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Sentinel Research Sites in Global Change Research: Whiteface Mountain, New York

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Abstract - Research at sentinel research sites focuses on long-term ecological monitoring related to global environmental changes. Despite the value of sentinel research sites during the Anthropocene, the factors that drive their development, success, and sustainability are not clear. Here we study the history of Whiteface Mountain, NY—a sentinel research site in global environmental change research. We review the origins of Whiteface Mountain as a research site, its contributions to forest ecosystem science, and the factors that contributed to the location's development, success, and sustainability. We identified 6 key characteristics that contributed to the success of Whiteface Mountain as a sentinel research site: (a) accumulation of high-quality long-term data, (b) features representative of a broad area, (c) availability of appropriate infrastructure and staffing, (d) sustained governmental and community support, (e) active communication and outreach programs, and (f) dedicated leadership. These characteristics provide a roadmap for the successful development and sustainable operation of sentinel research sites in global environmental change research.

Introduction

Detecting and responding to large-scale environmental change has often been triggered by findings from sentinel research sites. Sentinel research sites are focused on tracking biophysical indicators over time that inform the nature of these environmental changes and their effects on a broader regional ecosystem. Key findings from sentinel research sites include the long-term increase in atmospheric CO_2 concentration at Mauna Loa (Harris 2010) and the detection of acid rain in the northeastern United States (Likens and Bormann 1974). The contributions are often the result of routine, standard, and repeated measurements over decades that offer new insights into trends of environmental change. Indeed, the value of these sites is long recognized and incorporated into the design of new research networks including the National Science Foundations (NSF) Long-Term Ecological Research (LTER) Network (Callahan 1984) and National Ecological Observatory Network (NEON; Kao et al. 2012), the United States Forest Service Forest Inventory and Analysis (USFS FIA) network (Bechtold and Patterson 2005), and,

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importantly, many other long-term research sites that incorporate continuous environmental monitoring.

Early research on global environmental change impacts on ecosystems include the effects of land-use change, resource extraction, and pollution (Vitousek et al. 1997). In addition to these stressors, climate change has emerged as a major threat to ecosystems globally. Mountain ecosystems, and the associated socio-ecological services that they provide, are particularly threatened by climate change and its interactions with other environmental changes (Dobrowski and Parks 2016, Gratzer and Keeton 2017, Parobeková et al. 2018). Importantly, mountains are ideal systems to study the effects of climate change on ecosystems because they contain compressed climate gradients (Jump et al. 2009), species range limits (Kelly and Goulden 2008), and potentially, cool, high-elevation, climate-change refugia (Morelli et al. 2016). Sentinel research sites in mountains therefore play a foundational role in improving our understanding of ecosystem responses to climate change (e.g., Grabherr et al. 2000).

Valuable sentinel research sites should have a set of common characteristics that make them well-suited to provide key scientific contributions to environmental change research. The primary scientific value of the site is the high-quality and long-term data that, although it comes from only 1 location, is representative of a broader region or system (Fahey et al. 2015). However, collecting those data is only possible with extensive and continuous support networks including governmental, community, and research-entity partnerships that are coordinated and cultivated by dedicated leadership (Plotkin and Foster 2006). Public support is an important pillar for maintaining and growing these partnerships (Moorman 2006), and public outreach and education are increasingly recognized as equally important to generating new scientific information (e.g., NSF broader impacts criterion). Communicating the value of sentinel research sites to these various stakeholders is key for their long-term success. However, the factors that drive the development, success, and long-term sustainability of sentinel research sites are not clear.

The goal of this paper is to clarify the factors that influence the development of new sentinel research sites, the reasons for their success, and considerations for their long-term sustainability. We aim to achieve this goal by studying the history of and contributions from Whiteface Mountain (hereafter Whiteface), NY, to forest ecosystem research in the northeastern US. Whiteface has emerged as a sentinel research site in global change research that has made key contributions to atmospheric sciences research, the discovery and impacts of acid rain, and climate-change effects on forest ecosystems. Herein we describe (i) the origins of Whiteface as a sentinel research site in eastern North America, (ii) the key contributions from Whiteface to forest ecosystem science, and (iii) the factors that are critical to the development, success, and sustainability of Whiteface as a valuable sentinel site.

Whiteface Mountain Environmental Context

Whiteface Mountain (44°21057″N, 73°54010″W; summit elevation 1483 m above sea level, a.s.l.) is located in the northeastern US (Fig. 1). Soils on Whiteface are acidic and sensitive to acid rain (Johnson et al. 1994a). Soils transition from Spodosols at low elevations to Histosols at higher elevations (Holway et al. 1969, Witty 1968). The region generally has warm summers with cold, snowy winters. Mean annual temperature (2001–2011) on Whiteface has varied from 5.1 to 0.27 °C at 610 and 1483 m elevation, respectively (Wason et al. 2017b). Precipitation is relatively evenly distributed throughout the year, and average values from 1986 to 1990 varied from 97 to 152 cm $year^{-1}$ between 610 and 1483 m elevation (Miller et al. 1993a).

The vegetation on Whiteface changes dramatically with elevation, much like elsewhere in the northeastern United States (Cogbill and White 1991, Wason and Dovciak 2017). At elevations below 800 m, forests are dominated by northern hardwood species including *Acer saccharum* Marshall (Sugar Maple), *Fagus grandifolia* Ehrh. (American Beech), and *Betula alleghaniensis* Britton (Yellow Birch) (Fig. 2). Above 800 m elevation, tree species composition transitions to montane

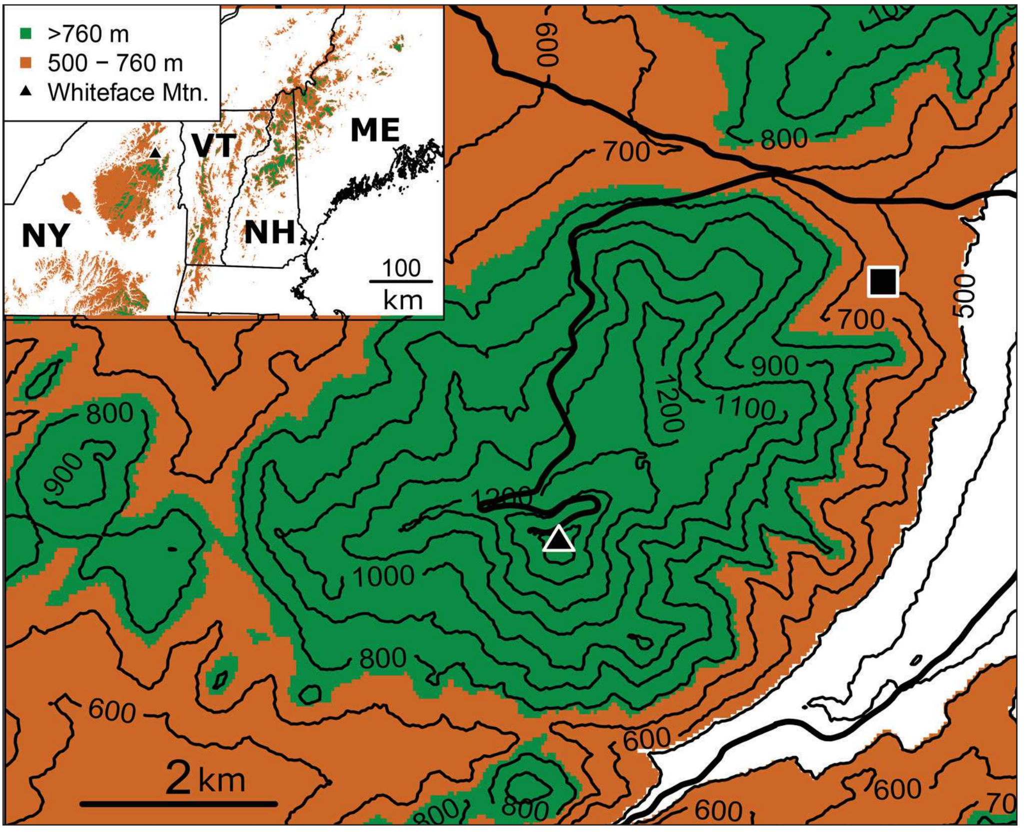

Figure 1. Location of Whiteface Mountain demonstrating that the elevational zonation is representative of the broader region. Areas with elevations suitable for supporting mountain spruce–fir forest are represented in green with the low-elevation transition to northern hardwood forest depicted in brown (Wason et al. 2017a). Continuous meteorological monitoring is conducted both at the Summit Observatory (triangle) and The Atmospheric Science Research Center field station at Marble Lodge (square). Bold lines depict roads. Inset shows the location of Whiteface Mountain within the broader region.

spruce–fir forests composed primarily of *Picea rubens* Sarg. (Red Spruce) and *Abies balsamea* (L.) Mill. (Balsam Fir) with a minor component of *Betula papyrifera* Marshall var. *cordifolia* (Regel) Fernald (Mountain Paper Birch) (Fig. 2). Above ~1100 m elevation, the forest is composed primarily of Balsam Fir. The summit is primarily composed of stunted krumholz forms of Balsam Fir and *Picea mariana* (Mill.) Britton, Sterns, & Poggenb. (Black Spruce) and alpine habitat. Although it varies predictably with latitude (Cogbill and White 1991), the elevational zonation of spruce–fir and northern hardwood forests is representative of the region (Figs. 1, 2), and this community distribution has remained mostly stable for the last 3000 years (Jackson and Whitehead 1991).

Early History: Whiteface Emerges As a Key Destination for Recreation and Science

The rugged nature of the High Peaks mountain region of the Adirondacks and the high cost of transporting lumber left the high-elevation forests of Whiteface largely untouched until pulping operations began in the 1890s. Logging and subsequent fires in the late 1800s and early 1900s impacted much of the mountain's

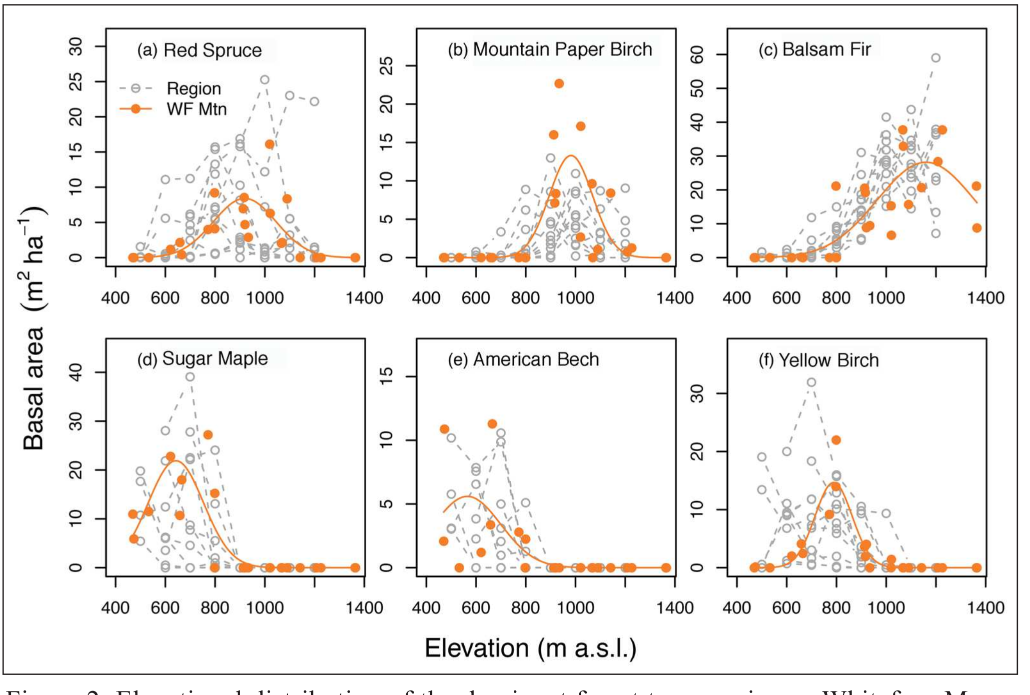

Figure 2. Elevational distribution of the dominant forest tree species on Whiteface Mountain, NY (WF Mtn.; orange solid symbols and lines), is representative of other mountains in the northeastern United States (grey open symbols and dashed lines). Each grey dashed line represents one mountain of 11 studied in Wason and Dovciak (2017). The orange points and model fit are produced from a 2012 survey from 23 Atmospheric Sciences Research Center vegetation plots on Whiteface Mountain following Wason et al. (2017b). Data include all live trees ≥10 cm diameter at breast height.

forests, although a few small pockets of relic old-growth forest remain (Battles and Fahey 2000, Holway et al. 1969, Scott et al. 1993). Between 1921 and the early 1930s, most of Whiteface was acquired by New York State to be integrated into the Adirondack Forest Preserve and deemed "forever wild". The "forever wild" designation limits timber management on state lands and has resulted in relatively stable regional land-use, thereby making Whiteface an ideal location for long-term scientific research in a natural environment (Falconer and Barry 1963).

The "forever wild" designation is key to the long-term value of Whiteface as a sentinel research site. However, several other key developments established Whiteface as a cultural site that added to its regional economic value and bolstered it as a scientific research site (Fig. 3). Following the 1932 Olympics in nearby Lake Placid, the state opened the Veterans Memorial Highway in 1935—a road to the summit of Whiteface for tourism. Whiteface gained more local recognition in 1948 when a small ski area on the northeast slope (Marble Mountain) was opened to the public. This facility was replaced by the larger Whiteface Mountian Ski Area on the southeast slope in 1958 that became a regional tourism destination. By the 1980 Winter Olympics held in nearby Lake Placid, NY, Whiteface had emerged as a key cultural and recreational destination in the region.

The cultural and recreational assets at Whiteface provided access and spurred investment in research. For example, summit temperature measurements started in 1937 as a collaborative effort of research universities, state programs, and federal agencies. Later, the installation of an olympic-quality ski area provided both the need and the resources to develop detailed, site-specific weather forecasts. Thus, by the time the State University of New York (SUNY) launched the Atmospheric

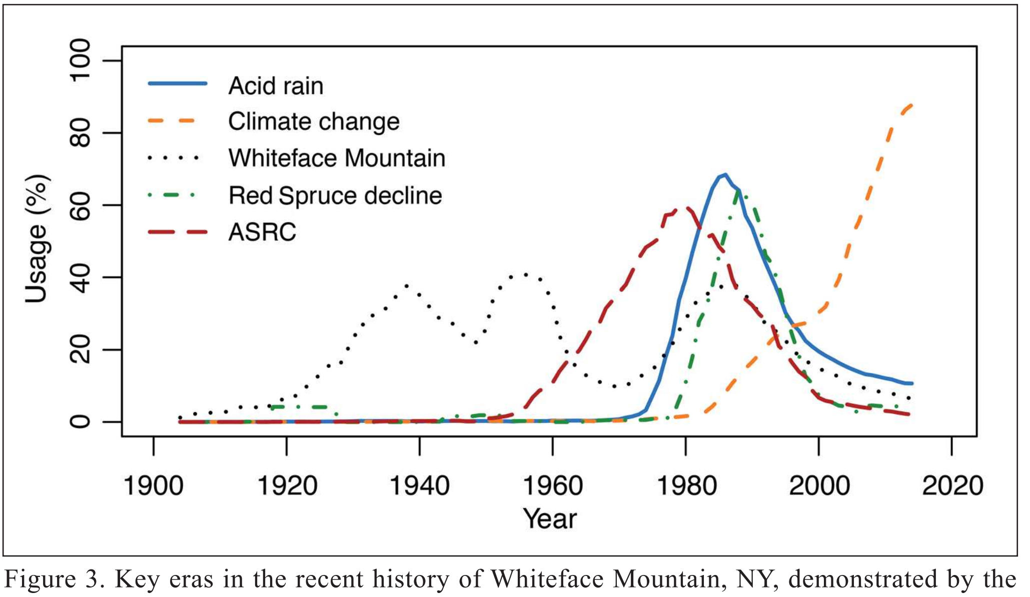

Figure 3. Key eras in the recent history of Whiteface Mountain, NY, demonstrated by the usage of common terms in English publications. Usage is derived from Google Ngrams and each term is scaled to its maximum value and then smoothed with a 10-year moving window to facilitate comparison. ASRC = Atmospheric Sciences Research Center.

Sciences Research Center (ASRC) hosted by the Albany campus in 1961, Whiteface with its investments in meteorological monitoring and instrumentation, was its preeminent field site (Fig. 3). To support the field site, ASRC built a headquarters in the retired Marble Mountain ski-lodge on the east slope of the massif (Schwab et al. 2016b). This collaboration with SUNY-Albany was a critical turning point for scientific research on the mountain. Whiteface now had many of the key elements of a sentinel research site: infrastructure, community support, and the beginnings of a new long-term scientific research partnership.

Research on Whiteface Mountain

Atmospheric sciences

The geography of Whiteface makes it ideal for atmospheric sciences research. Whiteface is a relatively isolated massif with frequent cloud cover at the summit facilitating studies on atmospheric transport, dispersion, and deposition of air pollutants as well as the study of cloud-water chemistry. For example, Whiteface has one of the longest records of tropospheric ozone measurements in the world (Gaudel et al. 2018), and Pye et al. (2020) noted that Whiteface was one of the few locations with a record of long-term investigations of cloud and fog composition. The history and accomplishments of the atmospheric science research program at Whiteface has been recently and thoroughly reviewed (Brandt et al. 2015; Schwab et al. 2016a, b). In particular, Schwab et al. (2016b) summarize the continuous meteorological data available at both the summit (as early as 1937) and lower elevation Marble Lodge (as early as 1976) (Fig. 1). Below we note the value of these contributions to understanding the dynamics of the mountain forest ecosystem.

Vegetation-environment relations

The middle of the 20th century produced seminal research on plant ecology and vegetation–environment interactions along climate gradients in North America (Curtis 1959, Whittaker 1956). During this period, the ASRC initiated a study to characterize the vegetation communities on Whiteface and their relationship to the local environment (Holway et al. 1969). In total, 182 research plots were sampled for forest over- and understory structure and composition including 40 research quadrats in the alpine zone. The original forest stands have been re-measured (Scott et al. 1984), and subsequent research efforts (e.g., Wason et al. 2017b) have continued to monitor these plots. The value of these initial baseline studies of vegetation is further amplified by a detailed soil survey of the entire mountain (Witty 1968), a comprehensive assessment of soil biogeochemistry (Johnson et al. 1994b), and the long-term meteorological and atmospheric chemistry data at the summit and the base of the mountain (Schwab et al. 2016b).

Following the initial wave of vegetation research, Whiteface continued to be a key research location for vegetation and forest dynamics in parallel with other work in the neighboring Green (Siccama 1974) and White Mountains (Leak 1975, Reiners and Lang 1979). For example, fir-waves were first identified and described on Whiteface (Sprugel 1976, Sprugel and Bormann 1981). Fir-waves are a global phenomenon (Bekker and Malanson 2008) describing a migrating pattern of tree mortality and regeneration common in mountain forests dominated by *Abies* spp. As small canopy gaps open in the forest, exposed trees become more susceptible to mortality from the prevailing wind direction (Holroyd 1970) leading to a migrating front of mortality followed by a wave of regeneration (Fig. 4). Fir-waves have been reported to move 1–3 m per year and are an example of the dynamic nature of natural forest communities (Sprugel 1976), and recent research on Whiteface has elaborated on the importance of the moss layer in fir-wave regeneration in these high-elevation forests (Berdugo and Dovciak 2020).

Success story: From research on spruce decline to ecosystem recovery

In 1974, researchers from Hubbard Brook Experimental Forest, NH, published the discovery of widespread acid rain across the northeastern United States (Likens and Bormann 1974). The scientific community rapidly began assessing the ecological implications of acid rain (Fig. 3) including the direct impacts on organisms in streams and lakes (Cronan and Schofield 1979). However, a less obvious impact

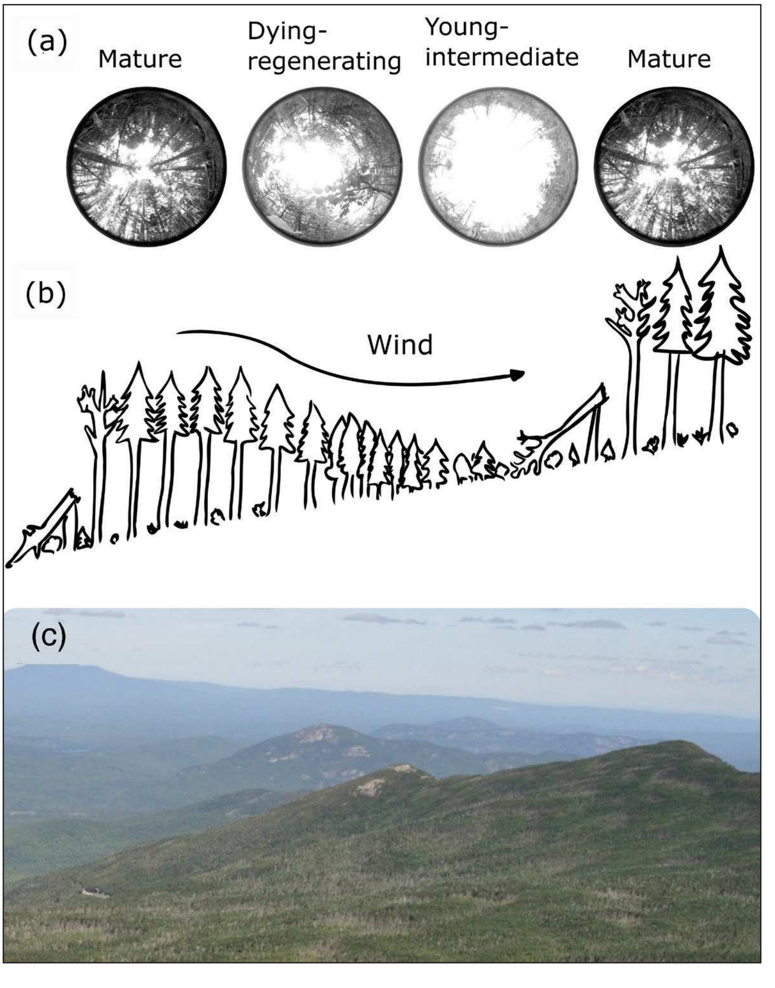

Figure 4. Fir-waves are migrating zones of mortality and regeneration that were first described on Whiteface Mountain and are found in mountain *Abies* spp. forests across the world. (a) Changes in canopy cover from hemispherical photos illustrate (b) the wave of regeneration following mortality of mature forest. (c) These patterns of wave-regenerated forests are clearly visible on the slopes of Whiteface Mountain as bands of dead trees. Panel (b) redrawn from Sprugel and Bormann (1981).

was also starting to emerge: the decline of Red Spruce observed on Whiteface (Scott et al. 1984) and other sites across the northeastern US (Johnson and Siccama 1983). Over years of study, scientists discovered that acidic precipitation deposited by clouds reduced the cold-tolerance of Red Spruce needles that would then often succumb to increased freezing damage in subsequent winters (DeHayes et al. 1999). Whiteface became a focal point for research on the decline of spruce. Not only did the mountain highway provide access to extensive spruce forests located in rugged terrain but also ASRC's emphasis on atmospheric chemistry provided extremely relevant local expertise. For example, ASRC scientists working at Whiteface were among the first to note that cloudwater was considerably more acidic than rainwater (Falconer and Falconer 1980). Research over the following 2 decades on Whiteface focused heavily on the decline of Red Spruce including the effects of acidic deposition (Miller et al. 1993b, Mohnen and Kadlecek 1989), causal mechanisms (Hamburg and Cogbill 1988, Johnson et al. 1988, McLaughlin et al. 1987), physiology and tree growth (Boyce 1995; LeBlanc 1990, 1992; LeBlanc and Raynal 1990), impacts on forest structure and competition (Battles and Fahey 2000; Battles et al. 1992, 2003), and ecosystem-level effects (Johnson et al. 1994a, b; Joshi et al. 2003). However, as the acidity of rainfall and cloudwater declined towards pre-industrial levels (Likens and Buso 2012), the intense interest in research on Whiteface and the funding for acid rain research began to decline (Fig. 3).

Nevertheless, the research on the decline of Red Spruce set the stage for research on the recovery of Red Spruce years later. The dominant feature driving recent growth patterns of Red Spruce is the large-scale reduction in the acidity of rainfall. Research on Whiteface helped to identify this growth surge in Red Spruce (Fig. 5; Wason et al. 2017b) and was accompanied by other studies demonstrating that the recovery of Red Spruce growth in these mountains was a regional phenomenon (Engel et al. 2016, Foster and D'Amato 2015, Kosiba et al. 2018, Wason and Dovciak 2017, Wason et al. 2019).

New Research Directions: Climate-change Effects on Sensitive High-elevation Ecosystems

Montane spruce–fir forests seem to be particularly vulnerable to climate change (Janowiak et al. 2018, Wason et al. 2017a). Leveraging historical datasets on Whiteface, studies have found that indeed, tree growth in these forests is sensitive to changes in climate (Wason et al. 2017b). However, contrary to some reports (Beckage et al. 2008), large-scale changes in forest composition and structure will likely take many years and lag behind accelerating climate change (Fig. 5; Wason et al. 2017b, Zhu et al. 2012). Instead, the major driver of recent regional forest change is ecosystem recovery following the decline in acid rain, impacts of pests and pathogens, and the localized effects of past forest management (Foster and D'Amato 2015, Verrico et al. 2020, Wason 2017b). However, the impact of climate change on forests in the region, and high-elevation forests in particular, is expected to increase over time (Janowiak et al. 2018, Koo et al. 2014). Recent research from Whiteface has built on the era of the early research on acid deposition by adding new data on forest microclimate. This fine-scale microclimate monitoring system is low-cost and was deployed under the forest canopy (Fig. 6) as part of a regional network of microclimate data on mountains (Wason et al. 2017a). In addition to links with the long-term climate data from Whiteface, historical aerosol and cloud data from the summit can contribute to a major knowledge gap in our understanding of climate systems (Lance et al. 2020, Pye et al. 2020). As climate-change research expands (Fig. 3), the value of these climate datasets (Fig. 6) and their implications for other ecosystem components is likely to increase.

A recent example of the important links between unique datasets at Whiteface is the combined impact of vegetation, climate, and pollution on montane boreal bird communities (Able and Noon 1976, Kirchman and Van Keuren 2017, Sauer et al. 2020). Indeed, Whiteface is one of many survey sites for the regional Mountain Bird Watch project of the Vermont Center for Ecostudies (https://vtecostudies.org/projects/mountains/mountain-birdwatch/). Importantly, Whiteface continues to

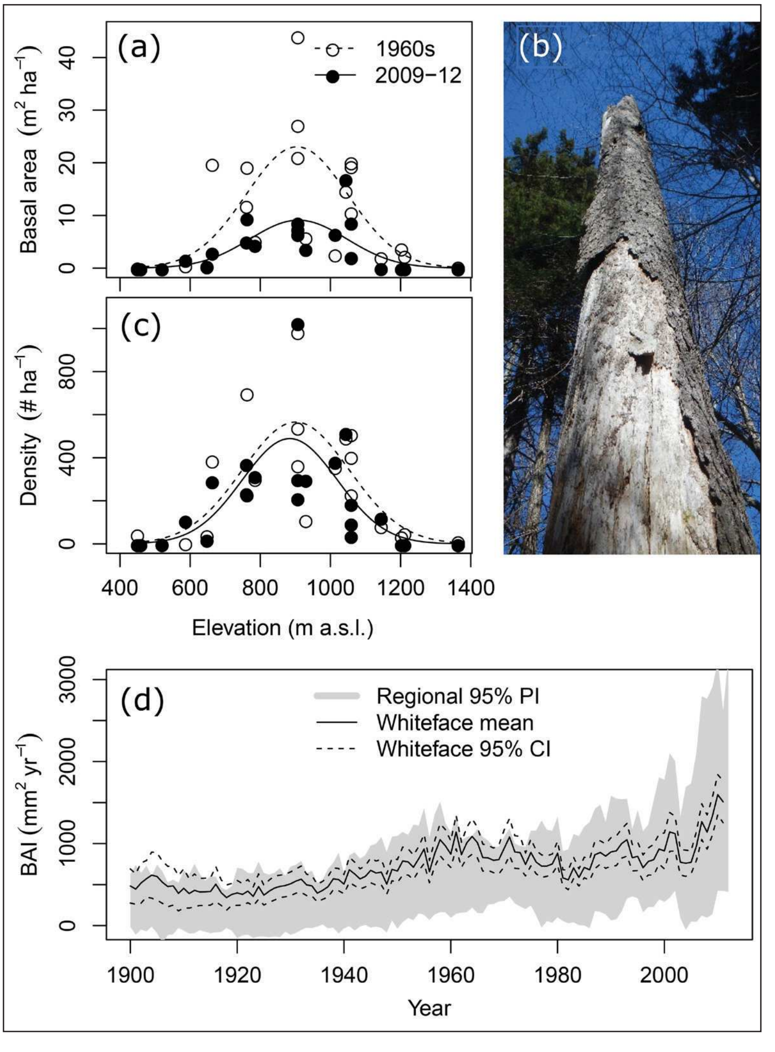

Figure 5. Red Spruce decline and recovery on Whiteface Mountain. (a) Major declines in Red Spruce basal area across elevation were driven by (b) canopy tree mortality. However, (c) saplings have persisted and maintained relatively stable tree density and (d) tree growth (basal area increment; BAI) has increased rapidly since ~2000 on Whiteface Mountain and across the region. Panels (a), (c), and (d) include data previously published and reprinted with permission (Wason et al. 2017b, Wason et al. 2019). PI = prediction interval, CI = confidence interval.

support other long-term research studies attracted to the mountain by the valuable infrastructure and long-term data on forests, climate, alpine habitats, and atmospheric chemistry (Berdugo and Dovciak 2020, Blackwell and Driscoll 2015, Boggs et al. 2007). Much of the historical data from Whiteface have been digitized and are available from recent publications or by contacting the ASRC Whiteface Mountain Field Station site manager. Some of the more recently collected atmospheric data are available from the ASRC's Air Quality Monitoring Products website (http://atmoschem.asrc.cestm.albany.edu/), the National Atmospheric Deposition Program

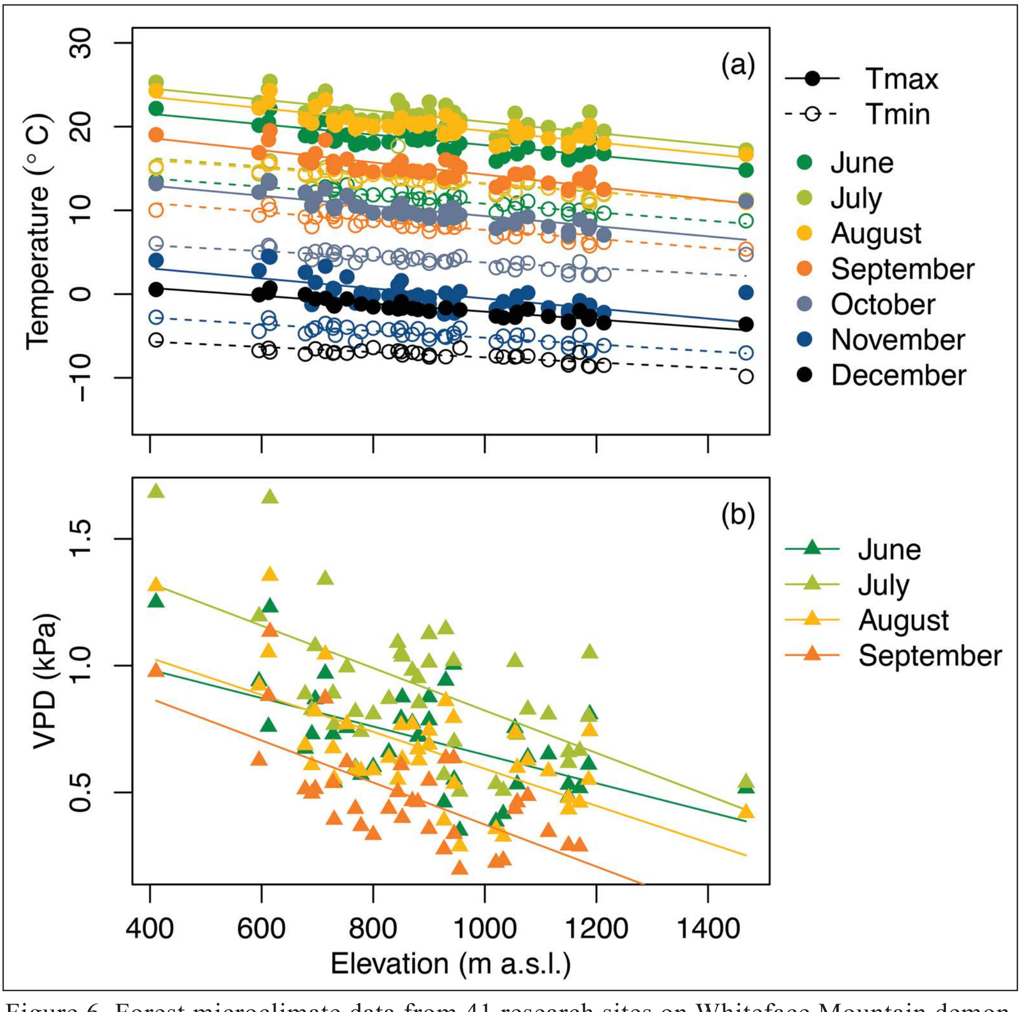

Figure 6. Forest microclimate data from 41 research sites on Whiteface Mountain demonstrate the intense level of detail available for both (a) temperature and (b) vapor pressure deficit (VPD, related to relative humidity). Temperature and humidity data were logged continuously every 2 hours from June through December 2011. Data were collected using iButton loggers housed in custom radiation shields and mounted 1 m above the ground (Wason et al. 2017b). Data are summarized as monthly means of daily maximum temperature (Tmax; solid circles), daily minimum temperature (Tmin; open circles), and daily maximum VPD.

(http://nadp.slh.wisc.edu/), the Clean Air Status and Trends Network (https://www.epa.gov/castnet), and the National Mesonet Program (https://nationalmesonet.us/). To better coordinate the increasingly diverse range of research occurring on the mountain and make it more widely available to researchers and the public, a major investment in data archiving is urgently needed.

The Success of Whiteface Mountain as a Sentinel Research Site

Research on Whiteface has made several key contributions toward our understanding of montane forest ecology and dynamics under changing environmental conditions over the past 60 years. Importantly, this rich history of long-term research into contemporary environmental problems and their effects on ecosystems provides a set of characteristics that made Whiteface successful and can inform the development and sustainability of other sentinel research sites in global change research (Table 1). The quality of the long-term data that are representative of the broader region is one of the most important characteristics driving the success of Whiteface. However, equally important to long-term success has been adequate infrastructure and staffing to support those research activities. ASRC and SUNY-Albany have been able to provide the continuity of funding and leadership needed to support baseline local staff and infrastructure. This continuity of funding and committed leadership has positioned Whiteface well to take advantage of the next wave of global change research. Indeed, a key pathway for this support was through

Table 1. Characteristics of Whiteface Mountain that contributed to its success as a valuable sentinel research site in global change research.

Characteristic	Details and examples
High-quality, long-term data	Continuous monitoring Integration into a broad research network Rigorous data management practices Multiple types of data available (e.g., climate, chemistry, biota)
Representative of broader area	Environment, biota, land-use history, environmental change drivers
Infrastructure and staffing	Research facilities (laboratories, field instrumentation) Accessibility Full-time staff for data management/facility maintenance
Support	Governmental support, often financial Community and public support (clear benefits to society and vice-versa) Research partnerships (University, research agencies) Education partnerships (local and remote institutions)
Communication and outreach	Connecting science to society Outreach and Education programs
Dedicated leadership and continuity	Long-term (>10 years) stability of regional land-use Short, mid, and Long-term planning Periodic assessments and improvement

fostering governmental and community support (e.g., The New York State Energy Research and Development Authority, New York State Department of Environmental Conservation) and developing research and education partnerships.

Another key to the success of Whiteface has been the summit observatory that acts as a unique tourist attraction. Communication and public outreach have been priorities on Whiteface since at least 1957 (Schaefer 1957) with the initial ideas to construct the "Museum of the Atmosphere" at the summit observatory. The summit observatory was originally funded by NSF and is now a top regional tourist attraction. Continually communicating the value of the research through the ASRC's Ray Falconer Natural History Lecture series and outreach activities coordinated with the Regional Office of Sustainable Tourism ensured that the research stayed relevant and its value to stakeholders was clear. As research on Whiteface continues to shift, investment in communication and outreach activities that take advantage of its unique characteristics and visitation will be critical to continued success. Finally, collaboration with the ASRC provided dedicated and continuous leadership that has been key for anticipating challenges and opportunities to ensure long-term sustainability of Whiteface as a sentinel research site.

Investment in the long-term research program at Whiteface and other sentinel sites in the region provided key environmental insights that would not have been possible otherwise. Importantly, there was a substantial regional "return-on-investment" because findings from acid rain research were used to improve environmental regulations and air quality that had cascading effects on regional forest and human health, tourism, and recreation opportunities, and fostered a healthier forest industry. By maintaining and investing in the research infrastructure at Whiteface as one of the key sentinel research sites, we can continue to reap the benefits of the long-term data available there and leverage those data as we approach the next big environmental challenges either known or unknown at this time.

Acknowledgments

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