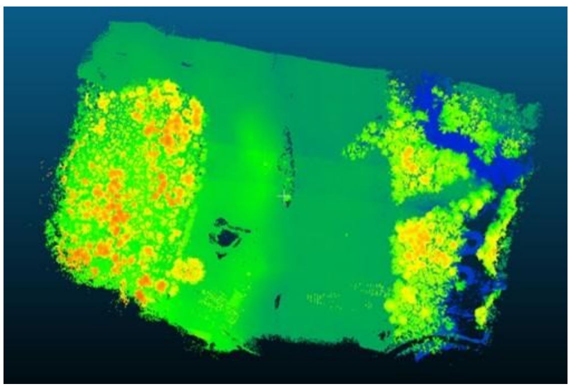

Figure 3. LiDAR image of a forested landscape from a drone flight near Durham, New Hampshire shows landscape heterogeneity and canopy structure variation. We will gather monthly LiDAR, hyperspectral, and thermal infrared data from the HBEF to evaluate spatial variation of forest canopy structure, carbon and nitrogen storage, evapotranspiration, stream network extent, and snowpack dynamics.

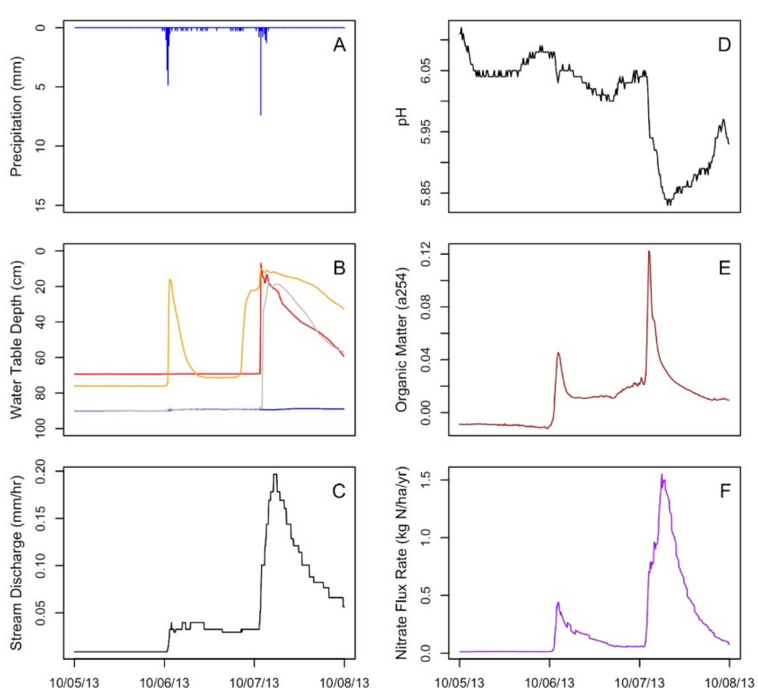

Figure 4. A multi-dimensional view of the ecosystem response to two storm events in Watershed 3 at the HBEF from existing sensors. Precipitation (A) occurred on two consecutive days, producing a more pronounced groundwater (B) response with the second day of rain in four landscape positions, which resulted in more streamflow (C) on the second day. The streamwater pH (D) dropped, partly due to the high organic matter and organic acid concentrations (E; absorbance at 254 nm); the export of nitrate (F) was greatest on the second day. The cumulative picture demonstrates the importance of precipitation patterns and antecedent wetting to ecosystem storage and fluxes.

Like other parts of the country, extreme weather events are increasing in frequency and intensity in the northeastern U.S. (e.g., Guilbert et al. 2015), with unclear consequences for forest ecosystems (Luce et al. 2016). Modern sensing systems collect data at high enough frequency to provide a more complete picture of forest response to interannual variability, seasonality, and weather events (e.g., Pellerin et al. 2012; Krause et al. 2015). These higher resolution ecosystem data help identify the major ecosystem processes that are susceptible or resilient to recent changes in extreme events (Fig. 4).

Research Community Priority

Forests have been recently highlighted as a major source of clean water in river basin headwaters (Abbot et al. 2017), a potential tool for reducing floods (Bradshaw et al. 2007), a source of sustainable building materials (Rovaniemi Action Plan 2014), and as a tool for mitigating elevated atmospheric CO_2 in the Paris Climate Accord. For example, the 2018 National Academies report, "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda", discusses forest management as a significant opportunity to reduce atmospheric CO_2. The report recommends new research addressing forest soil carbon processes, including those occurring in deeper mineral horizons. New data that help explain the environmental conditions that support the highest soil carbon storage – such as those produced by the HFFO – will make forest management practices more effective in CO_2 mitigation.

There have been public calls in the hydrologic community for radical field experiments to push new discoveries (Burt and McDonnell 2015; Bloschl et al. 2019), particularly those that examine the magnitude and controls on water storage (McDonnell et al. 2018). A "sensor revolution" was anticipated in the 2012 U.S. National Research Council report on Challenges and Opportunities in the Hydrologic Sciences, and with it, advances in basic understanding of water resources. The sensor revolution is arriving, with much of the initial focus on previously unrecognized temporal patterns in streamwater chemistry (Fig. 4; Rode et al. 2016; Floury et al. 2017). Novel hypotheses have been proposed and scientific advances made to explain these newly recognized patterns (Li et al. 2020). ***To date, however, no study exists that pairs high intensity streamwater chemistry measurements with high intensity soil and microclimate measurements to couple the aquatic and terrestrial ecosystem. This proposed HFFO would provide the novel field observations necessary to make this coupling.***

Sensing-intensive observatories to understand watershed ecosystems have been a community priority for over a decade (CUAHSI 2004; Bogena et al. 2018). NSF has invested in 1) long-term tracking of ecosystems through the Long-Term Ecological Research network (LTER), 2) understanding processes that control bedrock weathering through the Critical Zone Observatory (CZO), and 3) continental-scale ecology through the National Ecological Observatory Network (NEON). LTER and CZO sites have components of a high-fidelity observatory but without the resolution and replication to reveal a full range of spatial and temporal variation or the mechanistic connections that allow for upscaling. Better understanding of scaling is vital to predict how ecosystem changes will manifest in the Earth system (Peters-Lidard 2017).

This HFFO would address two of NSF's 10 Big Ideas. First, by generating big data to advance basic understanding of forests, we will provide a significant example of Harnessing the Data Revolution. Second, by providing insight into how small-scale, heterogeneous processes produce emergent behavior at the watershed scale, the HFFO would contribute data for uncovering the Rules of Life.

The Hubbard Brook Experimental Forest

The HBEF is part of the USDA Experimental Forest and the NSF Long-Term Ecological Research networks, and is consistently pushing the frontiers of ecological knowledge through NSF-funded investigations. The HBEF is a mixed hardwood forest in the White Mountains of New Hampshire underlain by spodic soils and metasedimentary bedrock (Likens 2013). One of our focus watersheds (Watershed 3; W3) is a reference site, last harvested in the early 1900s. This site has been intensively studied to understand groundwater dynamics (Detty and McGuire 2010), soil development (Bailey et al. 2014), and nitrogen cycling (Morse et al. 2014). The other site (Watershed 1; W1) has similar soils and vegetation and is of similar forest age as W3, but had calcium silicate applied at the rate of 4.6 metric tons per hectare of $CaSiO_3$ in 1999 to replace the calcium lost from forest soils due to acid rain. The W1 forest has responded to the treatment with a reversal in forest decline (Battles et al. 2013), but also with an unexpected transient change in the forest water use (Green et al. 2013), and an enhanced loss of nitrogen (Rosi et al. 2016). W1 was intended to be a multi-decade experiment, thus the HFFO would allow high-resolution examination of the continued forest response to base cation manipulation.

Soil characteristics play a vital role in regulating catchment ecosystem behavior, however they tend to be highly spatial heterogeneous, which makes relating soil dynamics to ecosystem functions complicated. Soil spatial heterogeneity at HBEF is well understood compared to other sites due to recent studies of soil development (Bailey et al. 2014). This recent work has allowed process-based disaggregation of the forested landscape based on topographic, hydrologic, and biogeochemical characteristics (Fig. 5). This conceptual model allows mechanistic descriptions of how different parts of the landscape regulate ecosystem processes. For example, Gannon et al. (2015) demonstrated how watershed-scale dissolved organic carbon yields are driven by intense rainfalls that cause bedrock-controlled soils to efficiently leach organic matter into streams. The different landscape units show distinctly different groundwater chemistry (e.g., pH, nitrate) and dominant flowpaths, enabling us to trace the hydrologic conditions that cause leaching of materials from different landscape units (Bailey et al. 2019). ***Understanding processes that produce landscape discretization is a critical challenge to understanding how internal spatial structure controls whole-ecosystem behavior. We are particularly poised to address this with the HBEF watersheds.***

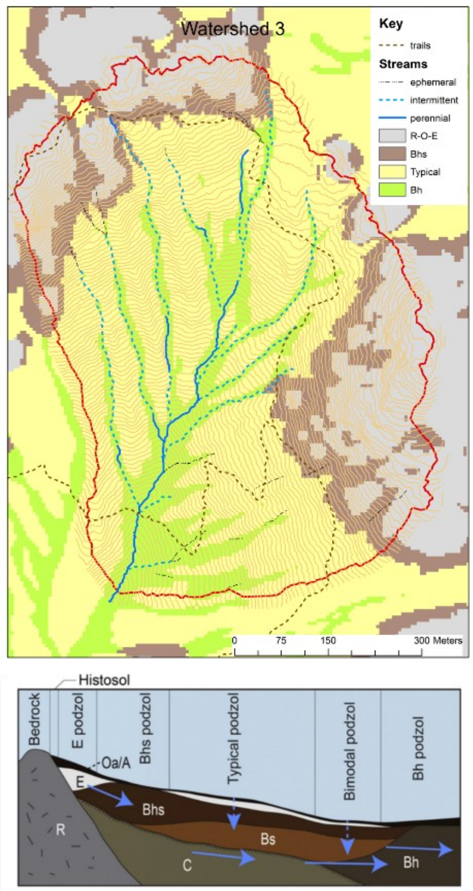

Figure 5. Soil units have been mapped within W3 (top), using recent concepts that describe how dominant flow pathways (blue arrows) cause soils to develop laterally from bedrock outcrops to near-stream zones (bottom; Bailey et al. 2014). This is an example of one landscape discretization model that we will use to understand how internal spatial structure controls emergent whole watershed ecosystem behavior.

<u>Proposed Infrastructure</u>

Since the mid-1960s, scientists from the Hubbard Brook Ecosystem Study have articulated a need to advance the instrumentation in the experimental watersheds by extending line power into the forest. This infrastructure project would represent a major leap in measurement capacity that has been discussed and planned for decades. Much of this planning has taken place in the context of the U.S. Forest Service Smart Forest initiative to install advanced sensors at multiple forests around the U.S., led by scientists working at the HBEF. This long history of planning and collaboration creates a strong platform for ongoing operations and maintenance, and we anticipate that all or parts of the HFFO will be assimilated as an ongoing component of the long-term monitoring and data sets associated with existing (LTER, Smart Forest) and potential (NEON, CZO) network collaborations active at the HBEF.

The HFFO will include:

(1) an unmanned aerial system that will measure forest biomass, canopy dynamics, stream network expansion and contraction, snowpack behavior, and estimate canopy biophysical parameters,

(2) an *in situ* sensor network consisting of intensive (n=8), primary (n=20), and satellite sites (n=100) distributed across W1 and W3 to track streamwater quality, subsurface water storage as groundwater and soil moisture, soil CO_2 and O_2 fluxes, subsurface and soil surface temperature, sub-canopy microclimate and incident radiation, snowpack amount and temperature, throughfall amount and quality, and sub-canopy air flows (katabatic and anabatic winds) that transport energy, CO_2, and water vapor. The sensors will be strategically placed to represent the spatial variation of topography, soils, and vegetation.

(3) two streamwater monitoring systems that include instruments that monitor solute concentrations, dissolved gases, water isotopes, and automated water samplers with climate-controlled on-site storage for further lab analysis.

Together, these measurements will provide new insight into subsurface storage of water, energy, and carbon; aboveground storage of carbon and energy; soil and streamwater gas fluxes; and environmental controls on all ecosystem budgets.

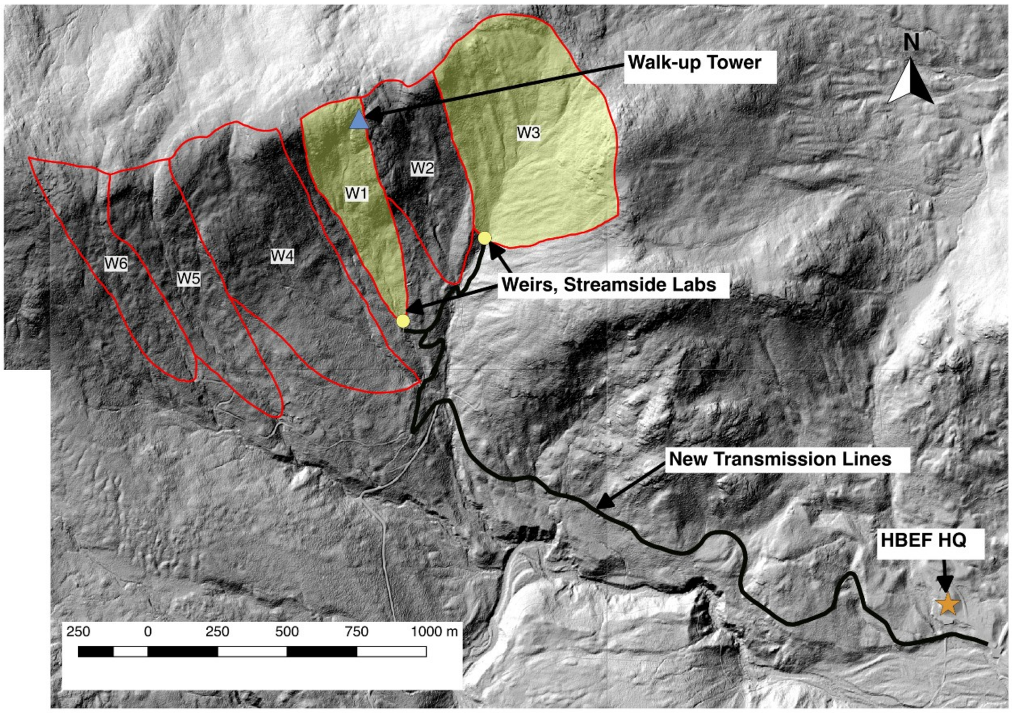

Figure 5. Map of the proposed infrastructure at the HBEF.

<u>Unmanned Aerial System:</u> The forest canopy, soil micro-topography, snowpack, and stream extent will be characterized on a monthly basis with drone-based LiDAR, hyperspectral, and infrared sensors. In order to facilitate flights over the watersheds, a walk-up tower will be constructed along the ridge of W1. Improvements in Unmanned Aerial Systems (UAS), including smaller and more stable sensors and data storage units, and miniaturized brushless motors, have greatly increased their ability to provide functionally relevant characterization of forested watersheds (Jacobs et al. 2020; Palace et al., 2018).

We will utilize a suite of sensors flown on our UAS. One payload will consist of co-aligned VNIR and SWIR hyperspectral line scanners which cover a cumulative spectral range of 400-2500 nm. This payload will provide spectral data from the visible to the short-wave infrared, which will be used to investigate canopy and snowpack dynamics, including snow cover, surface albedo, water content and other biophysical properties. A second hyperspectral payload will carry a VNIR sensor with a Velodyne LiDAR (e.g., Fig. 3). The third payload will consist of only a LiDAR sensor, as the lighter weight payload will allow for longer duration flights. Finally, a thermal sensor by FLiR will be used to look at canopy stress and be mounted on one of these UAS as needed.

Flights will be planned and executed using UgCS, an open source flight planning software. All three of these payloads will have an Applanix APX-15 GPS/IMU. The APX-15 measurement allows for accurate georeferncing of point clouds and hyperspectral data without the aid of ground control points. This is especially important in forested areas where ground visibility is obscured by vegetation. The GPS/IMU will be used on each payload to allow for correction of in-flight positioning and attitude using a base station. Surface directional reflectance images will be produced for our study areas using radiometric calibration parameters of the payloads provided by the vendor and with the aid of a reflectance calibration tarp. Orthorectification of hyperspectral data will be performed using Headwall's SpectralView software for the hyperspectral sensors. For RGB image acquisition, we plan to deploy DJI Phantom RTK UAS. Mosaicking and georeferencing of RGB data will be performed using Agisoft. Orthof hyperspectral data performed GBF or RGB image acquisition, we plan to deploy DJI Phantom RTK UAS. Data analysis of data acquired using our suite of payloads will be conducted using code developed using Python. Machine learning efforts to examine data with training and validation efforts will be done. These machine learning efforts include neural networks, random forests, maximum entropy, boosted trees, and lasso regressions (Palace et al. 2018).

In Situ Sensing Network: An intensive *in situ* sensor network within W1 and W3 will involve more than one thousand sensors, deployed in different landscape units so that we can measure hydrological and biogeochemical activity within the watersheds at any given moment. Nitrate, dissolved organic carbon, and energy fluxes with streamflow will be monitored with a UV-Vis spectrophotometer (nitrate) and a multi-parameter sonde (pH, dissolved oxygen, fluorescent organic matter, electrical conductivity, and water temperature). These sensors will be deployed at the W1 and W3 outlets, and four additional streamwater sensor packages will be used as mobile units for short-term (months) monitoring of tributary and groundwater chemistry. These instruments will be calibrated monthly.

A network of wirelessly-communicating sensors will be designed and built to provide spatially dense data covering the subsurface, snowpack, and microclimate within the watersheds. Multiscale subsurface sensing is required to resolve how above-ground processes interact with below-ground processes, and to quantify and predict the subsurface distribution of water, available nutrients, and solute dynamics. Our goal to take a holistic approach to understanding the boundaries of a forest ecosystem (Staudinger et al. 2019). Following the watershed stratification described above, subsurface sensors will be placed in the soil, deeper glacial deposits, and bedrock. Four depths will be established in the variably saturated soil portion of the subsurface for high-frequency (e.g., 5-min) measurements of soil CO_2, O_2, water potential, and moisture using state-of-the-art sensors at each of the extensive sites. Shallow wells will be co-located at each of these soil monitoring sites to measure groundwater levels at high frequency. During the installation of these sensors, soils will be collected for characterization. Variables that will be measured include: soil moisture retention (i.e., relation between pressure head and soil water content) characteristic, hydraulic conductivity, porosity, bulk density, particle-size distribution, microbial biomass carbon and nitrogen content, potential net nitrogen mineralization and nitrification rates, denitrification potential and potential microbial respiration.

At a subset of the primary sites (~8), deeper samples will be collected for the same set of physical, hydraulic and biological properties. Following procedures developed on a current NSF project, we will work with a drilling contractor to split-spoon sample unconsolidated material to the depth of bedrock and then core the bedrock deep enough to surpass the weathering zone. Wells with high frequency water level recorders will be placed with screening at the bedrock interface and within bedrock if fracture zones are encountered. All soil, glacial material, and bedrock samples will be analyzed for chemistry and a subset of samples will be used for mineralogical analysis.

Winter has shown the greatest rate of climate change at the HBEF (Campbell et al. 2010) and snow plays a major role in the forest ecosystem, providing insulation to mitigate soil freezing (Campbell et al. 2010; Templer et al. 2012), subnivean habitat (Zhu et al. 2019), seasonal water storage (WIlson et al. 2020), and mobilization of nutrients during the snowmelt period. The HFFO will therefore include automated snowpack monitoring of depth, water equivalent, and temperature at 8 sites, complementing weekly manual snowcourse (depth and density) sampling efforts dating back to 1955.

Sub-canopy microclimate provides a major control on all of the forest ecosystem water, energy, and nutrient budgets the HFFO is designed to monitor. Thus, we will monitor sub-canopy air temperature and relative humidity with sensors at two heights to evaluate evaporation gradients. Solar radiation will be sensed with pyranometers and net radiometers under the canopy and on the walkup tower for above canopy values. Katabatic and anabatic sub-canopy winds in HBEF (Kelsey et al. 2019) occur frequently and are important for energy balance in this forest, and will thus be tracked with 3D anemometers.

Streamside Laboratory: An automated streamwater sampler will be housed in a climate-controlled streamside shelter with several chemical analytical instruments. Water will be pumped into the shelter to be analyzed for stable water isotopes and greenhouse gases (CO_2, CH_4, and N_2O) on an hourly basis. The sampler will be linked to the *in situ* streamwater sensors so that water samples are automatically collected during dynamic, unusual streamwater conditions. Those samples will be collected and sent to a laboratory for full chemical analysis on an ICP-MS (cf. Neal et al. 2012). Precipitation from a nearby rain gauge and throughfall from the forest adjacent to the shelter at W3 will be supplied to the laboratories via temperature-controlled teflon lines.

Transmission Lines: The instrumentation and sensors that constitute the observatory will require new transmission lines that provide electricity and robust data transmission from the south-facing watersheds. The transmission lines will be buried to minimize maintenance costs. Beyond playing a fundamental role for the HFFO, we anticipate other projects will utilize these transmission lines, thus enabling other cutting-edge science at the HBEF.

Data Distribution Infrastructure: Data from the HFFO will be made openly and easily accessible. The data produced by this observatory will be distributed using an enhanced version of our longstanding data management system that has been used for the U.S. Forest Service, LTER site, and Smart Forest data streams. Data from the *in situ* sensor network will be transmitted in near real-time to servers using a combination of drone-based retrieval and LoRaWAN transmission between data loggers, and the fiber optic cable at the weir houses. Our current data transmission system experiences bottlenecks in wireless transmission to servers; by adding the fiber optic cables connecting to multiple antennas, the rapid movement of data will make the system more efficient. The data will be standardized on data loggers so that the large volumes of data can be automatically screened before being made available as provisional data to the public via FTP. A major challenge with so much data will be quality assurance. To combat this, scripts will be designed that automatically conduct QA/QC on the data, assisted by machine learning tools, so that final checks by humans are most efficient. We will target making provisional data available within a week of collection and quality assured data within three months. A data portal will be designed for simple visualization of our data for educational or outreach contexts. An Arc web service will be constructed for viewing of UAS-collected data. Screened data will be uploaded to a DOI-issuing repository that supports version control, immutability (e.g., EDI) and data accessed programmatically. Additional data submissions will be made to community-specific archives (e.g., CUAHSI). We will work closely with the User Advisory Group in years 4 and 5 to incorporate proto-user feedback on designs that will make the data easiest for the scientific community to use.

Broader Impacts

The HFFO will produce new knowledge about forests respond to climate variation and the resulting impacts on forest products, water resources, and carbon management. By documenting basic processes, we will build knowledge that is broadly applicable beyond the HBEF. The Hubbard Brook Ecosystem Study has a strong track record of discovering basic processes in forests, documenting how they respond to environmental disturbances, and sharing the results for smart policy and practice. For example, science from Hubbard Brook was central to the passage of the 1990 Clean Air Act amendments (Likens 2010), considered among the most significant science-to-policy success stories of our time. The HFFO will document forest function at an unprecedented resolution, bringing previously imperceptible ecosystem responses into sharp focus and pushing the limits of scientific discovery.

Through our outreach led by the Hubbard Brook Research Foundation (HBRF), we will bring these innovations and new discoveries to the public during briefings with lawmakers and land/resource/and recreation managers. The HBRF will record, summarize, and share news of the project within and beyond the Hubbard Brook community. HBRF's communication channels include Hubbard Brook's internal monthly newsletter, web-based multimedia stories, and features for radio, television, print and social media. HBRF will explore the possibility of designing lessons and activities for engaging organized groups with the data (e.g., K-12 math and science lessons). There is great potential to create interactive, multi-sensory experiences with the data that build on Hubbard Brook's innovative water cycle visualization and sonification platforms (Rustad et al. 2018).

All data produced by this observatory will be carefully curated and made openly available to the scientific community. In addition, we will build a data interface to make simple data exploration available for the scientific community and undergraduate scholars. We will build upon a data visualization platform for exploring the long-term water chemistry from the HBEF that has already been developed at Duke University. Data visualization will be guided by previous work at the HBEF to translate sensor data into universally designed learning tools. To bootstrap community use of the HFFO data set, we will host a catchment prediction competition in year 4 and 5 of this project. There will be competitions for different response variables (e.g., streamwater CO_2, soil temperature) where both empirical and mechanistic models can be entered and assessed for their ability to forecast the variable. Rewards will include stipends for students on the winning teams to aid further development and documentation of the models.

The construction and initial operations of the HFFO will involve training of other students. We will train a Ph.D. student at Virginia Tech through the Geospatial and Environmental Analysis program, a unique program in environmental informatics that trains students in data analysis, computational modeling, and information science. In addition, three MS students in Applied Meteorology at Plymouth State Univ. will be part of the sensor network installation and data QA/QC. Students associated with the Institute for Smart, Secure and Connected Systems at Case Western Reserve Univ. will be trained in building sensor mesh networks in dense forested environments.

As part of our Broader Impacts, we will develop virtual landscapes representing aspects of Hubbard Brook. This will be done using existing python code developed in Palace et al. (2015) that was used to generate three dimensional forests based on tree size distributions and canopy dimensions. Minecraft Education Software is free and can run on PC, Macs, iPads, and Chromebooks. Multiple users can log onto a shared world. Currently, Co-I Palace has developed landscapes from UAS-based vegetation classification and a digital elevation model at a Swedish fen and at Harvard Forest using tree stem map locations. Many virtual experiences require complex and expensive technology that limits the scalability of teaching and education. In addition, such immersive environments are often limited to one person at a time. Our goal is to provide both free access for multiple people at the same time in an interactive learning environment. We acknowledge the need for more interactive virtual homeschooling due to COVID-19 and this effort attempts to provide a dynamic approach to Broader Impacts.

We will also work with a team of artists, musicians and educators to translate the complex data generated from the sensors into real-time data visualizations and musical sonifications. This will be modeled after the Hubbard Brook WaterViz (available online at WaterViz.org). The goals are to 1) create data-driven art and forest symphonies, 2) use art and music to translate and demystify our science for a broader audience, and 3) foster new scientific discoveries through cross-disciplinary data exploration. The data sonifications are particularly suitable for sharing real-time environmental data with the visually impaired, and we will specifically engage with this underserved group.

Project Organization and Timeline

Organization: This project consists of a project management team, implementation teams for parts of the observatory, and a user advisory group. The PI will oversee the project with the consultation of the project manager and the HBEF site manager. Procurement will be led by project support staff at Case Western Reserve University under the direction of the PI and project manager. Major project activities will be led by sub-groups that report back to the project management team on quarterly progress. Technical staff responsible for assembly and construction within each sub-group will report to a sub-group team lead. We will employ an adaptive process in which our construction and commissioning plans undergo annual peer-review by a five-member user advisory group, and adaptations will be implemented in response. Detailed project organization is laid out in the Project Execution Plan (PEP) outline.

Timeline: Year 1 will involve intensive procurement activities and field site preparation. Years 2 and 3 will be devoted primarily to construction and assembly activities across the project, with initial data beginning to flow from the UAS platform and the early sensor network data. Year 4 will mark the major project activities transitioning from construction and assembly to commissioning of the workflows. Year 5 will involve final documentation of the system and polishing of the data distribution platform. A detailed timeline is laid out in the PEP outline.

Future Operations and Maintenance

The Hubbard Brook Ecosystem Study (HBES) has been operating as a collaborative research endeavor between the U.S. Forest Service and numerous research institutions since 1963, currently involving more than 20 institutions contributing to the HBES scientific mission. Research operations have been funded through congressional funding to the U.S. Department of Agriculture, federal research grants mostly from the NSF, private research grants, and investments from numerous universities. Our proposed HFFO would be part of the HBES, and thus maintained and operated by the HBES into the future.

If this proposal is funded, the HFFO would continue for ten years beyond the term of the NSF award through a collaboration of the USDA Forest Service Northern Research Station, the LTER site, and Long-Term Research in Environmental Biology (LTREB) programs active at the HBEF. We will work with the PIs from those programs to develop synergies where their long-term technicians could incorporate the operation of the HFFO into their existing routines. We will also work with the Hubbard Brook Research Foundation to seek private support for the HFFO. There are also potential collaborations with NEON, which operates a satellite site at the nearby USDA Bartlett Experimental Forest and a core site at the nearby Harvard Forest, which is also an LTER site. Multiple scientists active at the HBEF are also active in the CZO network, a further source of potential future collaboration to facilitate ongoing operations and maintenance. Finally, we expect that the HFFO to attract numerous new investigators to the HBEF, who will leverage new research from the HFFO platform. We will encourage these investigators to include support for ongoing HFFO technical support and instrumentation.