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Optimizing historic preservation under climate change: Decision support for cultural resource adaptation planning in national parks

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Optimizing historic preservation under climate change: Decision support for cultural resource adaptation planning in national parks

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ABSTRACT

Climate change poses great challenges for cultural resource management, particularly in coastal areas. Cultural resources, such as historic buildings, in coastal areas are vulnerable to climate impacts including inundation, deterioration, and destruction from sea-level rise and storm-related flooding and erosion. However, research that assesses the trade-offs between actions for protecting vulnerable and valuable cultural resources under budgetary constraints is limited. This study focused on developing a decision support model for managing historic buildings at Cape Lookout National Seashore. We designed the Optimal Preservation Decision Support (OptiPres) model to: (a) identify optimal, annual adaptation actions for historic buildings across a 30-year planning horizon, (b) quantify trade-offs between different actions and the timing of adaptation actions under constrained budgets, and (c) estimate the effectiveness of budget allocations on the resource value of historic buildings. Our analysis of the model suggests that: (1) funding allocation thresholds may exist for national parks to maintain the historical significance and use potential of historic buildings under climate change, (2) the quantitative assessment of trade-offs among alternative adaptation actions provides generalizable guidance for decision makers about the dynamics of their managed system, and (3) the OptiPres model can identify cost-efficient approaches to allocate funding to maintain the historical value of buildings vulnerable to the effects of climate change. Therefore, the OptiPres model, while not designed as a prescriptive decision tool, allows managers to understand the consequences of proposed adaptation actions. The OptiPres model can guide park managers to make cost-effective climate adaptation decisions for historic buildings more transparently and robustly.

1. Introduction

Climate change poses great challenges for cultural and natural resource management in coastal areas. Cultural resources in coastal national parks and other recreation areas are vulnerable to impacts from a changing climate, such as inundation, deterioration, and destruction from sea-level rise and storm-related flooding and erosion (Rockman et al., 2016). In the United States, cultural resources are considered trust resources and the U.S. National Park Service (NPS) has been entrusted to preserve and protect cultural resources under their purview[1] . The NPS has recognized climate change as the great threat to the integrity of cultural resources in national parks, and emphasizes the importance of incorporating climate changes approaches with ongoing cultural resource research, planning, and stewardship practices as Goal

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[1] In this paper, cultural resources are defined either as tangible entities (e.g., archeological site, cultural landscape, historic district, historic site, historic building, historic structure, historic object) or intangible cultural practices associated with a way of life (e.g., musical performance, craft production) (NPS, 2014).

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3 of its cultural resources climate change strategy (Rockman et al., 2016). Yet, limited policy guidance (NPS, 2014) exists, which challenges managers ability to make specific adaptation decisions (Fatorić and Seekamp, 2017b). Given climate change impact projections from sea level rise and storm-related flooding (Caffery et al., 2018), cultural resources managers need information and tools that can inform adaptation planning decisions.

Scholars have recently recognized the dearth of literature on cultural resources and climate adaptation planning (Fatorić and Seekamp, 2017a) with most studies focused on the forecasting impacts to cultural resources from climate change threats. For example, previous studies have assessed the impact of sea-level rise on archaeological sites (Anderson et al., 2017), climate influences on relic landscapes (Dupont and Van Eetvelde, 2013), and severe weather impacts on historic buildings (Huijbregts et al., 2012). Others have used climate simulation models to assess the risks of climate changes on artifacts, structures, and architectural details of historic buildings (Leissner et al., 2015), but these studies generally focused on the indoor climate (i.e., how the changes of indoor climate might affect the indoor collections). In this paper, we briefly summarize the current literature of climate adaptation planning for cultural resources and the use of decision analysis for adaptation planning, introduce a new tool for optimizing climate adaptation planning decisions (OptiPres), and evaluate this tool by analyzing decisions, trade-offs, and consequences under varying budget scenarios at a specific site managed by the NPS: Cape Lookout National Seashore.

1.1. Literature review

Scholars are developing processes, such as community-based approaches (Carmichael, 2016) and value-based approaches (Daly, 2014; Fatorić and Seekamp, 2017a), to help managers prioritize cultural resources given the risks from climate change impacts and likelihood of loss. Despite these laudable initial efforts, most of these studies have only focused on the early stage of the decision-making process (e.g., structuring the problem, defining values and objectives, and developing alternative actions; Fatorić and Seekamp, 2017b). We are only aware of one study by Carmichael et al. (2018) that integrates the projected impacts of climate change on cultural resources (i.e., perceptions of exposure and sensitivity risks of archeological sites) with the value-based decisions necessary for the long-term preservation of cultural heritage (i.e., perceptions of relative cultural value of those archeological sites). Moreover, we are unaware of any study that explicitly integrates the costs of adaptation into a planning framework, even though costs, in addition to cultural values, are necessary to determine the feasibility or practicability of adaptation decisions (Smit and Wandel, 2006). As such, rigorous quantitative analysis of the consequences of adaptation planning decisions, including an explicit evaluation of trade-offs, is lacking in the cultural resources literature.

To address uncertainty and cost-effectiveness surrounding climate adaptation, quantitative methods from the field of decision analysis could be beneficial in adaptation planning for cultural resources. Decision analysis refers to a body of qualitative and quantitative tools developed from normative decision theory to formally structure the selection of an alternative under uncertainty, typically by deconstructing the important components of a decision, appropriately analyzing the components, and then reintegrating them in order to identify the best course of action (Howard, 1988; Parnell et al., 2013). Normative decision theory refers to a prescriptive framework describing the process by which a rational individual should consider the context of the management problem—as well as objectives, alternatives, uncertainty, and possible consequences—when making informed decisions (Gregory et al., 2012). This normative approach compensates for cognitive limitations when making complex decisions. Much of the quantitative work of decision analysis involves statistical analysis or numerical optimization to find the best solution when considering constraints, uncertainty, and trade-offs among desired outcomes (Clemen and Reilly, 2013).

Past work by Fatorić and Seekamp (2017a) focused on the use of decision analysis structuring tools for understanding the complexity of decision makers' and diverse stakeholders' values, priorities, preferences, challenges, and opportunities in cultural resource adaptation planning. Their efforts advanced the theoretical understanding of historical significance by developing a novel measurement framework to distinguish the relative importance of cultural resources, specifically historic buildings within districts (Fatorić and Seekamp, 2018). In this study, we extend the approach described above by developing a numerical model, the Optimization Preservation Model (OptiPres), which integrates all components of the decision problem to optimize the timing and location of adaptation actions for a portfolio of cultural resources. For our climate adaptation planning application, we have adapted optimization techniques commonly used in wildlife management and landscape planning (Post van der Burg et al., 2014). More broadly, the application of decision science—a well-established discipline originating from applied mathematics, economics, engineering, and psychology (Gregory et al., 2012; Keeney, 1982)—to develop insights into complex problems has gained recent popularity in resource management. Examples from this field include endangered species recovery (Runge, 2011), harvest management (Nichols et al., 2007), decision-focused monitoring design (Lyons et al., 2008), and quantifying the value of new information to reduce uncertainty for improved decision-making (Williams et al., 2011).

We developed the OptiPres Model as a pilot study of adaption planning for buildings listed on the National Register of Historic Places at Cape Lookout National Seashore, a dynamic system of barrier islands in the southeastern U.S that are vulnerable to storm-related flooding and sea level rise (Peek et al., 2017). Our goal with this particular application of the model was to identify the tradeoffs among adaptation actions applied to a subset of 17 buildings located in two historic districts among a series of budget scenarios, and the temporal patterns of adaptation actions to maintain the highest resource value of historic buildings. For instance, we were interested in exploring the possible trade-offs between reducing vulnerability to climate change impacts and preservation of historical value when faced with the decision to maintain a vulnerable building in-situ or to move it to a safer location, thus removing it from its historical context. Additionally, we were interested in exploring under what circumstances would it be more effective to invest in one of these decisions to achieve a higher resource value across the collection of buildings. Likewise, because budgets are often constrained and not all structures receive the appropriate attention, managers make triage decisions that involve deferring maintenance of some resources so that funds can be freed up to manage others. As such, we examined how patterns of optimal adaptation actions would be applied across a 30-year planning horizon to satisfy a range of specified financial constraints while allowing for triage decisions. It is our hope that the decision support tool presented in this paper can help enhance the transparency of the trade-offs park managers must consider during climate adaptation planning, including the cost-effectiveness of adaptation actions in coastal parks and recreation areas.

2. Methods

2.1. Study site and historic buildings

Cape Lookout National Seashore (CALO), managed by the National Park Service (NPS), is a 56-mile chain of barrier islands off the North Carolina coast. The cultural resources of CALO include historic buildings, historic structures, archeological sites, and a feral horse population. These and CALO's natural resources are highly valued, bringing nearly 400,000 visitors to the National Seashore in 2017 (Cullinane et al., 2018). Although coastal systems are naturally dynamic, with erosion, flooding, dune transport and other geomorphological processes being characteristic features of the barrier islands, increasing rates of sea-level rise and storm intensity present highly consequential threats to CALO infrastructure, including cultural resources (Peek et al., 2017). Hence, climate adaptation planning is essential for enhancing the resilience of cultural resources and safeguarding these invaluable and irreplaceable resources for future generations (i.e., sustainability; (Adger et al., 2013).

As a pilot study, we selected 17 buildings located in two historic districts listed on the National Register of Historic Places, Portsmouth Village (PV) and Cape Lookout Village (CLV), that represent a range of structural conditions, vulnerability to flood-related climate impacts, levels of historical significance, and levels of current and potential uses. We developed the decision support tool to assess climate adaptation actions to the 17 buildings over a 30-year time horizon, expanding upon the work of Fatorić and Seekamp (2018) who used deliberative workshops, individualized meetings, and opinion surveys to structure the management objectives and quantitatively express those objectives with numeric attributes. The management objectives included maintaining historical significance and maximizing use potential of the buildings, each of which was measured through a series of weighted attributes [*historical significance*: association to the park's fundamental resources, resource condition, historic character (chronological development and uniqueness), and National Register (spatial significance and eligibility); *use potential*: operational, third-party, visitor, interpretive, and scientific].

The attribute weights were assigned through elicitation surveys in which respondents (n = 23), who were the participants from three separate workshops conducted during the period 2015–2017 (Fatorić and Seekamp, 2018), were first provided an overview of the objectives and attributes of the measurement framework, as well as the CALO study site and the vulnerability of its historic districts. The respondents include broad audiences of cultural resources management and historic preservation professionals, such as representatives from federal government (i.e., NPS personnel from the Washington Office, the Climate Change Response Program Office, the Southeast Regional Office, and CALO), state government (i.e., various State Historic Preservation Offices), non-governmental organizations (i.e., the International Council on Monuments and Sites), academia, and private sector (i.e., tourism firm, architectural firm). The assigned weights were averaged for each set of attributes, sub-attributes, and between historical significance and use potential, and then converted to decimals (values between 0 and 1 where the total for each set equaled 1), with higher weight indicating greater importance (Fatorić and Seekamp, 2018).

To evaluate potentially differential impacts of climate change, each building was also evaluated by a vulnerability assessment. The vulnerability assessment metrics included exposure and sensitivity, which were developed for a regional study of 40 coastal parks conducted by researchers at Western Carolina University and the NPS (Peek et al., 2017). Attributes used to quantify exposure included: flooding exposure based on FEMA flood maps; storm surge estimates of mean high tide during category 3 hurricanes; sea level rise projections for 2050 under a high (RCP 8.5) emission scenario; erosion and coastal proximity; and evidence of historical flooding. Sensitivity attributes included: flood damage potential; storm resistance; historical damage; and the presence of protective engineering.

Six climate adaptation actions were informed by strategies suggested in NPS policy (Rockman et al., 2016), identified in the initial workshops (Fatorić and Seekamp, 2017b), refined by park managers, and used in the optimization model: core and shell preservation, elevate, relocate, relocate and elevate, document and monitor, and active removal. It is important to note that relocation zone maps were developed to identify if relocation would be possible within each historic district where mean high-tide of Category 3 hurricanes would not result in flooding. Using the expert knowledge of CALO managers, it was determined that the relocation area in PV would require both elevation and relocation of buildings (i.e., the relocate and elevate adaptation actions would be considered together) due to recurring standing water following storm-events. It was also suggested that there was no suitable relocation zone near the Lighthouse and Keeper's Quarters area within CLV due to the likelihood of impacting other cultural resources. Therefore, relocation was not an option for those two buildings. Additional actions also included in the model were annual maintenance and no action to incorporate realistic and standard management decisions. The detailed definition of each action and how each action dynamically affects the historical significance and use potential are described in Appendix A.

2.2. Optimization model

The optimization model combines all of the components of historical significance, use potential and vulnerability into the objective function, which maximizes total resource value of historic buildings given a certain annual budget:

$$max\ RV = \sum_{j=1}^{n} \sum_{i=1}^{m} \left(\frac{(\sum_{k}^{o} H_{ijk}*w_k)*w_h + (\sum_{l}^{p} U_{ijl}*w_l)*w_u}{V_{ij}} \right) | \, b_j \le B \qquad (1)$$

where RV is the total resource value of all i buildings over all j time steps; H represents the performance of each of the k historical significance attributes; w_k represents the weight of the sub-attributes; U represents each of the *l* attributes for use potential; w_h and w_u represent the weights given to the total values of H and U, respectively; V_{ij} represents the vulnerability of building i in the year *j*, b represents the amount of budget spent in time unit j, and B represents the annual budget cap.

The scores assigned to each attribute of resource value for each building represents a snap-shot of the current state of each building. We expected that the condition (an attribute of historical significance), overall historical value (the historical value was calculated as the sum of others three attributes of historical significance besides condition[2]), use potential, and vulnerability could change over time. Thus, the intended impact of each adaptation action would be to influence these changes over time. We constrained the application of actions so that only one type of adaptation could be applied to a building during the 30-year planning horizon, with the exceptions of "no action" and "annual maintenance."

The original resource value of historic buildings and the cost of adaptation actions for each building are presented in Appendix B and Appendix C, respectively. We simulated these changes by assuming that some of the attributes would evolve over time at different rates, as a function of the action applied:

(1) No action: 8%, 17%, and 25% annual decrease in a building's condition depending on whether its current condition was good, medium, or fair, respectively; 5% one-time decrease in historical value, and no change for vulnerability.
(2) Annual maintenance: 6%, 10%, and 15% annual decrease in a building's condition depending on whether its current condition was good, medium, or fair, respectively; no decrease in historical value, and no change for vulnerability.
(3) Document and monitor: 8%, 17%, and 25% annual decrease in a building's condition depending on whether its current condition was good, medium, or fair, respectively; 5% annual decrease in

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[2] We estimated changes in historical value by (a) consulting with NPS personnel at CALO, in the Southeast Regional Office, and in the Washington Office with experience in cultural resource and facilities management, and (b) by developing a framework of how each action would influence one of the seven aspects of historic integrity considered during listing decisions on the National Register of Historic Places (i.e., location, design, setting, materials, workmanship, feeling, and association).

historical value, and no change for vulnerability. The use potential score set to 0.

(4) Active removal: condition score set to 0, 90% one-time decrease in historical value, and vulnerability score set to 0. The use potential score set to 0.
(5) Core and shell preservation: condition changes to the good class, no decrease in historical value, and no change for vulnerability.
(6) Elevate: condition changes to the good class, 43% decrease in historical value, and sensitivity component of vulnerability changes to low level.
(7) Relocate: condition changes to the good class, 30% decrease in historical value, and sensitivity and exposure changes to low level.
(8) Relocate and elevate: condition changes to the good class, 61% decrease in historical value, and sensitivity and exposure change to low level.

For all actions, when the condition of a building decays to poor class, the operational use score and visitor use score are downgraded to the lowest category ("the building has no current use but potential use in next 5 years").

2.3. Simulated annealing algorithm

Our pilot study involved finding the optimal sequence of eight adaptation actions applied annually across seventeen buildings over a 30-year planning horizon given a budget constraint. To solve this function in a large dimensional space, we use a heuristic optimization algorithm: simulated annealing (Possingham et al., 2000). Simulated annealing is a probabilistic search algorithm that approximates the global optimum of a given function. This approximate algorithm has been applied to studies on climate adaptation planning for water resources, biodiversity, and ecological landscapes (Arsenault et al., 2013; Chen et al., 2017; Vieira and Cunha, 2017), as it is an efficient search method for finding global optima by occasionally accepting neighboring solutions in the state space that decrease the objective function to prevent being trapped in a local optima. Pseudocode for a simulated annealing algorithm is structured as follows:

(1) Set the starting temperature T, which is the acceptance parameter.
(2) Generate an initial solution to the function. We assumed "no action" for each historic building every year as the baseline solution.
(3) Randomly select a building and time step. Then, randomly select an action that satisfies all of the constraints, including (a) the total cost of adaptation actions cannot exceed the annual budget; and (b) only one large adaptation action (core and shell preservation, elevate, relocate, relocate and elevate) per time-step. This now becomes a candidate solution. Repeat selection of action for building until each action for each building is selected for every time step.
(4) Compute RV (Eq. 1) for the candidate solution and compare it to the current solution: $\Delta \mathrm{RV} = \mathrm{Candidate} - \mathrm{Current}$. Accept the candidate according to $e\Delta^{RV/\mathrm{T}}$. If the candidate is selected, it now replaces the current solution. If it is rejected, the current solution remains current.
(5) Return to step 2 for a set large number of iterations.
(6) After many iterations, decrease the acceptance temperature. We decreased our temperature according to a set of 30 predefined temperatures, which decreased exponentially from largest to smallest. After each decrease of temperature, the algorithm is run again for a large number of iterations. Once the algorithm finishes running, a local iterative search algorithm is used to check whether a better solution is available.

2.4. Simulated budget scenarios for modeling testing and analysis

We proposed a series of budget scenarios to test the optimization model. First, we tested the OptiPres model under a range of scenarios from $0 annual allocation to $500,000 annual allocation to identify the threshold of annual budget allocation to maintain the original resource value of historic buildings under climate change for 30-year planning horizon. Second, five specific budget scenarios were proposed and tested by OptiPres model to identify (1) factors affecting the trade-offs among historic buildings for adaptation actions when the budget is insufficient to achieve the maximum resource values; (2) temporal patterns in maximizing resource value under different budget scenarios; and (3) the effectiveness of the various budget allocation scenarios to maintain and enhance the value of historic buildings. These scenarios were selected based on suggestions by CALO management staff and regional NPS managers about feasible future managerial contexts. The budget scenarios included: (a) a low budget scenario of historic preservation where the annual budget allocation is $50,000; (b) an industry standard budget scenario of historic preservation where the annual allocation is $222,000; (c) a high budget scenario of historic preservation where the annual allocation is $500,000; (d) a low periodical funding increase budget scenario, where the annual allocation is $70,000 with an additional $225,000 every five years; (e) a high periodical funding increase budget scenario, where the annual allocation is $222,000 with an additional $225,000 every five years.

3. Results

3.1. Dynamics of resource values of historic buildings and annual budget allocation

Our model results show that as annual allocated budgets increase, the total resource value over the 30-year planning period also increase (Fig.1). The red line displayed in Fig. 1 represents the original accumulated resource value for historic buildings (assuming the historic buildings were not subject to the risk of climate change, and resource values did not change at the end of the 30-year planning horizon). The results suggest that if "no action" was applied to buildings (budget is $0), the accumulated resource value of buildings would decrease by 45% of the original value. Intuitively, the OptiPres model results demonstrate that the accumulated resource value of historic buildings increases when the annual budget allocation increases.

Comparing the original accumulated resource value of historic buildings (the red dash line in Fig.1), we found that the threshold for an annual budget allocation to maintain the resource value of historic

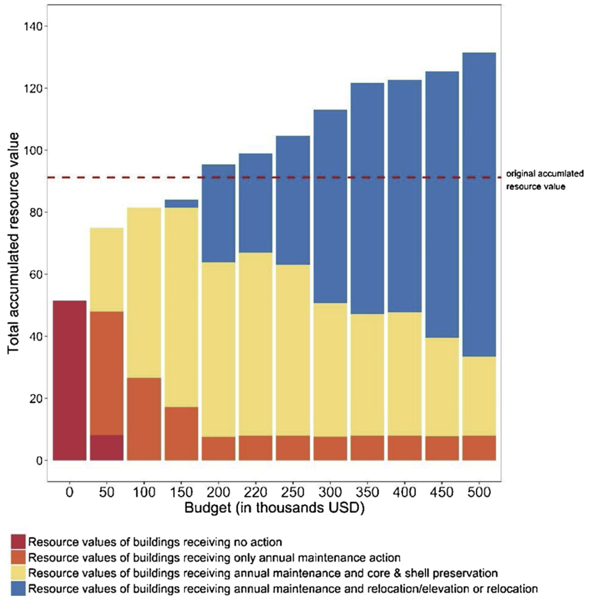

Fig. 1. The expected accumulated resource value under varying annual budget allocations.

buildings for the 30-year planning horizon is approximately $175,000. The trend of the annual budget allocation – accumulated resource value curve indicates four stages.

- Stage 1: From the scenario of $0 annual allocation to the scenario of $50,000 annual allocation, the marginal gain of total resource values was relatively high because the increased budget could make more buildings eligible for annual maintenance, which could reduce the decay rates of condition and the integrity for historic buildings.
- Stage 2: From the scenario of $50,000 annual allocation to the scenario of $150,000 annual allocation, the marginal gain of accumulated resource value tended to be lower because the budget within this range only enabled a few buildings to be eligible for core and shell preservation actions, which improved the condition of buildings but was insufficient to apply actions that also reduce the vulnerability of buildings.
- Stage 3: From the scenario of $150,000 annual allocation to the scenario of $350,000 annual allocation, the slope of the curve increased, and an additional annual allocation of $50,000 would lead to a much higher marginal gain of resource value than found within Stage 2. These gains from the increased funding made relocation and elevation adaptation actions (which also includes core and shell preservation cost) eligible for more buildings, where the vulnerability of buildings could be reduced to low and the conditions of the buildings could be improved to the good class.
- Stage 4: From scenario of $350,000 annual allocation to scenario of $500,000 annual allocation, the marginal gain of total resource value slowed as most of buildings had received certain levels of preservation actions (core and shell preservation, relocation, or relocation and elevation) under Stage 3, and the increased funding could not provide more choices of adaptation actions for most buildings to enhance the accumulated resource value, as the model restricts buildings to only one large preservation action across the planning horizon.

3.2. Trade-offs among historic buildings for adaptation actions under different budget scenarios

The optimal set of actions applied to historic buildings varied greatly under different budget scenarios (Fig. 2). When budget allocations were limited (lower than the total cost of relocation and elevation of all buildings), the optimization model evaluated the trade-offs among adaptation actions for different buildings to achieve the highest accumulated resource value for the set of historic buildings. Comparing the adaptation portfolios among the five budget scenarios, several important factors were identified as the criteria to determine whether a building was selected for an adaptation action. For example, under scenario (a) with an annual allocation of $50,000, approximately 25% of buildings were not identified for any management actions across the planning horizon, resulting in significant declines of resource values of the "unmanaged" buildings (Figs. 2a and 3). The primary reasons why these buildings were not candidates for annual maintenance were either their relatively low values for historical significance or the relatively high costs of annual maintenance. More specifically, two historic buildings (Gordon Willis and the O'Boyle-Bryant houses located in CLV) had the lowest value of historical significance among 17 building; therefore, when the budget was limited and insufficient to meet the total annual cost of annual maintenance for all buildings (i.e., $68,000), the optimization model suggested that the buildings with relatively low values for historical significance be left unmanaged in order to allocate adequate funding to maintain other buildings. Additionally, the limited budget induced trade-offs among buildings to be selected for annual maintenance depending on the cost of actions. For instance, two buildings (Church PV and Keeper's Quarters CLV) were not selected for annual maintenance because of their relatively high costs of annual maintenance compared to the other buildings.

Another interesting pattern emerged in scenario (a): about 30% of the historic buildings were selected for core and shell preservation adaptation actions. The buildings selected for this action had associated core and shell preservation costs lower than $50,000 and, as such, the allocated funding was sufficient for applying this adaptation action to these buildings. Applying the core and shell preservation action improved the building condition to the good class, which led to a higher gain of accumulated resource value than if annual maintenance was applied to more buildings. However, the substantial cost of this action often resulted in other buildings being unmanaged in the year when the core and shell preservation was applied to a specific building.

The factors for evaluating the trade-offs for the industry standard scenario [scenario (b)] and the high annual budget scenario [scenario (c)] were more complicated than for scenario (a) because the higher budget allocation made more adaptation actions possible for the historic buildings (Fig. 2b & c). For scenario (b), about 95% of historic buildings were selected for adaptation actions (core and shell preservation, relocate, and relocate and elevate). Moreover, all of the buildings received annual maintenance for most years over the 30-year planning horizon (excluding years in which relocate or core & shell preservation actions were applied). The annual costs of major interventions induced a large portion of the trade-offs among buildings that were chosen for relocate actions. The five buildings (Summer Kitchen PV, Frank Gaskill House PV, Jetty Workers House 1 CLV, Gordon Wills House CLV, and O'Boyle Bryant House CLV) that were selected for relocation (or in the case of PV where elevation is also necessary when relocation is selected) had lower relocation or relocation and elevation costs than other buildings. Although the relocate or relocate and elevate actions decrease the historical value of the building, the higher marginal gain of resource value from condition improvement and reduced vulnerability by relocating and elevating the building made it an optimal action to achieve the highest accumulated resource value under this scenario. Therefore, the optimization model selected the maximum number of buildings ($n = 5$) for the relocate or relocate and elevate actions where the costs of relocation action were lower than the annual allocated budget. The trade-off of applying the relocate or relocate and elevate action for a building is that it leaves several buildings unmanaged in a particular year, which accelerates the deterioration of those buildings' condition. For buildings with relocation or relocation and elevation costs higher than the annual budget, the optimization model applied the core and shell preservation adaptation action with one exception: the Lighthouse CLV where the cost of core and shell preservation was higher than the annual budget. Again, the logic behind the selection of the core and shell preservation action is similar to what was described for the results of scenario (a): this action enhances the condition of the building while also maintaining its historical value.

The pattern of trade-offs between adaptation actions of scenario (c) was similar to the pattern of scenario (b) (Fig. 2). The model selected 12 buildings for relocate or relocate and elevate adaptation actions when the costs were lower than the annual budget. Four buildings were selected for core and shell preservation actions, with two of these buildings (Church PV and LifeSaving Station PV) being ineligible for relocation and elevation (i.e., the costs of these actions were higher than the annual budget), one building (Keeper's Quarters CLV) not having a feasible relocation area identified (and costs of elevating were higher than the annual budget), and another (Galley Coast Guard CLV) already being located in the least vulnerable area of CLV where relocation of other buildings would occur (i.e., no gain in reduced vulnerability by applying the relocate action). The Lighthouse CLV was not eligible for any adaptation action other than annual mantenance because the cost (e.g., core and shell preservation) was much higher than the annual budget.

It is also interesting to note that elevate, document and monitor, and active removal were never selected for any building by the OptiPres model although the budget would have allowed these actions.

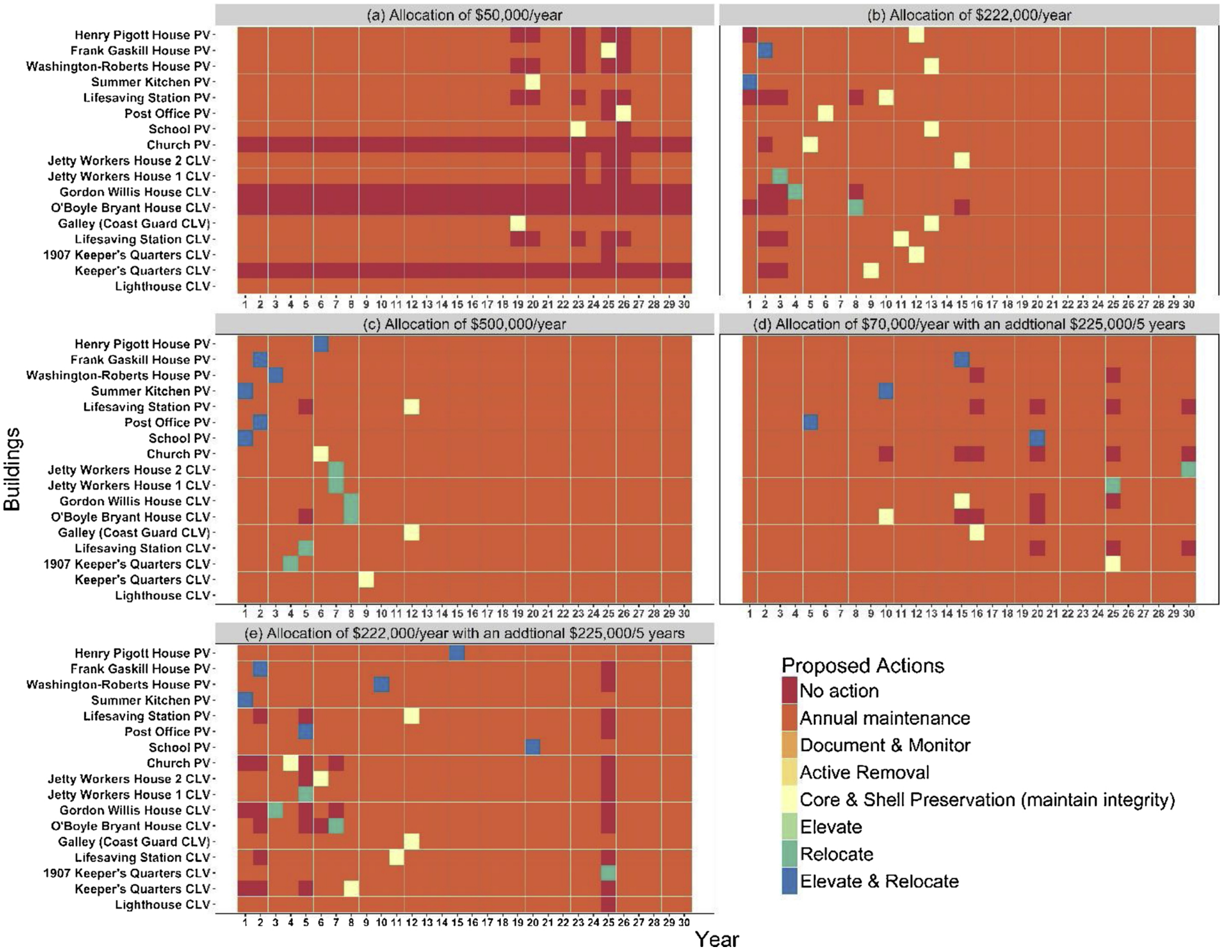

Fig. 2. Adaptation actions applied to buildings across 30-year planning horizon for budget scenarios.

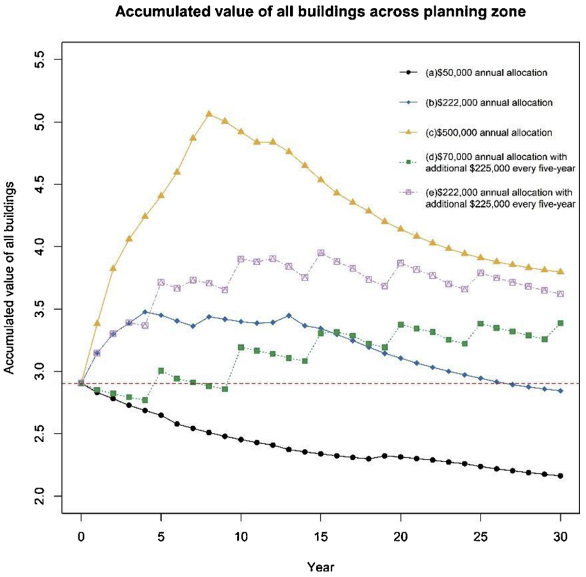

Fig. 3. Annual resource values of all buildings across the 30-year planning horizon for different budget scenarios.

Comparing to the relocation and elevation action, the elevation action could only reduce the sensitivity of a building to storms and flooding, but would not affect the exposure to climate change. Also, the high rate of historical value loss made the elevation action less effective to improve the overall resource value of historic buildings. As for document and monitor and active removal, these two actions reduced the use potential scores to 0 and had relatively higher costs comparing to no action, which made them less optimal to maintain the resource value of historic buildings. Since the annual funding allocation of scenario (c) was much higher than that of the industry standard scenario, a trade-off of leaving some buildings “unmanaged” in order to apply costly adaptation actions was required but only occurred in one year during the 30-year planning horizon.

For periodical funding increase scenarios [scenarios (d) & (e)], similar adaptation strategies were found as in scenarios (a) and (b): the primary adaptation actions applied to most buildings were either relocate, relocate and elevate, or core and shell preservation. Annual maintenance was applied to most of buildings in years when the typical annual funding was allocated. In general, more buildings in PV were eligible for the elevate and relocation action than CLV because the costs for relocating buildings in PV were relatively lower. The buildings that were selected for relocation actions in scenario (d) were similar to the buildings in scenario (b), but the percentage of buildings that were eligible for the relocate or relocate and elevate were slightly higher than that in scenario (b). This result is caused by the fact that, when additional funding was available on a 5-year interval, the total funding in those years was higher than the annual budget of scenario (b), thereby the number of buildings eligible for the relocate or relocate and elevate actions increased. However, since the baseline annual budget of scneario (d) was much lower than that of scenario (b), the percentage of buildings (24%) that were eligible for core and shell preservation was much lower than that of scenario (b). For scenario (e), the buildings that were selected for the relocate or relocate and elevate actions and core and shell preservation action were similar to scenario (c). All buildings except the Lighthouse CLV were chosen for large adaptation actions in scenario (e), as the Lighthouse CLV adaptation costs exceeded the annual budget even in years of periodic increase.

3.3. Temporal pattern of adaptation actions under different budget scenarios

To identify the tradeoffs of timing to apply adaptation actions for historic buildings under different budget scenarios, we generated a visualization of the accumulated resource value of the buildings by year across the 30-year planning horizon (Fig. 3). For the low budget scenario [scenario (a)], the core and shell preservation actions were generally applied to buildings late in the planning period (year 20–30) (Figs. 2a & 3). As the core and shell preservation action improves a building's condition to the good class and the condition and the historical value of buildings decayed across the planning horizon when only the annual maintenance actions were applied, the model applied the core and shell preservation action (to buildings for which the action was affordable) only when the condition decreased to the poor class (later in the planning cycle) to achieve the maximum gain of accumulated resource value (improved condition). Specifically, the accumulated resource value for the low budget scenario (Fig. 3) indicates that applying the core and shell preservation action could slow down the decay rate of the accumulated resource value of historic buildings from year 20 to year 30.

The temporal patterns of adaptation actions for the industry standard scenario and high budget scenario [scenarios (b) & (c), respectively] involved more complicated trade-offs within the solutions. The temporal patterns for the scenarios (b) and (c) illustrate the importance of applying adaptation actions as early in the planning cycle as is feasible when budgets are sufficient to either relocate or relocate and elevate some of the buildings (Figs. 2b,c, and 3). Both scenarios typically prioritize allocating budgets to perform the relocation or relocation and elevation actions, requiring a deferment of annual maintenance on another building(s), before core and shell preservation actions are applied. In other words, this finding illustrates that reducing vulnerability while enhancing the condition of a building is prioritized temporally. Applying the relocate or relocate and elevate actions under the industry standard budget scenario from year 1 to 4 increased the resource value by 20% from the original resource value at the beginning of the planning horizon (Fig. 3). Once most buildings were identified for relocation (or relocation and elevation), the model selected core and shell preservation actions for the remaining buildings as early as possible in the planning horizon (again, with the exception of the Lighthouse CLV due to the cost prohibitive nature of all adaptation actions). The key differences between scenarios (b) and (c) are the accumulated resource values of all buildings, with the higher annual allocation able to proportionally increase the historical value across the 17 buildings, with a maximum value reaching its peak once the last two buildings are relocated in year 8 (Fig. 2c). When the last core and shell preservation actions are applied [in year 15 and year 12 for scenarios (b) and (c), respectively], a similar rate of decay in accumulated resource value occurs in both scenarios.

The temporal patterns of adaptation actions under periodical funding increase scenarios [scenarios (d) & (e)] are different than for the scenarios with a constant budget allocation. Instead of applying the relocation actions at the beginning of planning period, the optimization model dispersed the relocation actions across the planning horizon (Fig. 2d and e). The relocation or elevation and relocation costs determine when these actions occur (in most cases, buildings were selected for relocation when the periodic funding was allocated on 5-year intervals). The dispersed pattern of relocation actions periodically increased the accumulated resource value of buildings (Fig. 3); that is, the accumulated resource value increased at the 5-year interval and decreased thereafter until additional funding was allocated again. As such, the temporal patterns of adaptation actions of two periodical funding increase scenarios were similar, with the accumulated resource value of historic buildings being higher in scenario (e) than scenario (d) because the total allocated funding in scenario (e) was more than double that of scenario (d) (Fig. 3).

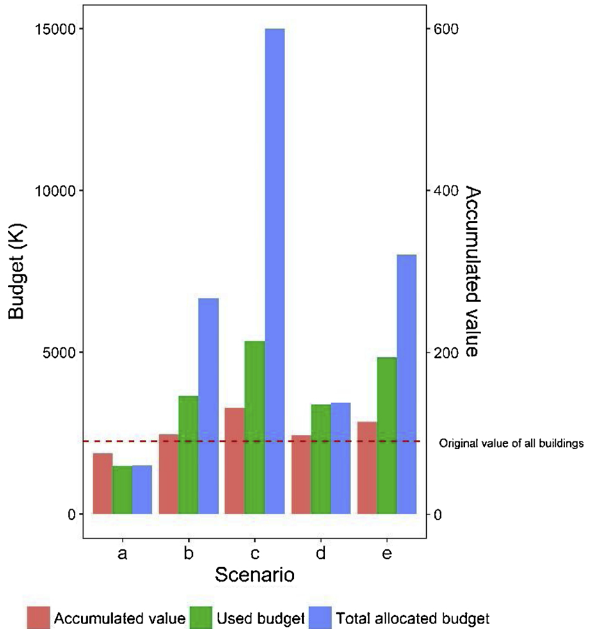

Fig. 4. Allocated budget, budget used for adaptation, and resource value of historic buildings among different scenarios [X-axis represents different budget scenarios: (a) Allocation of $50,000 every year; (b): Allocation of $222,000 every year; (c): Allocation of $500,000 every year; (d): Allocation of $70,000 every year and an additional $225,000 every five years; (e): Allocation of $222,000 every year and an additional $225,000 every five years.].

3.4. The effectiveness of budget allocation on resource value of historic buildings

To analyze how to use the budget to apply adaptation actions to historic buildings effectively, we calculated the accumulated resource value of historic buildings over 30 years, the total amount spent on the adaptation actions, and the total allocated budget for each scenario (Fig. 4). It is important to recall that a model constraint is that only one adaptation action can be applied to a building in the 30-year planning horizon, which was assumed to result in some budget allocation insufficiencies. As such, an important factor to determine the accumulated resource value of historic buildings is maximizing the percentage of funding to be used for adaptation actions.

When the budget allocation was low [scenario (a) $50,000 annual allocation], the optimized portfolio used almost 100% of the allocated budget because the annual allocation was lower than the cost of annual maintenance (i.e., the lowest cost action) for all buildings. When more funding was allocated every year [scenarios (b) and (c)], the resource value of historic buildings increased, but the portion of the allocated budget that was used for adaptation actions decreased [55% in scenario (b), and 36% in scenario (c)] (Fig. 4). In the periodical funding increase scenarios [i.e., scenarios (d) and (e)], more effectiveness was found. Specifically, scenario (d) utilized nearly all of the allocated budget (98%), while scenario (e) utilized 60%; as such, both periodic funding increase scenarios proved more efficient than either scenarios (b) or (c) with consistent annual allocations. Additionally, the periodic funding increase [scenario (d), $70,000 annual allocation with $225,000 every five years] improved the accumulated resource value to nearly the same level as the industry standard scenario [scenario (b), $222,000 annual allocation], but at a much lower total cost. Interestingly, the accumulated resource values in scenarios (b) and (d) were nearly equal, but the allocated budget of scenario (b) was nearly double that of scenario (d).

Despite the increased efficiency, the risk of a periodic funding scenario is the increased probability of storm-related impacts to buildings not yet relocated or relocated and elevated, which currently is not accounted for in the OptiPres Model. Therefore, careful consideration of vulnerabilities not included in this model—in particular, flooding and erosion impacts, as well as wind and precipitation impacts to the interior of buildings, from stochastic storm events—is necessary when using the model's output for informing adaptation planning and decision-making.

4. Discussion

This study addresses a fundamental gap in climate adaptation planning for cultural resources (Fatorić and Seekamp, 2017a) by presenting a systematic approach to decision making for complex resource management problems. This comprehensive approach identifies explicit values of historical significance and use potential, develops appropriate and measurable attributes to quantify objectives and the state of managed resources, and specifies dynamic models to link management actions to predicted outcomes over the planning horizon. We formalize this process into a flexible decision support tool, the OptiPres Model, that integrates quantification of the historical value of cultural resources—in our case, buildings in historic districts (Fatorić and Seekamp, 2018)—with vulnerability assessment data (Peek et al., 2017) to optimize adaptation strategies under climate change. The application of the OptiPres Model identifies a dynamic portfolio of adaptation actions for 17 historic buildings over a moderate time horizon and considering a variety of annual budget allocation scenarios. More specifically, the study estimated the resource value of a subset of buildings within historic districts across a 30-year planning horizon, examined the trade-offs among alternative adaptation actions, identified the temporal pattern of adaptation actions to maximize historic preservation, and evaluated the effectiveness of budget allocations on the maintenance and improvement of accumulated resource value. The results from quantitative structured decision modeling efforts, such as reported here, address Goal 3 of the National Park Service's Cultural Resources Climate Change Strategy (i.e., to incorporate climate change into ongoing cultural resources research, planning, and stewardship (Rockman et al., 2016) by providing guidance for long-term adaptation planning for cultural resources in national parks facing climate change impacts related to sea-level rise and storm-related flooding and erosion.

Our study results suggest that a substantial allocation of funds ($175,000 to $250,000 annually) is necessary for CALO to maintain the historical significance and use potential of the 17 selected historic buildings under climate change. Moreover, this study explores the trade-offs of adaptation actions and provides an explicit means for measuring the consequences to resource value under a given budget allocation. For example, if no funding is allocated (as is the trend in the ongoing deferred maintenance situation facing NPS managers; Watson et al., 2014), the accumulated resource value of the 17 historic buildings at CALO is expected to decrease by 45% during the 30-year planning horizon. This finding may provide NPS administrators with additional leverage to support the case for enhanced congressional budget allocations, as they can demonstrate the losses occurring to resource values under the trend of insufficient budgets that has left a backlog of deferred maintenance in parks across the nation. However, annual budgets sufficient for recurring maintenance remain deficient for the agency to meet its mandate of cultural heritage preservation given the inevitability of climate change impacts and the need for adaptation funding.

Additionally, we found that when the annual allocated budget is lower than the total cost of annual maintenance, some buildings that have high maintenance costs may be left "unmanaged" despite having high historical significance and use potential (e.g., Keeper's Quarters CLV and Church PV) because of the budget insufficiencies. Such scenarios result in a type of selective deferred maintenance and could lead to an unideal management situation because buildings like the Keeper's Quarters CLV and Church PV are considered "iconic" sites within a cultural landscape, serve the visiting public, and provide local communities a gathering place in which to celebrate their heritage. In fact, these specific buildings are key symbols of the area's cultural heritage to local community members, who refer to deferred maintenance as neglect (Henderson and Seekamp, 2018). Therefore, although temporal analysis of dynamics between allocated budgets and changes in resource value provides park managers and decision-makers with information about the budget thresholds necessary to maintain as much resource value as possible across a collection of cultural resources, integrating of these insights with stakeholder engagement processes could enhance the ability to determine the policy implications of tradeoffs that may not uphold local priorities related to economic development (tourism) and local heritage. Regardless, applying the OptiPres model can benefit adaptation planning by enabling managers to (a) evaluate the tradeoffs represented by an optimal portfolio of preservation actions for enhancing acumulated resource values (i.e., maximizing the preservation and use potential of historically significant buildings) under insufficient budget allocations, (b) make more transparent justifications for increased funding to mitigate the loss of value from important but costly buildings, or both.

Rather than offering prescriptive recommendations for specific actions to be applied to particular structures in a given year, the OptiPres Model reveals general patterns of inference for adaptation actions under different budget constraints to further consider the tradeoffs under a range of resource conditions and financial scenarios. For example, given a minimal budget, the optimization model tends to recommend core and shell preservation targeting buildings with the lowest costs associated with the action, temporarily suspending management on some buildings to cover those costs, and permanently suspending management of buildings with either the lowest historical values or the highest annual maintenance costs. At higher budgetary levels (i.e., industry standard and above), the optimization model prioritizes reducing vulnerability and enhancing the condition of a portfolio of buildings either through relocation or relocation and elevation, despite the reductions in historical values from changing a building's location. Therefore, the OptiPres Model's guidance, as currently constructed, suggests that lowering vulnerability is more optimal than maintaining its historical value to maximize overall preservation outcomes across a landscape (in this case, across a national seashore and within its two historic districts). Importantly, these findings provide more operational management guidance on how to implement the National Park Service's policy on stewardship of cultural resources Memorandum 14-02, which states that "management decisions should be directed toward resources that are 'both significant and most at risk'"(NPS, 2014).

The OptiPres Model also provides general inference on temporal patterns of implementing adaptation actions. For instance, at higher budget levels, relocation or relocation and elevation are prioritized early in the 30-year planning horizon, suggesting that delays in moving buildings (if affordable) to less vulnerable locations can increase the losses of accumulated resource value. If applied in practice, such management guidance could also substantially minimize the risks of episodic storm-related impacts, including complete destruction of a building. Under conditions of budget fluctuations (i.e., periodical funding increases), relocation or relocation/elevation are limited to the years in which additional funding is available, necessitating that many of these decisions are made later in the planning horizon and, thereby, increasing the risks from episodic storm-related events. Additionally, the core and shell preservation action is generally applied when the condition of a building had decayed to poor under a low budget scenario. This strategy provides the largest marginal gain from the one-time improvement of condition. When higher funding amounts are available, this type of preservation action is selected as soon as the budget is available, following the application of relocate or relocate and elevate actions. Given that the risk of catastrophic events are likely to increase over time (IPCC, 2013), providing substantial funding for major adaptation actions in the near-term will likely offer disproportionate benefits relative to similar funding allocated later in the planning horizon.

Our results also highlight the ability of the OptiPres Model to document the dynamics of optimization solutions under various budget scenarios while considering the gains, losses, or maintenance of accumulated resource value. In general, the periodic funding allocation scenarios have greater effectiveness on improving the resource value of historic buildings than constant budget allocation scenarios, but the prerequisite condition is that the annual allocated funding should be higher than the cost of annual maintenance for all buildings so that each building can receive the basic management action during the planning horizon. For example, the resource values for the scenario of $222,000 annual allocation and the scenario of $70,000 annual allocation with additional $225,000 every five-year was nearly equal, but the allocated budget of the periodically increasing budget scenario was much lower than the constant budget scenario. This finding is due to the fact that the percentage of allocated budget used for adaptation actions for the periodically increasing budget scenario is much higher than the constant budget scenario. These results may be helpful for decision-makers to select adaptation strategies when the additional funding is allocated to improve the resilience of historic buildings in the face of storms or other climate extreme events during the planning horizon.

The outputs of the OptiPres model's results (i.e., visualizations such as those provided in Figs. 1–4) can assist park managers in selecting the appropriate modes of funding allocation for climate adaptation planning for cultural resources in a way that does not require specialized knowledge of optimization programming. However, the complexity of the OptiPres model's algorithm would likely necessitate the assistance of a scientist versed in optimization programming if it were to be applied to all historic buildings at CALO or at another park. Regardless, this type of analysis is a critical step forward, as public agencies (such as the National Park Service) are driven by economic efficiencies (Adger et al., 2005) but, to date, demonstrable examples of approaches for achieving economic efficiencies for climate adaptation actions are surprisingly scant (Fletcher et al., 2016).

5. Limitations and future research

Although the OptiPres Model and its application for this pilot study offers new insights for cultural resource climate adaptation planning, it is not without limitations. First, the vulnerability assessment in this study does not include temporal dynamics or probability metrics for stochastic storm events, which are predicted to increase in frequency and severity with climate change. Incorporating stochastic forecasting of extreme events (e.g., flooding, erosion, wind and precipitation impacts) into future studies will enhance the usefulness of outputs from the OptiPres model. Second, sea level rise projections driving the vulnerability assessment originate from a high (RCP 8.5) emission scenario; future studies may consider expanding the scenario outputs from OptiPres model to include a range of uncertainty for climate change projections. Third, future studies may consider including a sensitivity analysis of stakeholders' (e.g., community members, CALO visitors, or the general public) preferences regarding resource objectives and climate adaptation actions when implementing the optimization model. For example, if the changes to a building's historical value from relocation (e.g., location and feeling aspects of historical integrity) impact local residents' connections to place, as was found by Henderson and Seekamp (2018), then weighting or penalizing specific adaptation actions could enhance public acceptance of any adaptation decisions that are informed by similar modeling efforts. Additionally, comparing outputs based on different types of stakeholders' perceptions of appropriate weights of the historic significance and use potential objectives and associated attributes (e.g., comparing local to regional NPS personnel's perspectives, or local community members' to NPS personnel's perspectives) is needed to determine the sensitivity of the model to different cultural values. Finally, future studies should consider extending this approach to enhance adaptation planning of other park units or other types of cultural resources, such as archeological sites, to illustrate the transferability of the OptiPres Model. Ultimately, advancing the OptiPres Model to larger spatial scales (regions, nations, international contexts) can advance climate adaptation planning and ensure preservation of diverse cultural heritages in parks and protected areas globally.

6. Conclusion

The OptiPres Model identifies optimal climate adaptation strategies based on quantitative assessment of trade-offs among alternative actions and budget scenarios, which provides an advanced methodology for long-term adaptation planning of cultural resources. In contrast to the published decision support processes for cultural resource adaptation planning (e.g., Carmichael, 2016; Daly, 2014), this study developed an optimization approach using advanced quantitative modeling that accounts for complexities of interacting factors such as dynamically changing conditions, historical value, and climate change vulnerability. The simulated annealing algorithm used in this study achieves the highest accumulated resource value of historic buildings across a long-term planning horizon, and makes the decision-making process more transparent for climate adaptation planning. The approaches presented in this study can be used for adaptation planning of historic buildings in parks, protected areas, and natural and cultural landscapes, and provides a robust assessment of adaptation options in the decision-making process. It is our hope that advanced methodologies like the OptiPres Model will be applied and refined in other contexts and with other cultural resources to enhance heritage preservation in the face of climate change.

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Appendix A. Definition of Adaptation Actions

Action	Definition
No action	This option allows managers to repurpose annual maintenance from one building(s) to another as a way to "capture" enough budget in any given year to apply a costly adaptation action to another building.
Annual maintenance	Regular, annual maintenance that is supposed to occur to keep buildings in good condition (base funded operations; inspections, corrective maintenance, and preventative maintenance). Note: values are lower corrective maintenance costs than for "Core and Shell Preservation", as they reflect the bare minimum or maintenance of the status quo through application of small fixes.
Core and shell preservation: maintain integrity	Maintenance of historic character of the building & its historic materials (i.e., similar as possible to the materials used in the original construction), which includes annual maintenance (inspection, full corrective maintenance, and preventive maintenance) and non-annual maintenance to bring to standard (cyclic maintenance & recurring maintenance; also referred to as deferred maintenance). This action also included costs affiliated with fully (extensively) documenting the resource in its new condition (conditions report).
Elevate	This action consists of (a) bringing the building to standard (Core & Shell Preservation: Maintain Integrity) and (b) raising the minimum floor elevation to reduce the likelihood of structural damage from storm-related flooding and/or sea level rise. This action also included costs affiliated with fully (extensively) documenting the resource in its new condition (historic structure report), as well as minimal interpretation (e.g., one panel sign that addresses adapting to climate change).
Relocate	This action consists of (a) bringing the building to standard (Core & Shell Preservation: Maintain Integrity) and (b) moving the building to a less vulnerable location (within the historic district) to reduce the likelihood of structural damage from storm-related flooding and/or sea level rise. This action also included costs affiliated with fully (extensively) documenting the resource in its new location (conditions report), as well as extensive interpretation (e.g., multiple panel signs that address adapting to climate change).
Relocate and elevate	This action consists of (a) bringing the building to standard (Core & Shell Preservation: Maintain Integrity), (b) moving the building to a less vulnerable location (within the historic district), and (c) raising the minimum floor elevation to reduce the likelihood of structural damage from storm-related flooding and/or sea level rise. This action also included costs affiliated with fully (extensively) documenting the resource in its new condition (conditions report), as well as extensive interpretation (e.g., multiple panel signs that address adapting to climate change).
Document and monitor	This action includes costs associated with erecting a six-foot chain-link fence around a building and monitoring the condition. The fencing reduces the potential for human injury as there is potential for the building to deteriorate by the natural elements. This action also includes costs affiliated with extensive interpretation (e.g., multiple panel signs that address adapting to climate change).
Active removal	This action consists of physically removing the building from the historic district (debris and hazard demolition) and disposing the materials according to federal guidelines (debris and hazard disposal). This action also included costs affiliated extensive interpretation (e.g., multiple panel signs that address adapting to climate change).

Appendix B. Original resource value of historical buildings

Building Names	Historic Value*	Condition*	Use Potential*	Exposure	Sensitivity	Vulnerability	Resource Value
Cape Lookout Village							
Lighthouse CLV	0.71	0.66	1.00	3	3	3	0.29
Keepers Quarters CLV	0.66	0.38	0.88	4	3	4	0.19
1907 Keepers Quarters CLV	0.66	0.66	0.54	3	3	3	0.23
Lifesaving Station CLV	0.66	0.66	0.54	3	3	3	0.23
Galley (Coast Guard CLV)	0.66	0.66	0.35	2	2	2	0.32
O'Boyle Bryant CLV	0.23	0.38	0.00	3	3	3	0.07
Gordan Willis House CLV	0.23	0.66	0.00	3	4	4	0.06
Jetty Workers House 1 CLV	0.53	0.66	0.00	3	4	4	0.11
Jetty Workers House 2 CLV	0.53	0.38	0.00	3	4	4	0.11
Portsmouth Village							
Church PV	0.58	0.66	0.71	4	4	4	0.17
School PV	0.58	0.66	0.35	4	4	4	0.15
Post Office PV	0.58	0.66	0.43	4	4	4	0.15
Lifesaving Station PV	0.66	0.66	0.67	4	4	4	0.18
Summer Kitchen PV	0.66	1.00	0.71	4	4	4	0.20
Washington-Roberts House PV	0.49	1.00	0.67	4	4	4	0.17
Frank Gaskill House PV	0.49	0.00	0.26	4	4	4	0.11
Henry Pigott House PV	0.49	1.00	0.47	4	4	4	0.15

*The raw scores for historical value, condition, and use potential were normalized for all historical buildings.

Appendix C. Adaptation strategy and maintenance costs for each of the 17 pilot buildings (unit: thousand US dollar)

	Active Removal	Core & Shell - Maintain Integrity	Core & Shell - Improve Adaptability	Relocate the Building	Elevate the Building	Document & Monitor	Annual Maintenance
Cape Lookout Village							
Lighthouse	10050	1018	13126	N/A	10626	74	5.4
Keepers Quarters	112.5	125	1086	N/A	311	42.5	6
1907 Keepers Quarters	95	78	656	435	199	37	4.5
Live-Saving Station	122	154	796	450	264	40	7.8
Galley (Coast Guard)	70	25	271	N/A	81	22	3.5
O'Boyle Briant	105	65.5	301	166	127	25	3.4
Gordan Willis House	95	53	251	145	111	25	2.4
Jetty Workers House 1	95	91	251	183	149	25	2.4
Jetty Workers House 2	95	158	251	250	216	25	2.4

Portsmouth Village							
Church	234	95	1111	2819	306	38	6
School	94.5	31	397.5	256	98.5	33.5	2.7
Post Office	84.5	34	374.5	228	95.5	33.5	2.4
Lifesaving Station	320	76	1611	952	273	58	7.2
Summer Kitchen (Live-Saving Station)	70	23	165	170	86	24	2.4
Washington-Roberts House	125.5	67	524.5	302	144.5	33.5	3.6
Frank Gaskill House	75	36	321	188	104	27	2.4
Henry Pigott House	82.5	63	366	295.5	133	33.5	3.3

References

Adger, W.N., Arnell, N.W., Tompkins, E.L., 2005. Successful adaptation to climate change across scales. Glob. Environ. Chang. A 15 (2), 77–86.

Adger, W.N., Barnett, J., Brown, K., Marshall, N., O'brien, K.J.N.C.C., 2013. Cultural dimensions of climate change impacts and adaptation. Nat. Clim. Chang. 3 (2), 112.

Anderson, D.G., Bissett, T.G., Yerka, S.J., Wells, J.J., Kansa, E.C., Kansa, S.W., et al., 2017. Sea-level rise and archaeological site destruction: an example from the southeastern United States using DINAA (Digital Index of North American Archaeology). PLoS One 12 (11), e0188142.

Arsenault, R., Poulin, A., Côté, P., Brissette, F., 2013. Comparison of stochastic optimization algorithms in hydrological model calibration. J. Hydrol. Eng. 19 (7), 1374–1384.

Caffery, M.A., Beavers, R.L., Hoffman, C.H., 2018. Sea Level Rise and Storm Surge Projections for the National Park Service. N. P. Service, Fort Collins, Colorado.

Carmichael, B., 2016. Supporting Indigenous rangers' management of climate-change impacts on heritage sites: developing an effective planning tool and assessing its value. Rangel. J. 37 (6), 597–607.

Carmichael, B., Wilson, G., Namarnyilk, I., Nadji, S., Brockwell, S., Webb, B., et al., 2018. Local and Indigenous management of climate change risks to archaeological sites. Mitig. Adapt. Strateg. Glob. Chang. 23 (2), 231–255.

Chen, P.-Y., Tung, C.-P., Li, Y.-H., 2017. Low impact development planning and adaptation decision-making under climate change for a community against pluvial flooding. Water 9 (10), 756.

Clemen, R.T., Reilly, T., 2013. Making Hard Decisions With DecisionTools. Cengage Learning.

Daly, C., 2014. A framework for assessing the vulnerability of archaeological sites to climate change: theory, development, and application. Conserv. Manag. Archaeol. Sites 16 (3), 268–282.

Dupont, L., Van Eetvelde, V., 2013. Assessing the potential impacts of climate change on traditional landscapes and their heritage values on the local level: Case studies in the Dender basin in Flanders, Belgium. Land Use Policy 35, 179–191.

Fatorić, S., Seekamp, E., 2017a. Are cultural heritage and resources threatened by climate change? A systematic literature review. Clim. Change 142 (1-2), 227–254.

Fatorić, S., Seekamp, E., 2017b. Evaluating a decision analytic approach to climate change adaptation of cultural resources along the Atlantic Coast of the United States. Land Use Policy 68, 254–263.

Fatorić, S., Seekamp, E., 2018. A measurement framework to increase transparency in historic preservation decision-making under changing climate conditions. J. Cult. Herit. 30 (3), 168–179.

Fletcher, C.S., Rambaldi, A.N., Lipkin, F., McAllister, R.R., 2016. Economic, equitable, and affordable adaptations to protect coastal settlements against storm surge inundation. Reg. Environ. Change 16 (4), 1023–1034.

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T., Ohlson, D., 2012. Structured Decision Making: a Practical Guide to Environmental Management Choices. John Wiley & Sons, Oxford, UK.

Henderson, M., Seekamp, E., 2018. Battling the tides of climate change: the power of intangible cultural resource values to bind place meanings in vulnerable historic districts. Heritage 1 (2), 220–238.

Howard, R.A., 1988. Decision analysis: practice and promise. Manage. Sci. 34 (6), 679–695.

Huijbregts, Z., Kramer, R., Martens, M., Van Schijndel, A., Schellen, H., 2012. A proposed method to assess the damage risk of future climate change to museum objects in historic buildings. Build. Environ. 55, 43–56.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Keeney, R.L., 1982. Decision analysis: an overview. Oper. Res. 30 (5), 803–838.

Leissner, J., Kilian, R., Kotova, L., Jacob, D., Mikolajewicz, U., Broström, T., et al., 2015. Climate for Culture: assessing the impact of climate change on the future indoor climate in historic buildings using simulations. Herit. Sci. 3 (1), 38.

Lyons, J.E., Runge, M.C., Laskowski, H.P., Kendall, W.L., 2008. Monitoring in the context of structured decision-making and adaptive management. J. Wildl. Manage. 72 (8), 1683–1692.

Nichols, J.D., Runge, M.C., Johnson, F.A., Williams, B.K., 2007. Adaptive harvest management of North American waterfowl populations: a brief history and future prospects. J. Ornithol. 148 (2), 343–349.

NPS, 2014. Policy Memorandum 14-02, Climate Change and Stewardship of Cultural Resources. National Park Service, Washington, DC.

Parnell, G.S., Terry Bresnick, M., Tani, S.N., Johnson, E.R., 2013. Handbook of Decision Analysis, vol. 6 John Wiley & Sons.

Peek, K., Tormey, B., Thompson, H., Young, R., Norton, S., McNamee, J., Scavo, R., 2017. Adapting to Climate Change in Coastal Parks: Estimating the Exposure of Park Assets to 1 M of Sea-level Rise. CO, Fort Collins.

Possingham, H., Ball, I., Andelman, S., 2000. Mathematical Methods for Identifying Representative Reserve Networks. Springer, New York, NY.

Post van der Burg, M., Bly, B.B., Vercauteren, T., Grand, J.B., Tyre, A.J., 2014. On the role of budget sufficiency, cost efficiency, and uncertainty in species management. J. Wildl. Manage. 78 (1), 153–163.

Rockman, M., Morgan, M., Ziaja, S., Hambrecht, G., Meadow, A., 2016. Cultural Resources Climate Change Strategy. N. P. Service, Washington, DC.

Runge, M.C., 2011. An introduction to adaptive management for threatened and endangered species. J. Fish Wildl. Manag. 2 (2), 220–233.

Seekamp, E., Post van der Burg, M., Fatorić, S., Eaton, M., Xiao, X., and McCreary, A., in press, Optimizing historic preservation under climate change—An overview of the Optimal Preservation Model and pilot testing at Cape Lookout National Seashore: U. S. Geological Survey Open-File Report 2018–1180, https://doi.org/10.3133/ofr20181180.

Smit, B., Wandel, J., 2006. Adaptation, adaptive capacity and vulnerability. Glob. Environ. Chang. Part A 16 (3), 282–292.

Vieira, J., Cunha, M.C., 2017. Nested optimization approach for the capacity expansion of multiquality water supply systems under uncertainty. Water Resour. Manag. 31 (4), 1381–1395.

Watson, J.E., Dudley, N., Segan, D.B., Hockings, M., 2014. The performance and potential of protected areas. Nature 515 (7525), 67.

Williams, B.K., Eaton, M.J., Breininger, D.R., 2011. Adaptive resource management and the value of information. Ecol. Modell. 222 (18), 3429–3436.