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ARTICLE

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Novel threats and response to Acadia National Park forests: Simulating the resist–accept–direct management framework

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Abstract

How future pathogens will interact with climate change to affect forests is unknown. While specific predictions of complex interactions may be unreliable, exploring a gradient of disturbance severity and management can be informative. We simulated forests in Acadia National Park (ANP) in Maine, USA, under climate change. Rather than simulate known pathogens, we explored black swan disturbances—that is, unknown pathogens having large consequences. Specifically, we simulated a low and high severity pathogen affecting the dominant species in ANP (red spruce [*Picea rubens*]) along with a drought scenario affecting all species. We coupled these disturbances with management under the resist–accept–direct (RAD) framework: resist management included planting red spruce as a replacement, accept included continuing ANP business-as-usual management, and direct included planting novel climate adapted species. Under the black swan disturbances, spruce declined relative to the severity of the disturbance. Resist management resulted in moderate resistance to the loss of red spruce when disturbance severity was low, but had little effect when disturbances were more severe. The direct management resulted in the greatest increase in total biomass. However, this represented the greatest shift in species composition and shifts in the current management approach. Exploring black swan disturbances within the RAD management framework provided a useful intensity gradient of plausible management scenarios. There is huge uncertainty in the structure and function of future forests in ANP. While our results suggest ANP forests will be resilient to climate change, interacting disturbances may result in declines in specific species. In considering these threats, this research provides an assessment of a gradient of management responses.

KEYWORDS
black swan disturbance, forest management, forest pathogen, LANDIS-II, resist–accept–direct

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INTRODUCTION

There is great uncertainty in how current and future shifts in climate and interacting disturbances will affect Acadia National Park (ANP) and more broadly the temperate-boreal transition zone in which ANP occurs. The future trajectory of climate change and related impacts is unknown due to uncertainty in emission pathways and limited knowledge of tree responses to climate and interacting stressors. Coastal regions of Maine, such as ANP, have experienced greater shifts in temperature than further inland (Fernandez et al., 2020). A future pathogen or other disturbance that interacts with a changing climate may have significant and devastating consequences for ANP's forests, with potentially cascading effects on ecosystem functions, forest-dependent taxa, and visitation and public safety as dying trees become hazards along roads and trails. Thus, there is a desire for managers and ecologists to assess through modeling the potential future forest.

Forests in ANP offer a unique landscape of conserved forests within a region that is otherwise largely affected by an active and intensive land-use regime (Duveneck & Thompson, 2019). Given their protection from logging for over a century (Miller et al., 2016), the National Park Service mandate to protect cultural and natural resources unimpaired for future generations (National Park Service, 1916), and ongoing long-term forest monitoring efforts (e.g., Miller et al., 2016), forests in ANP also offer a unique opportunity to examine current and future threats. Receiving nearly 4 million visitors annually and contributing over US$744 million in economic benefit to the region in 2024 alone, the fate of ANP's forests is important beyond the boundaries of the park (Flyr et al., 2025; National Park Service, 2024).

Based on pollen records from the past several thousand years, we know that ANP provided coastal spruce refugia during historic warmer periods when inland sites experienced a loss (Schauffler & Jacobson Jr, 2002). However, climate change is now exceeding those warmer periods. Previous modeling research of forest tree distribution, disturbance, and climate change exists that encompass ANP's footprint (e.g., Duveneck & Thompson, 2019; Iverson et al., 2019; Wang et al., 2017); however, those efforts were not designed for the management-relevant resolution required to assess microscale composition, disturbances, and climate for the region. Other research from the Acadian region has explored how potential habitat of ecotone species like spruce will fare under climate change (e.g., Andrews et al., 2022; Fisichelli et al., 2014). These models, focusing on potential habitat, largely show a decline in spruce under climate change in the region.

The resist–accept–direct (RAD) framework (Schuurman et al., 2022) provides a gradient framework of management strategies from resisting change, to accepting change, to directing change. Resist provides a strategy to maintain current conditions by resisting change. Accept allows nature to function with limited management intervention. Direct provides the most intensive intervention by allowing managers to direct change (e.g., independent of historical conditions). Today, managers seek and require local (finer) scale information that will inform decisions such as how, when, and where to implement management actions. Although previous modeling within ANP included climate change and management response, the scale was limited in its ability to effectively inform management within ANP.

Specific effects to future ANP tree species under future climate are also unknown. Some models covering the ANP region suggest red spruce (*Picea rubens*), the dominant tree species in ANP's forest (Lubinski et al., 2003), will decline in biomass (Simons-Legaard et al., 2025), or will decline in suitable habitat under a future climate (Andrews et al., 2022; Iverson et al., 2008, 2019). However, other modeling efforts suggest that longer growing seasons under a future climate will be beneficial for spruce biomass and other New England forest species (Duveneck & Thompson, 2017, Duveneck & Thompson, 2019). Historical provenance trials conducted in eastern Canada suggested that warming experienced by spruce individuals collected from cooler provenances was not yet harmful to spruce growth, and that the northern range of red spruce remained cold-limited (Li et al., 2020). Empirically, we observe strong regeneration of boreal species including spruce in Maine (Miller & McGill, 2019) and ANP (Miller et al., 2023) suggesting that the potential for a future boreal forest exists, at least for the moment, at the seedling stage.

Ultimately, the largest source of uncertainty may come from an unpredictable or currently unknown disturbance or combination of disturbances that have the potential to interact with climate change. These, "black swan events" (Orlik & Veldkamp, 2014) are by definition unexpected with large consequences. These black swan disturbances could be associated with land use, fire, drought, insects, and/or other pathogens. For example, mountain pine beetles (*Dendroctonus ponderosae*) in western North America (Sambaraju & Goodsman, 2021) and hemlock woolly adelgid (*Adelges tsugae*) in eastern North America (Ellison et al., 2018) have each experienced warmer winters resulting in less insect mortality and large increases in tree mortality. And locally, beech leaf disease (BLD), an emerging pathogen known to be linked to increased temperature and changing moisture regimes (Zhao et al., 2023), was first detected in ANP in

2022 and has spread rapidly (Maine Forest Service, 2024). How climate change will interact with future disturbances is indeed unknown (and exceedingly challenging to predict). Recently, however, physiologically based spatially explicit forest simulation models have proven useful for exploring "what if" scenarios (e.g., MacLean et al., 2021). These simulations have provided planners plausible future scenarios to help guide management decisions. Despite the potential for black swan events to cause rapid and dramatic shifts in forest composition and function, they are rarely incorporated in models predicting forest response to climate change, nor are they often considered while planning for climate change. To fill these gaps, we explored scenarios of significant and unexpected disturbances in ANP forests, including two scenarios of unknown cause to widespread spruce decline, and a prolonged extreme drought at a magnitude not experienced over the more than century-long history of the park. While black swan events are unpredictable by definition, we selected a range of no-analog scenarios to represent black swan events likely to have large effects. Furthermore, we explored plausible management responses to these disturbances. As a starting point, we explored the resilience of the current ANP forests to future climate change. We then explored the possible outcomes of a black swan disturbance on ANP forests. Finally, we examined how the RAD framework could be used to manage forests under uncertain future disturbances. The results of this study are both directly relevant to managers in ANP and the broader transition zone. Results also demonstrate the importance of both investigating black swan events and incorporating them into adaptive management and planning for climate change.

METHODS

Study area

Our study area encompassed ANP along the northeastern coast of North America (Figure 1). This 15,289-ha national park is largely surrounded by the Atlantic Ocean, with many islands, the largest of which is Mount Desert Island (MDI). ANP soils are primarily shallow acidic soils. These soils contribute to relatively slow vegetative growth. Loam and sandy loam soil textures are commonly found throughout ANP. The vegetation within ANP is dominated by red spruce, which represents 47% of live tree species density and basal area (Lubinski et al., 2003) (Figure 1). Other common forest species include white pine (*Pinus strobus*), balsam fir (*Abies balsamea*), and red maple (*Acer rubrum*) (Lubinski et al., 2003).

A disturbance regime at ANP comprised of frequent low intensity disturbances, such as windthrow (since forests regenerated after 19th century logging and land clearing), has resulted in the dominance of late successional shade-tolerant conifers (Davis, 1966; Seirup, 2024). The exception is the region of eastern MDI that experienced a large stand replacing fire covering over a quarter of MDI in 1947 (Patterson et al., 1983). Today, much of this part of the landscape stands out as transitioning from earlier successional deciduous species to red spruce (Wheeler et al., 2015) (Figure 1). The climate at ANP is moderated by the surrounding ocean with cooler summers and warmer winters (compared to the surrounding region) but has been warming in recent decades and is expected to continue to change (Conkey et al., 1995; Fernandez et al., 2020).

Experimental design

To simulate forest change across ANP from 2010 to 2110, we used the LANDIS-II forest landscape model (v.7) (Scheller et al., 2007) within 30 m cells. The LANDIS-II model has been widely used throughout temperate forests to simulate climate interactions with forests (e.g., Gustafson et al., 2016) and specifically within temperate-boreal transition zones of the northeast (e.g., Duveneck & Thompson, 2017, Duveneck and Thompson, 2017; Maclean et al. 2021). Species in LANDIS-II are represented as cohorts that grow biomass, age, regenerate, and senesce. These species-age cohorts can have one-to-many each within cells. Species are represented by user-defined species traits such as longevity, shade tolerance, and sexual maturity age. Species-specific natural regeneration within each site is modeled as a probability of establishment based on the distance of mature cohorts to each source cell and the site conditions of each site (i.e., water and light). We simulated 21 scenarios stratified across varying climate, disturbance regimes, and management (Table 1). We simulated both "historic" climate and climate change. The historic climate was estimated by the 800 m Parameter-elevation Regressions on Independent Slopes Model model (Daly & Gibson, 2002) based on the period from 1981 to 2013 utilized by previous research (Duveneck & Thompson, 2019). In order to represent climate variation within each simulation we imputed randomly selected years from the historical time series to populate simulated climate inputs. Climate change was simulated with the RCP 8.5 emission scenario coupled to the Community Climate System Model (CCSM4) Global Circulation Model (GCM). Climate included monthly projections of precipitation, temperature, carbon dioxide, and light. Climate projections were delineated across the landscape within relatively homogeneous

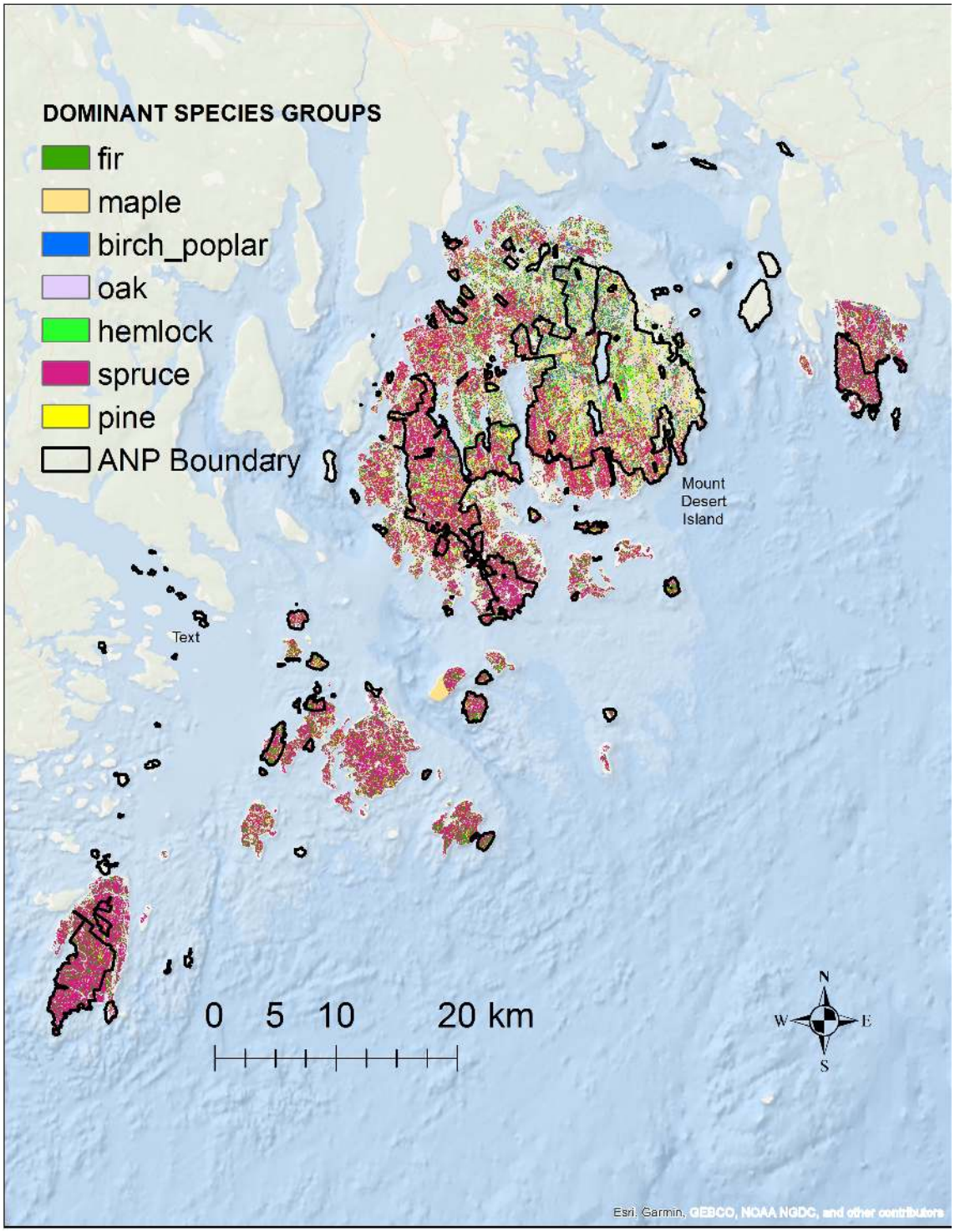


FIGURE 1 Study landscape extent shown on this map where dominant species groups exist. Note that the study landscape encompassed Acadia National Park (ANP) and also includes some of the surrounding islands. Dominant tree species groups were based on initial simulation conditions.

regions of observed temperature and precipitation (i.e., climate regions). In addition to simulating disturbance and management scenarios described below, we simulated grow-only scenarios where no disturbance nor management was implemented.

We simulated three separate unexpected "black swan" disturbance regimes. We did not attempt to predict a specific disturbance regime, rather simulated three future unexpected disturbance regime pathogens (*slow, fast*, and *drought*) that we expected to have a large effect

TABLE 1 Experimental design for simulated scenarios numbered 1:21.

Disturbance	Management	Historical climate	Climate change
Grow	None	1	11
Fast pathogen affecting spruce	Accept (no planting)	2	12
	Resist (plant spruce)	3	13
	Direct (plant other spp.)	4	14
Slow pathogen affecting spruce	Accept (no planting)	5	15
	Resist (plant spruce)	6	16
	Direct (plant other spp.)	7	17
Drought affecting all species	Accept (no planting)	8	18
	Resist (plant spruce)	9	19
	Direct (plant other spp.)	10	20
Medium pathogen affecting spruce	Accept (no planting)		21

on the landscape. The slow pathogen disturbance regime causes mortality to 3% of red spruce biomass every year across 80% of cells on the landscape starting at year 2020 and continuing until the end of the simulation. The fast pathogen disturbance regime caused mortality to 100% of red spruce biomass within patches starting at year 2020 resulting in 80% of the landscape affected by these patches by year 2035. We delineated patches using the LandscapeR package in R (Thomas et al., 2020) by creating patches randomly on the landscape between 10 and 1000 cells in size. The remaining 20% of the landscape for both the slow and fast pathogen scenarios were unaffected by the simulated pathogens to emulate isolated resistant patches of the landscape. Unlike the species-specific slow and fast disturbance regimes, drought affected all species. Our drought regime consisted of simulating a 10-year drought starting in 2070. Drought was simulated by reducing the otherwise predicted precipitation by 75% per month during the drought period for each climate scenario.

Management regimes followed the RAD framework to resist, accept, and direct. The resist management response was based on the goal to resist the loss of red spruce. The scenario included planting red spruce within 10% of all disturbed sites every 5 years starting in 2030 (and starting in 2055 when coupled to the drought scenarios which started later than slow and fast). The accept management response was a business-as-usual response, which is by-in-large the recent approach to forest management implemented by ANP. The current business-as-usual response at ANP typically includes extensive monitoring to assess extent and impact, and managing invasive plants, where detected (mostly shrubs), but otherwise allows overstory trees to develop through dispersal, recruitment, and successional processes without management intervention (Lima et al., 2024).

The direct management response included planting climate-adapted species within 10% of disturbed sites every 5 years starting in year 2040 (and 2055 when coupled to the drought scenarios). The direct scenario was based on the assumption that red spruce would not persist. Rather, in this set of scenarios, we assumed that *other* more climate-adapted species would provide favorable ecosystem functions to ANP. Specifically, in the direct scenario, we planted chestnut oak (*Quercus prinus*), pignut hickory (*Carya glabra*), and loblolly pine (*Pinus taeda*). We selected these species in consultation with ANP management based on species that are predicted to do well under climate change (Iverson et al., 2019) rather than species already present in ANP (e.g., red maple and white pine). Modeling the potential benefits of introducing new species is informative to management. Additionally, current species dispersal and recruitment are already accounted for in the models. The northern range of chestnut oak and pignut hickory are within 100 km of ANP. The northern range of loblolly pine is further south. We selected loblolly pine as a potential functional replacement for red spruce, as it is one of the more shade-tolerant southern pine species. However, loblolly pine is considerably less shade tolerant than red spruce.

As a separate scenario (outside the RAD management framework), we simulated a "recovery" scenario in order to explore regions that could be future spruce refugia. In this recovery scenario, we included climate change and a "medium" disturbance that removed 40% of the red spruce biomass from 2020 to 2090 in 80% of sites. We assumed business-as-usual management for this scenario (i.e., the "accept" approach). We then allowed the spruce to recover for the final 20 years of the simulation and assessed the spatial distribution of spruce biomass within disturbed sites within a 5×5 moving window across 30 m cells. We then examined the spatial pattern of potential spruce recovery to identify regions within ANP that could be good future spruce refugia.

To simulate succession, we used the PnET-Succession physiological model (v 5.1) (Gustafson et al., 2024) that is coupled to LANDIS-II. PnET-Succession simulates photosynthesis for each cohort based on physiological demands including water, light, and foliar nitrogen. Through photosynthesis and respiration processes cohorts accumulate biomass. Cohorts are then assigned to vertical layers based on their size. Competition among cohorts within layers is controlled by cohort demands where the largest cohorts generally are given access to water and light resources first. New to PnET-Succession v.5, cohorts can occupy partial space, (i.e., less than 100% of a canopy layer) allowing better representation of competition and cohort sharing of light within a stand (Gustafson et al., 2024). In addition, we utilized the Land Use Plus (Thompson et al., 2016) extension to LANDIS-II in order to simulate the disturbances and management response. Land Use Plus is coupled to the Biomass Harvest (Gustafson et al., 2000) extension, which allows input maps (e.g., disturbance maps) to be developed external to LANDIS and provide temporal and spatial explicit representation of disturbances and management response. We evaluated total aboveground biomass (AGB) density within each scenario as well as individual species biomass density.

To represent initial conditions, we used a 30 m initial vegetation layer based on a wall-to-wall imputed Forest Inventory and Analysis (FIA) plot following imputation methods described by McRoberts et al. (2007). We evaluated this FIA layer against independent permanent plots within ANP (Miller & Seirup, 2024) and found that species biomass density as measured by the imputed cells across ANP were within ±1 SD of permanent plot biomass density. We used surface soil texture and rooting depth based on the SSURGO database. Given the high computational time and "what-if" scenario design, we did not simulate multiple replicates; rather we evaluated multiple scenarios of a single replicate. Validation of model behavior (simulated species biomass growth) against independent data is described previously in Case Study D in Reese et al. (2024). Further description of model sensitivity can be found in McKenzie et al. (2019), and evaluation can be found in Duveneck and Thompson (2017) and Maclean et al. (2019). All post model processing was done with the terra package (https://github.com/rspatial/terra) in R. Input files to the scenarios simulated are available from Zenodo: https://doi.org/10.5281/zenodo.19946262.

RESULTS

No-disturbance scenario effects

Under succession and climate change (in the absence of other disturbances), the "accept" management scenario (i.e., business-as-usual management), resulted in a 96% increase in simulated total aboveground biomass (AGB) by 2110 compared to starting conditions (Figure 2). This can be compared to a 64% increase in total AGB experienced by the historical climate scenario under business-as-usual management. As red spruce makes up a large proportion of the total biomass, red spruce AGB largely followed the trajectory of total biomass, with a 95% and a 57% increase under climate change and historical climate, respectively. Indeed, the landscape started with 43% of cells dominated by red spruce. At the end of the simulations with succession only (no disturbance), red spruce dominated 42% and 47% of cells under the historical and climate change scenarios, respectively. White pine and red maple also responded positively to climate change alone.

The historical climate scenarios were more favorable to balsam fir compared to climate change. Balsam fir biomass increased by 247% at the end of the simulation compared to starting conditions under historical climate. Under climate change, balsam fir AGB increased until 2060 and then leveled off and decreased by the end of the simulation. Despite the mid-century decline under climate change, balsam fir still resulted in an overall 82% increase in AGB compared to starting conditions. In the absence of disturbance, these climate change results reflect an increase in atmospheric carbon dioxide likely resulting in a fertilization effect along with longer growing seasons where net photosynthesis exceeds increased respiration demands (Duveneck & Thompson, 2017).

Black swan disturbance effects

The "slow" disturbance scenarios resulted in a steady decrease in simulated red spruce biomass throughout the simulation (Figure 2). Specifically, red spruce experienced 42% and 14% less biomass than starting conditions for the historical and climate change scenarios under "accept" management at the end of the simulation. Despite the steady decline in red spruce, the slow disturbance allowed substantial persistence of red spruce. Indeed, by the end of the simulation, red spruce was still the dominant species on 19% and 25% of sites throughout ANP under historical and climate change, respectively. In terms of total biomass, the slow disturbance resulted in a 45% and 58% increase in total biomass for the historical and climate change scenarios, respectively. This represents a decline in red spruce, but an increase in other species. Indeed, balsam fir, white pine, and red maple all responded to the slow disturbance with greater biomass compared to the grow-only scenario.

Under historical and climate change, the "fast" disturbance scenario resulted in a 69% and 61% reduction in

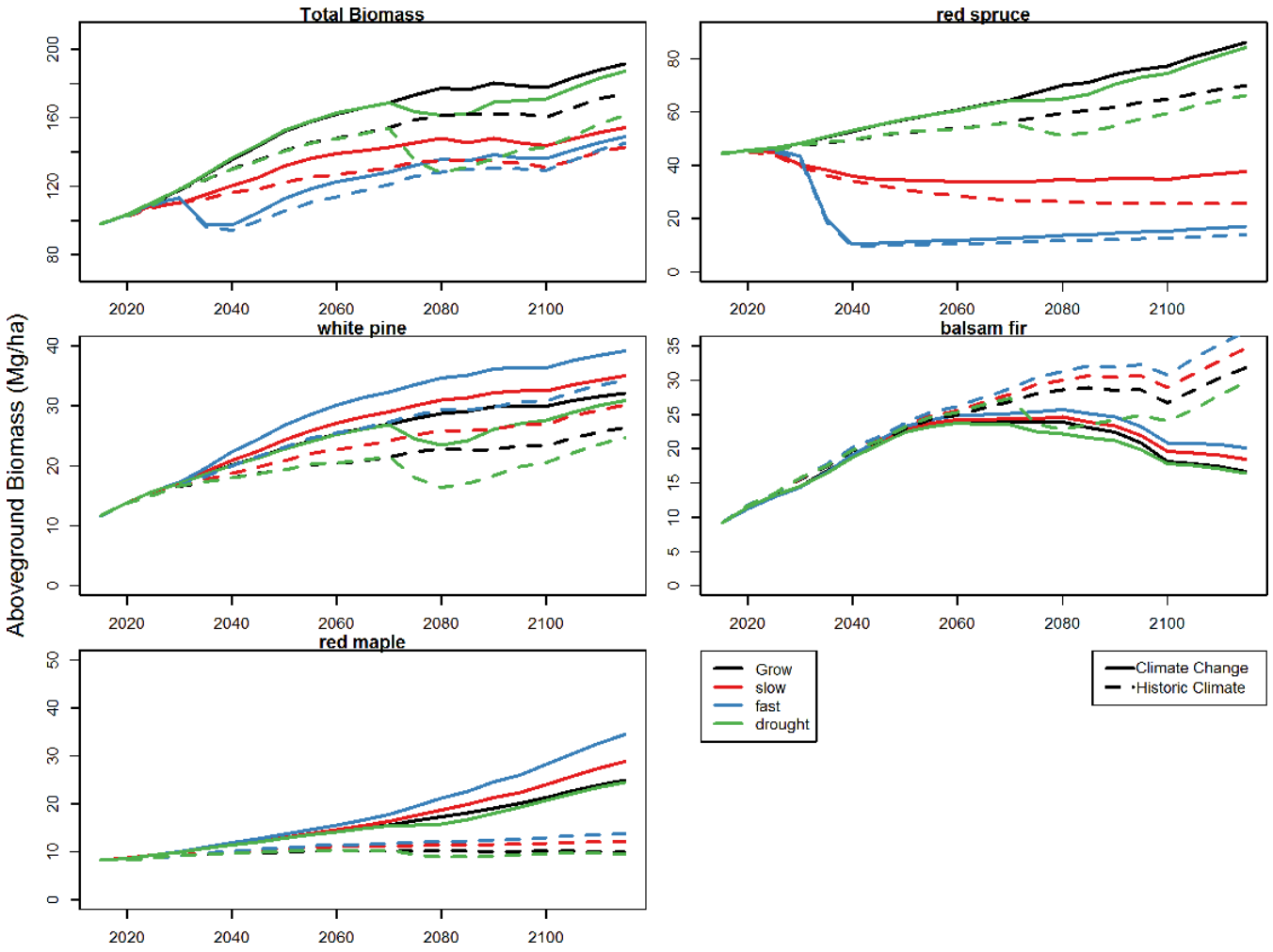


FIGURE 2 Average simulated total and species aboveground biomass over time. Scenarios represented in this figure include each disturbance and climate scenario coupled to the accept management regime. Species shown here include only the four most dominant species simulated.

simulated red spruce biomass under the "accept" management scenario. By the end of each simulation, this resulted in only 0.1% red spruce dominance on the landscape for both the historical and climate change scenarios. However, the large decrease in red spruce still resulted in an increase in total biomass made up of the other species. Specifically, total biomass under the fast disturbance scenario with business-as-usual management resulted in a 47% and 52% increase, respectively under historical climate and climate change. Balsam fir, white pine, and red maple all responded to the fast disturbance with greater biomass compared to the grow-only scenario.

Unlike the spruce-specific pathogen simulated with the fast and slow disturbance scenarios, the drought disturbance affected all tree species (Figure 2) but was generally less severe than the slow and fast scenarios. Although the drought scenarios resulted in a reduction in total biomass mid-century (during the simulated drought), recovery post-drought resulted in 64% and 91% more biomass than starting conditions for the historical and climate change scenarios, respectively. Likewise, under the drought scenario, red spruce resulted in a 48% and 91% increase in simulated biomass over the course of the simulation under the historical and climate change scenarios, respectively. Compared to the grow-only scenarios, the end of the drought simulations were similar among species. For species dominance on the landscape, the drought scenario resulted in similar red spruce (i.e., 42% and 48% for the historical and climate change scenarios, respectively) compared to starting conditions (i.e., 43%). The drought scenarios also reduced biomass for white pine, balsam fir, and red maple slightly compared to the grow-only scenario for both historical and climate change.

MANAGEMENT (RAD FRAMEWORK) EFFECTS

Management effects from the RAD framework are described here for the climate change scenario (Figure 3). Additional management effects under historical climate

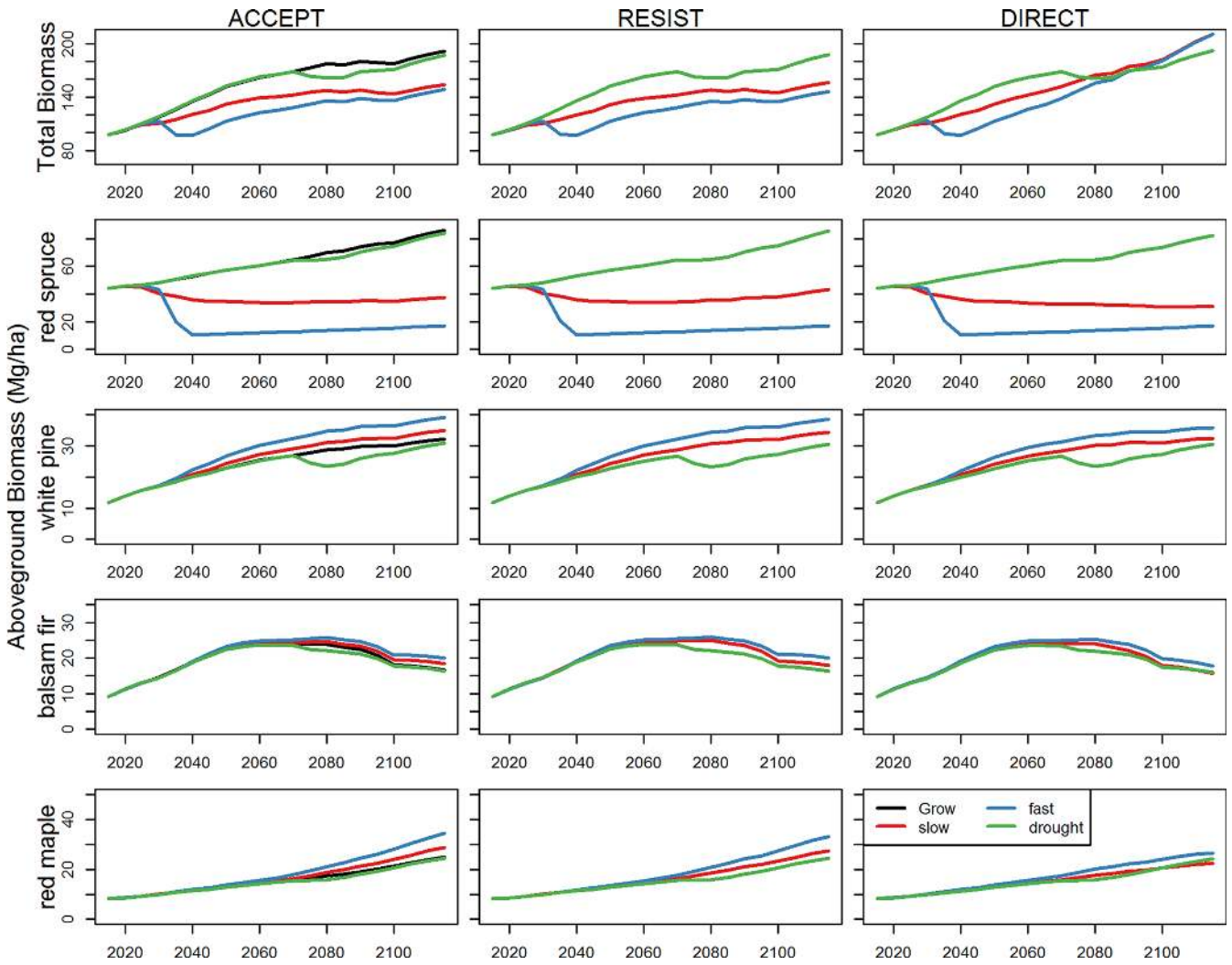


FIGURE 3 Mean aboveground biomass and dominant species biomass for each management and disturbance scenario under climate change.

are included in the Zenodo deposition (https://doi.org/10.5281/zenodo.19946262). The effects of the accept scenarios were described above under disturbance effects as accept implies business-as-usual management; the resist and direct management scenarios are described below.

The resist scenarios (i.e., planting red spruce) had moderate effects on red spruce biomass under the slow pathogen but no positive effects under the fast pathogen scenarios. Specifically, under the slow pathogen disturbance, the resist scenario resulted in 1.6% more total biomass and 15% more red spruce biomass at year 2110 compared to the slow pathogen disturbance under accept (business-as-usual management) (Figure 3). Under the fast pathogen disturbance, the resist scenario resulted in 1.7% less total biomass and 1% less red spruce biomass at year 2110 compared to the fast pathogen disturbance under accept (business-as-usual management). The resist scenarios had minimal effects on other species. For example, red maple under the fast pathogen and resist management resulted in 3.6% less biomass at year 2110 compared to the accept management scenario.

Under the drought disturbance scenarios, the resist scenario resulted in 0.5% and 1.9% more total and spruce biomass, respectively in the year 2110 compared to accept management. Unlike the slow and fast disturbances, drought directly affected all species as described earlier (Figure 2). The effects on other species under resist coupled to drought were minimal.

The direct management scenarios (i.e., planting climate adapted species) resulted in the greatest increase in total biomass. For example, under both the slow and fast disturbance scenarios, direct management resulted in a 115% increase in total biomass from starting conditions. This represented 36.6% and 41.6% greater total biomass than the accept management for the slow and fast disturbance, respectively (Figure 3). As the direct scenario

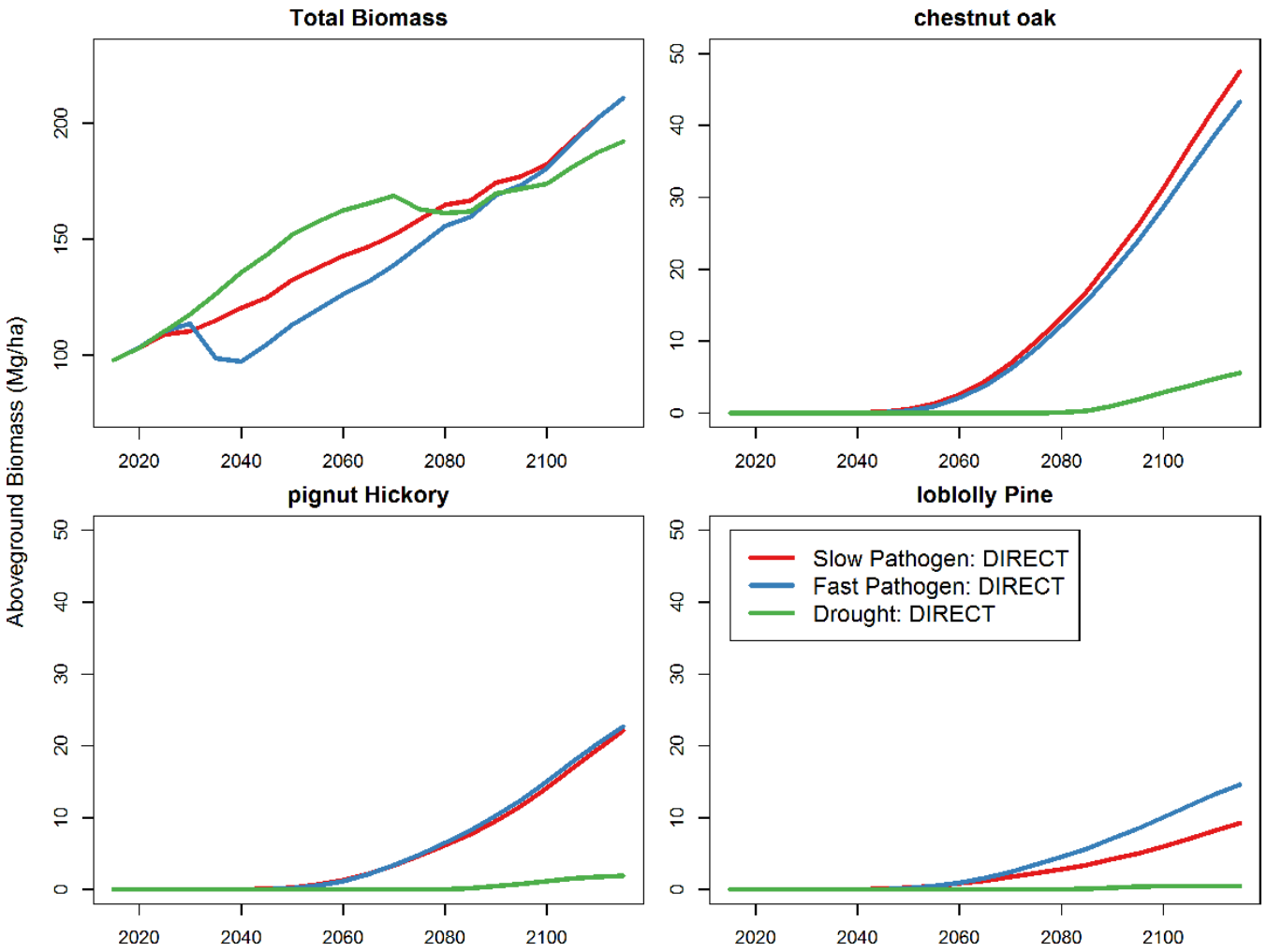


FIGURE 4 Simulated total biomass and each planted species for the direct management scenarios under climate change over time.

favored non-red spruce species, the increase in total biomass came at the expense of an 18% and 1% reduction in red spruce biomass compared to the accept management at year 2110 under slow and fast disturbance, respectively. Under the drought disturbance scenario, direct management resulted in a 96% increase in total biomass from starting conditions representing a 2.7% increase in total biomass compared to the accept disturbance scenario at year 2110.

All three planted species under the direct management scenarios responded positively to the disturbance scenarios (Figure 4). Chestnut oak experienced the largest increase in simulated biomass, especially under the slow and fast disturbances. The slow disturbance resulted in more chestnut oak compared to the fast disturbance; however, loblolly pine biomass increased more with the FAST disturbance. Compared to the FAST and slow disturbances, the drought disturbance did not result in large increases in the planted species.

Spatially, some components of the landscape experienced more shifts than others under each set of scenarios. Under climate change, fast disturbance, and direct management, the proportion of cells dominated by each forest type (species group) suggests that as spruce declined, cells dominated by oak species increased while birch/poplar, hemlock, maple, and northern pine stayed relatively stable (Figure 5, inset). The southern pine group (i.e., loblolly pine) dominated only a small proportion of cells as also indicated by its minor biomass contribution under these scenarios (Figure 4). Cells dominated by fir declined even though fir was not directly targeted by the direct disturbance. Spatial variability of forest type change included less shifts in eastern MDI than other parts of ANP. This represents the targeted (red spruce) and severe disturbance regime of the fast disturbance. In eastern MDI (i.e., the area burned in the 1947 wildfire), the current vegetation represents relatively less red spruce and more early successional species. Thus, the

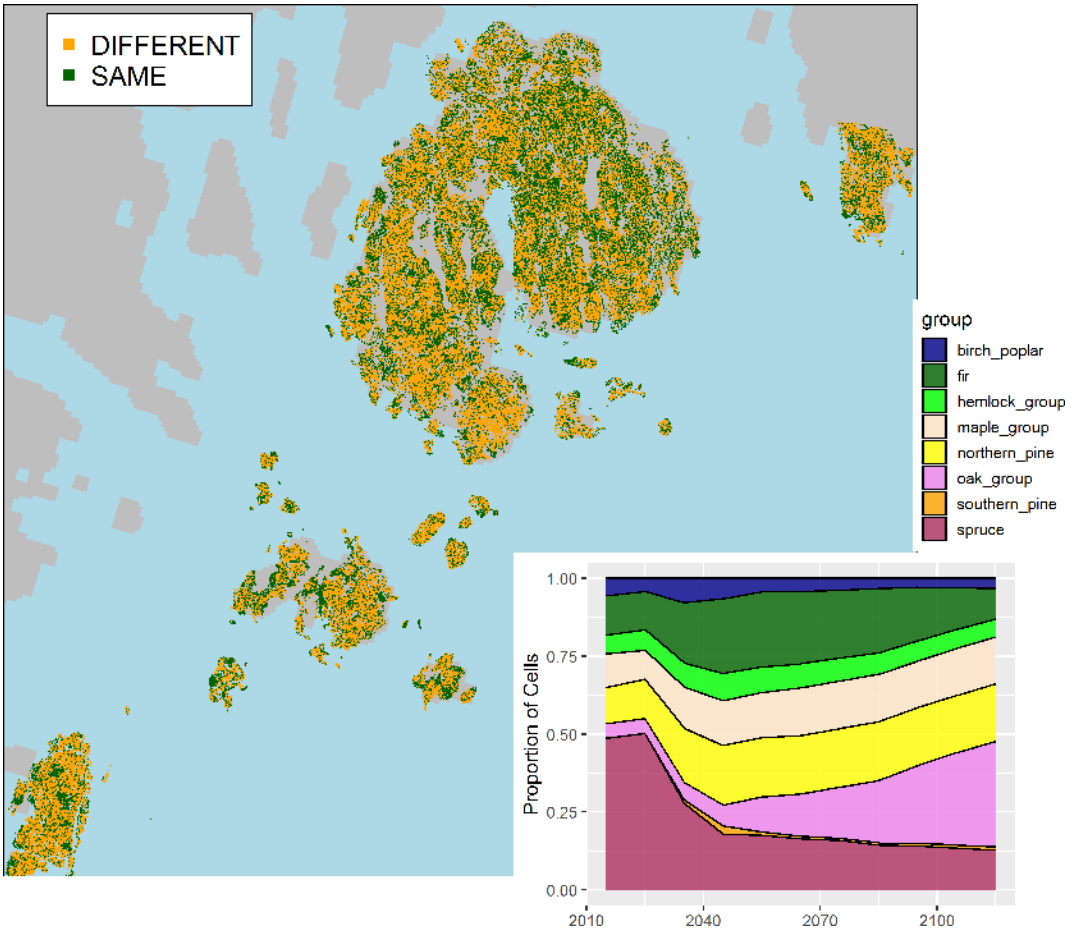


FIGURE 5 Spatial extent of the study area showing sites where forest types (species groups) compared to starting conditions stayed the same and changed after 100 years under climate change under both a fast disturbance and direct management. The inset shows how the proportional area of all cells on the landscape changed over time in terms of dominant forest types. In this scenario, for example, results show spruce forests were greatly reduced in area in the first few decades while oak forests expanded in area.

targeted spruce disturbance had less of an effect in this part of the landscape resulting in more similar forest types after 100 years. Additional scenario figures of forest maps are found in the Zenodo deposition (https://doi.org/10.5281/zenodo.19946262). Under the "recovery" scenario (where we simulated a "medium" pathogen intensity until 2090 and then allowed the spruce to recover for the remaining 20 years without management intervention) we found limited spatial patterns in spruce biomass recovery (Figure 6). Low, medium, and high spruce recovery sites occurred scattered across the landscape.

DISCUSSION

This modeling research suggests ANP red spruce, and forest carbon in general, may be resistant to the next century of climate change; though interacting disturbances may result in episodic declines in specific species and total ecosystem carbon. These results are in contrast to other studies, particularly species distribution modeling approaches that have projected major loss or extirpation of red spruce suitable habitat in the ANP region (e.g., Andrews et al., 2022; Fisichelli et al., 2014). Moreover, there is presently abundant red spruce in the understory (Miller et al., 2023), and this modeling shows red spruce to continue to outcompete other species under climate change. In the absence of large disturbance, this would result in the continued red spruce dominance in the future forest. While previous modeling efforts also suggested continuation of forest cover in the coastal northeastern region, major shifts in canopy composition were often predicted (Duveneck et al., 2017, Duveneck & Thompson, 2019, Liang et al., 2018, Wang et al., 2017). Further field-based and modeling assessments are needed to better understand how warming temperatures, drought stress, and related changes will impact growth and survival of spruce and other tree species.

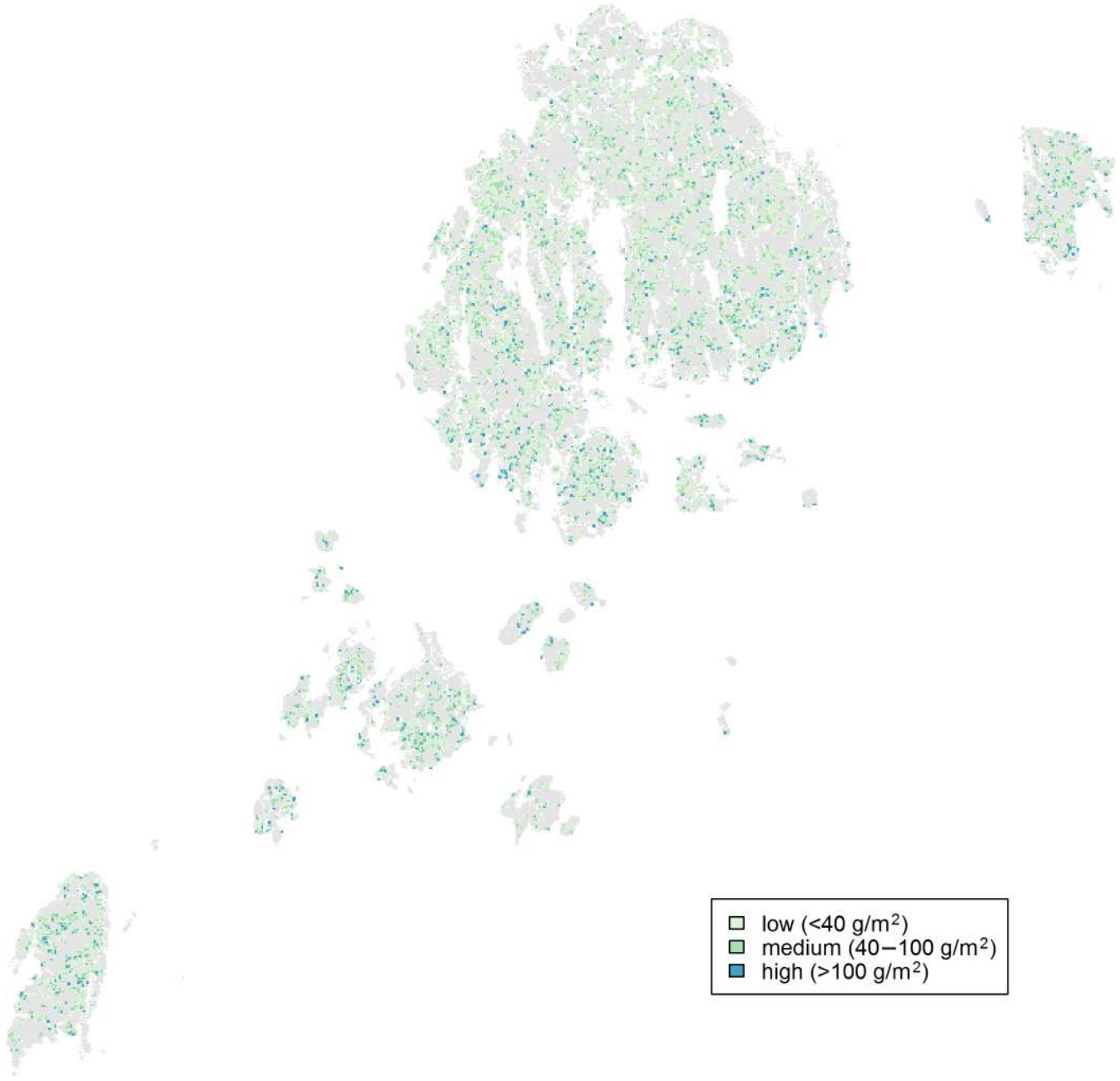


FIGURE 6 Spatial distribution of spruce biomass under the "recovery" scenario at year 2080. Spruce-occupied sites within disturbed patches is classified by the low, medium, and high abundance of aboveground biomass and a 5 × 5 moving window across 30-m cells. Sites with high spruce biomass (i.e., refugia) within the recovery scenario indicate where spruce may be more resilient.

The coastal region around ANP and elsewhere may act as a climate refuge for species that would otherwise be sensitive to large swings in temperature (Carroll et al., 2023; Schauffler & Jacobson, 2002). Indeed, the marine influence provides a tempering of climate extremes (Conkey et al., 1995; Fernandez et al., 2020).

Red spruce is both dominant in ANP and has unique life history traits. Specifically, red spruce is one of the most shade-tolerant conifers in the region. If a species-specific disturbance (such as those simulated) were to remove spruce, other species are likely able to fill in the biomass lost to spruce (e.g., Figure 2). However, the species responding to such a disturbance would likely not be made up of shade-tolerant conifers. Indeed, there are no conifer species native to eastern North America that are both shade tolerant and expected to respond well to climate change, particularly considering southern conifers. Unfortunately, shade-tolerant balsam fir, while also co-dominant at ANP, is not expected to do as well under climate change (Figure 2). Shade-tolerant Eastern hemlock

would have had the potential to partially fill that niche under a warming climate, but the recent (2022) arrival of hemlock woolly adelgid makes the expansion of hemlock unlikely (Ellison et al., 2018). Similarly, eastern white pine is currently struggling with a suite of needle cast diseases (and is only mid-tolerant of shade).

Our recovery scenario failed to identify specific regions within ANP where red spruce refugia may be stronger than other regions under a spruce pathogen disturbance (Figure 6). Nevertheless, our simulations indicated that all of the separate "islands" of the fragmented landscape experienced some sites with high biomass recovery. While this modeling effort attempted to use the finest resolution climate and soils inputs, there will likely be microclimate sites that we did not delineate that will be better than others for spruce refugia. For example, our modeling research did not capture future microclimate conditions at the scale that may affect refugia (e.g., north aspect of a hillside). Further research is warranted to identify the sensitivity of abiotic factors affecting potential spruce recovery following a black swan disturbance.

Black swan disturbances

The "black swan" disturbances were useful scenarios in that they are unexpected but had large consequences (Orlik & Veldkamp, 2014). Although the disturbance scenarios we simulated (slow, fast, and drought) are not predictions, they are plausible in the sense that the region has experienced large, unexpected disturbances in the past. For example, the chestnut blight resulted in the loss of millions of hectares of American chestnut trees in a few decades starting around 1900 (Anagnostakis, 1987). The 1947 wildfire spread across a large portion of ANP with successional dynamics still being observed today (Butler, 2014; Miller et al., 2023). In addition, red pine scale (*Matsucoccus matsumurae*) caused the near extirpation of red pine from ANP in roughly 5 years (https://www.nps.gov/articles/red-pine-scale-acadia.htm). And, the recent abrupt arrival of BLD, first detected in 2022 in ANP, is impacting nearly all observed beech trees in the park just 2 years later.

Management

There is huge uncertainty in the future forest, hence the need to assess many management options rather than prescribing a single, specific management regime. The RAD management framework was therefore useful for this modeling effort by providing an intensity gradient of plausible management scenarios. Management objectives are also crucial for determining preferred approaches and can vary considerably among landowners. For example, in forests that are not managed for timber production, such as in ANP, maintaining business as usual practices (i.e., accept management) that allow for the capacity of natural systems to adapt and be self-sustaining, may be most practical and preferable to expensive and intensive interventions that either resist or direct change. While forest adaptation is a justifiably large and growing literature (e.g., D'Amato et al., 2023; Nagel et al., 2017, 2025; Swanston et al., 2016), the more passive forest management approaches typical of national parks provide contrast with more active management approaches. Moreover, evidence suggests that forests protected from logging develop greater structural complexity store more carbon, and show increased resilience to disturbances than more intensively managed forests (Bradley et al., 2016; Faison et al., 2023), some of which has been documented in ANP specifically (Miller et al., 2016).

There is a need for co-production of science and management to understand change and the efficacy of direct management actions. Given the rapid pace of climate change and newly arriving forest pests, management cannot wait for the science to be produced separately. An integrated approach that tests RAD actions is needed as efficacy may shift among RAD options as the climate continues to change and interact with other disturbances (Nadeau et al., 2024), or as management objectives and priorities shift over time.

Climate-suitable planting under direct management has the potential to help increase biomass under climate and a black swan disturbance like simulated, but the scale of which is not feasible based on the current management capacity in ANP. Our Direct scenario included the simulation of planting climate suitable species on nearly 1000 ha annually. This type of management intervention (i.e., planting) would have to be on a very large scale to minimize the time and area of forest loss. Planting under both the resist and direct scenarios occurred within disturbed sites replacing cohorts of spruce that were otherwise competing for resources (i.e., light and water). We should not assume that planting without a large disturbance regime would produce similar results. Among other management concerns, the lack of nursery capacity in the region for planting at such a large scale makes this challenging (Clark et al., 2023).

Local moderation of climate at ANP, and the unique management objectives make this modeling research significant. While not predictions, the results of this study describe plausible future scenarios that will aid managers within ANP and within other protected areas. This research provides a framework to assess both black swan disturbance and the management response to them. The

investment in this model parameterization should provide useful future scenario planning. The results of this study are both directly relevant to managers in ANP and the broader temperate-boreal transition zone, but also demonstrate the importance of both investigating black swan events and incorporating them into adaptive management and planning for climate change.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data (Duveneck, 2026) are available from Zenodo: https://doi.org/10.5281/zenodo.19946262.

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