Assessing Ecosystem Service Benefits from Military Installations

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Military bases provide substantial ecosystem services to local communities and other members of the public. This project conceptualizes and quantifies ecosystem services provided by U.S. military bases developing an integrated modeling platform called MoTIVES (Model-based Tracking and Integrated Valuation of Ecosystem Services). MoTIVES manages probabilistic simulations of biophysical and economic models for relevant ecosystem services provided by alternative base management scenarios, and then assigns values where valuation is possible. The project demonstrated a proof of concept at Eglin Air Force Base, showing that current management provides approximately $110 million in ecosystem services per year, $40 million more than a scenario where no base was present, and $90 million more than a scenario where no base management was occurring.

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List of Acronyms

BRI: benefit-relevant indicator

CMECS: Coastal and Marine Ecosystem Classification System

CMAQ: Community Multiscale Air Quality

FEMA: Federal Emergency Management Agency

DEM: digital elevation model

DOD: Department of Defense

FNAI: Florida Natural Areas Inventory

LULC: land use and land cover

INRMP: Integrated Natural Resources Management Plan

InVEST: Integrated Valuation of Ecoystem Services and Tradeoffs

LiDAR: Light Detection and Ranging

MTBS: Monitoring Trends in Burn Severity

MoTIVES: Model-based Tracking and Integrated Valuation of Ecosystem Services

NOAA: National Oceanic and Atmospheric Administration

NWI: National Wetlands Inventory

NVCS: National Vegetation Classification System

RCW: red-cockaded woodpecker

SERDP: Strategic Environmental Research and Development Program

STSM: state-and-transition simulation model

SWMM: Storm Water Management Model

USGS: United States Geological Survey

USFS: United States Forest Service

USFWS: United States Fish and Wildlife Service

Keywords

Bayesian modeling, Benefit-relevant indicators, Ecosystem services, Eglin Air Force Base, Integrated modeling

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Equally important to the project success was the help provided by Dan Hipes and Jon Otting at the Florida Natural Areas Inventory of Florida State University, who provided us with data, helped with the analysis linking forest states to Eglin threatened and endangered species, and, because of their expertise and experience with Eglin species, were able to help us solve many of the complex questions that arise in a project involving multiple models.

At Fort Hood, we received data and guidance from Amber Dankert, Virginia Sanders, and David Preston from the base, and Charlotte Reemts of The Nature Conservancy provided time and information from her work at the base to help understand the relationship between habitats, endangered birds and management at the base.

Abstract

Introduction and objectives: The United States military operates many military bases in extremely diverse geographic contexts. Many of these bases feature large areas of land that are undeveloped or sparsely developed in comparison to surroundings, providing a wide range of important functions such as flood protection, habitat for plant and wildlife species, recreational opportunities, and carbon sequestration. Therefore, military bases provide substantial ecosystem services, primarily to residents and users of nearby land. This project develops methods to conceptualize and quantify ecosystem services provided by U.S. military bases.

Technical approach: We developed conceptual ecosystem service models and related benefit-relevant indicators to visualize and quantify the potential services provided by military bases. We then developed an integrated modeling platform called MoTIVES (Model-based Tracking and Integrated Valuation of Ecosystem Services) to quantify and evaluate ecosystem services provided by alternative base management strategies. This platform manages probabilistic simulations of biophysical and economic models for relevant ecosystem services. These biophysical and economic models in turn leverage the latest scientific understanding of how management influences environmental endpoints and, where possible, how these endpoints are valued economically.

Results: This report presents conceptual ecosystem service models developed for a number of habitat types and four military bases. We provide a proof of concept for MoTIVES by quantifying ecosystem services at Eglin Air Force Base in Florida and outlining how this model can be adapted to other sites. At Eglin, we simulated changes in carbon storage, species habitat, flooding, timber harvest, and hunting/fishing across three scenarios: 1) continuation of current management, 2) no natural resource management, and 3) no base.

Our simulations show that current natural resource management at Eglin provides important and valuable services, particularly in providing flood protection and habitat for red-cockaded woodpecker. The subset of services we modeled total over $110M in value each year. Net benefits of the current management approach at Eglin is associated with net benefits that are greater than alternative scenarios for land use: net benefits are $40M per year greater than a hypothetical scenario in which the base does not exist and $90M per year greater than a scenario in which base management activities are discontinued. In comparison with these alternative land-use scenarios, current management practices provide more habitat area for 10 out of 12 other at-risk species in the longleaf pine ecosystem (including all pond and beach species), which could not be valued monetarily. Other services provided by Eglin, such as shoreline protection, were not modeled for this pilot case study, but also provide value.

Benefits: MoTIVES provides relatable estimates of ecosystem service value for individual sites that are readily understandable. We also demonstrate how use of an integrated modeling framework improves confidence in overall valuations by tracking interrelated values and uncertainties. Our approach is modular and easily transferable to very different contexts, including military bases throughout the U.S. Finally, including uncertainties and complex environmental phenomena enhances the realism and credibility of our valuations.

Executive Summary

Objectives

This project addresses the following three objectives from the SERDP Statement of Need:

1. Define and delineate the biological, physical and chemical services provided, including natural and nature-based features that provide benefit.
2. Understand cumulative effects, feedbacks and compensatory behavior of complex systems related to management of natural ecosystems and biological diversity.
3. Examine models that incorporate economic concepts and that may improve decision-making to evaluate trade-offs.

To meet these objectives, we are developing an integrative ecosystem services model called **MoTIVES (Model-based Tracking and Integrated Valuation of Ecosystem Services)** that can be applied to any military base or DOD facility to estimate the impact of base management on the provision of ecosystem services while accounting for interactions, offsets, and co-benefits among services.

Approach

Ecosystem services are the benefits that nature provides to people. Often, the existence of healthy natural systems and species is of sufficient importance to decision makers that no further information is needed, but in many cases, it can be more impactful and informative to quantify the specific benefits that nature is providing. To this end, we are developing the integrated ecosystem services model MoTIVES so that it can be applied to any military base or DOD facility at which natural resource management is being undertaken or considered. The model encompasses a wide range of habitats and management activities and will produce an assessment of a wide range of ecosystem services while accounting for interactions among habitats and services. To date, we have developed methods for evaluating **two scenarios relative to a baseline of current management**: (1) a no management scenario to assess how ecosystem services would differ if the base did not conduct any natural resource management, and (2) a no base scenario to assess how ecosystem service provision would differ if the base did not exist.

We developed and piloted our conceptual models at four bases: Eglin Air Force Base in Florida, Fort Hood Army Base in Texas, Camp Lejeune Marine Base in North Carolina, and Joint Base Lewis–McChord in Washington. We then applied this approach using more specific data and relevant ecosystem services to **Eglin Air Force Base**, as an example of how it could be applied elsewhere.

The development of our integrated ecosystem services modeling approach involved:

1. Creating a set of generalized ecosystem service **conceptual models** as the foundation for a modeling framework that links management actions to ecosystem services while identifying potential interactions,
2. Selecting and applying biophysical **ecological models** (terrestrial, aquatic, and flood models) that characterize ecological state, condition, and function under the various scenarios of interest,

3. Translating ecological state, condition, and function to **benefit relevant indicators (BRIs)** of ecosystem service provision,
4. Estimating the **economic value** of the BRI levels whenever appropriate using approaches including benefits transfer and direct estimation,
5. Joining the components above into the **integrated ecosystem services model (MoTIVES)** to quantitatively and holistically account for cumulative effects, co-benefits, feedbacks, and compensatory behavior.

Conceptual models

Ecosystem service conceptual models visually display how a base management action can cause changes to biophysical aspects of an ecosystem and how these changes translate to benefit relevant indicators and, when applicable, their economic values (Figure 1). Such conceptual models form the basis of our subsequent quantitative modeling. Because there are common habitat types that occur across DOD lands and there are often a defined set of management actions being taken within these habitats, we determined that we could formulate a limited set of **generalized habitat conceptual models** to be adapted and applied to any military base to then create a **base-specific model**. These base-specific models are then used as the framework for quantitative estimates of ecosystem services under specific base-relevant scenarios. Thus the conceptual framework creates consistency in ecosystem service assessment across bases, displaying how different elements of the system interact and providing a visual summary of the relevant ecosystem services being quantified at each base.

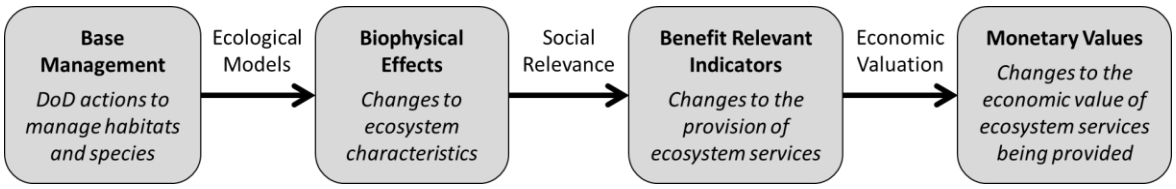


Figure E1. General structure of an ecosystem services conceptual model. The actual conceptual models include a detailed representation of each of the four stages shown here.

Generalized habitat conceptual models: Eight generalized habitat conceptual models have been created to reflect common ecosystem service flows on military bases. These models illustrate how management actions on bases result in changes to ecosystem services being provided by specific terrestrial and aquatic habitat types that occur on bases all over the U.S., including: 1) fire-maintained forests, 2) forests not maintained by fire, 3) fire-maintained grasslands, 4) grasslands not maintained by fire, 5) deserts, 6) rivers, streams, and riparian areas, 7) lakes, ponds, and wetlands, and 8) estuaries, saltmarsh, bays, and shorelines.

Base-specific conceptual models: Generalized habitat models are adapted and combined to create base-specific conceptual models that reflect the ecosystem service changes resulting from management at a particular base. Since the generalized models include *potential* ecosystem service outcomes, some outcomes may not be applicable to a particular base of interest. Therefore, to build a base-specific model, the user selects only the habitat models relevant for the base and removes irrelevant components. Once each relevant habitat model has been adapted to reflect the base-specific context, the resulting connected habitat models represent the integrative conceptual modeling framework to be used to quantify the base total ecosystem service flows.

Quantitative predictive model MoTIVES

Ecological models are used to represent the biophysical connections between management actions and changes to ecosystem type, condition, function or extent. Following are the two classes of ecological models being used:

Terrestrial Vegetation Condition Models: State-and-transition simulation models (STSMs) describe the primary states of vegetation composition and structure, and how individual states change over time under various disturbances (e.g., wildfire) or with management. We used STSMs to project the effects of management actions such as prescribed burning and timber harvest, disturbances such as wildfire and floods, and other processes on future vegetation condition using the open source ST-Sim software. STSMs provide outputs describing the amount of area occupied by each vegetation condition on a base under a set of management actions. These area estimates can then be tied to certain ecosystem services that are dependent on vegetation condition.

Aquatic Models: A series of models are available to model how management, wetlands, riparian vegetation, streams and other water bodies, soils and other factors influence the type and amount of aquatic ecosystem services provided by a base. These include flood risk and flood amelioration, provision of water for drinking, livestock, irrigation or industrial use, and reduction of sedimentation and nutrients, and habitat for valuable aquatic species. For this project we included a flood risk model (HAZUS) to calculate the flood hazard, or the annual chance of inundation at specific flood depths associated with inland flood risk as a function of local elevation and land use characteristics. Flood events are valued economically within HAZUS using data from the U.S. Census. In some cases, high resolution aquatic data sources specific to military installations can be used to parameterize models or provide economic valuation for services provided on the base.

Services were quantified using metrics referred to as **benefit relevant indicators (BRIs)**. BRIs are the hand-off between ecological function and social impact, connecting the supply of benefits and the reception of those benefits by people. For example, water storage capacity of a wetland is an ecological indicator, but the reduction in flooding risk to the downstream community resulting from that wetland is a BRI. In some cases, these BRIs can be extended to a monetary value, but in others monetary valuation is not possible or appropriate. When possible, we assign **economic valuation** to these BRIs using literature or base-specific data.

For final evaluation, the various steps and components described above were joined into a **single integrated ecosystem services model called MoTIVES** (Model-based Tracking and Integrated Valuation of Ecosystem Services). This has the advantage over parallel assessment of individual ecosystem services in that it allows for quantitative and holistic consideration of interactions, including co-benefits and offsets. This is especially important when accounting for uncertainty or potential site-to-site variability in assessment results. Changes in individual habitats and ecosystem services may be positively or negatively related to one another at any particular base. These relations may counterbalance one another, resulting in a smaller change than expected, or may reinforce one another, resulting in a larger-than-expected change. Representing such relations and interactions in an integrated model provides a more robust and realistic comparison of ecosystem service differences between evaluated scenarios.

Proof of Concept: Eglin Air Force Base

Eglin Air Force Base is the largest forested military base in the United States, supporting the largest remaining mature longleaf pine (*Pinus palustris*) forest in the world, habitat for 24 listed threatened or endangered species, and extensive freshwater and estuarine wetlands, ponds and riparian meadows. The base has a number of coastal streams and bays that support at-risk fish, along with desirable fishing locals. The base allows access for fishing and boating in all appropriate areas. Much of the eastern portions of Santa Rosa Island, a Gulf of Mexico barrier island, is part of Eglin, supporting turtle nesting, habitat for endangered shorebirds and a sand adapted threatened lichen, along with providing protection from storm surges and coastal flooding to the communities of Fort Walton Beach and Navarre. The base supports recreation, hunting, and fishing, while providing the necessary infrastructure for its primary training mission.

We used the MoTIVES model to evaluate **three scenarios for Eglin Air Force Base**:

- **Current management scenario:** The baseline scenario of current management assumes that current natural resource management on the base would continue at current rates, primarily consisting of widespread use of prescribed burning to create the open conditions favorable to longleaf pine and associated wildlife species.
- **No-management scenario**: In this scenario, we assumed that the base continued all military operations but did not (currently or historically) manage for natural resources, with no prescribed fire or other management activity specific to natural resources.
- **No-base scenario**: To assess the total ecosystem services being provided by the base, we created a counterfactual scenario in which the base does not exist, and based projections on land use and land cover consistent with surrounding areas.

Annualized results from these scenarios were calculated for the future time period of 2020-2035. Results for these analysis were reported for 1) vegetation condition, 2) flood exposure and protection, 3) summarized for all monetized ecosystem services and 4) for habitat for at risk species.

1: Vegetation condition. Currently, late open conditions cover roughly half of the forested area at Eglin (roughly 77,000 ha). Under the current management scenario (consisting of continuing large-scale prescribed burning), the area of late open forest is expected to increase to roughly 115,000 hectares, covering the majority of the base (Figure E2). Conversely, under the no management scenario (without any prescribed burning either currently or historically), the base would likely contain very little (<5%) older, open longleaf pine and largely consist of older, closed forest. Closed canopy forests burn rarely, tend to become invaded by sand pine, and provide low quality wildlife habitat. Under the no base scenario, we expect ~50,000 hectares of conversion from forest to other land use types, and of the remaining forest, very little is projected to remain in late open conditions due to frequent clear-cutting and dense replanting on private timberlands.

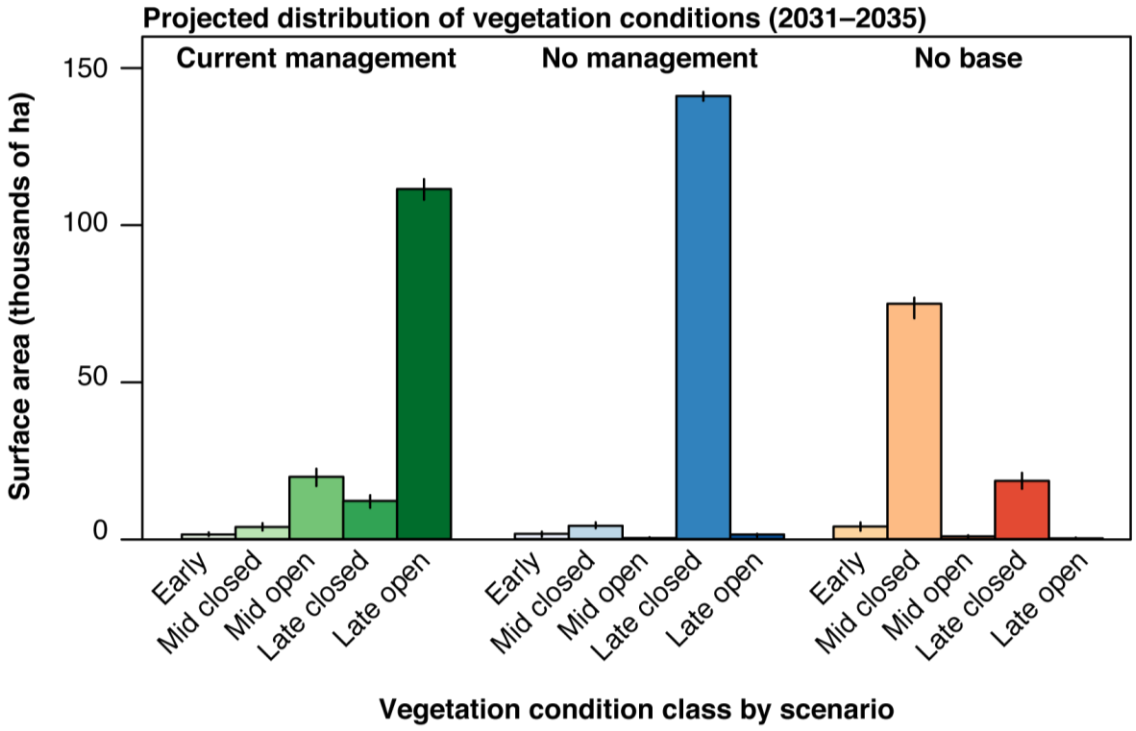


Figure E2. Projected longleaf pine forest condition classes at Eglin Air Force Base across the current management, no management and no base scenarios in years 2031-2035. Without active management of longleaf pine through prescribed fire under the current management scenario, condition degrades from open (desirable) to closed (undesirable) canopy conditions.

2: Flood exposure and protection. Under current management, expected losses from flood events over the period 2020–2035 average $610.4 million per year for the three counties surrounding Eglin Air Force Base. Under no-management and no-base scenarios, these losses are expected to be $579.8 million per year and $637.3 million per year respectively. However, increased density of all trees under the no-management scenario means that this counterfactual scenario would be associated with flood risks roughly $31 million per year lower than with current management conditions.

Table E1. Modeled valuations of future flood risks (damages) by scenario over period 2020–2035. Values displayed are means (95% CI)

Units	Current management	No management	No base
M$/yr [(b)]	610.4 (251.7–1,689.2)	579.8 (239.1–1,604.7)	637.3 (262.8–1,763.6)

3: Monetized ecosystem services. Current management practices generate ecosystem service benefits that are most often greater than the benefits associated with counterfactual no-base and no-management scenarios. However there are trade-offs: flood risk may be lower with no base; timber harvest would likely be greater with no base; and above-ground carbon storage is greatest with a base that is not managed for natural resources.

Annualized results from these scenarios are presented for the future time period of 2020-2035. They include very high flood hazard reduction values, with no management preventing ~ $31

million in flood damage than current management, and ~$57 million more than a no base scenario. Because these represent risk probabilities, they were treated separately. All other services that could be valued in dollars were compared, with the results shown in Figure E2.

Table E2. Modeled ecosystem service values under three scenarios. Values displayed are means (95% confidence interval in parentheses where modeled probabilistically)

	Current management	**No management**	**No base**
	***Monetized services in millions of dollars/year*[(a)]**		
Timber harvest	1.0	0	39 (24–48)
Recreational hunting	36	0	0
Recreational fishing	11	0	0
Carbon storage	1.6 (0.7–3.5)	3.1 (1.4–6.7)	1.2 (0.6–2.6)
Red-cockaded woodpecker value	56 (35–70)	30 (18–36)	11 (6.8–14)
Total monetized services[(b)]	**109 (87–123)**	**33 (20–40)**	**51.2 (32–63)**

[(a)] Annualized net present value over period 2020–2035 assuming a 5% discount rate
[(b)] Total adjusts for correlated uncertainties and may not equal arithmetic sum of individual services

4: Habitat of critical species. Eglin Air Force Base is home to a number of threatened, endangered, and endemic species, many of which rely almost entirely on the base for their survival. Thirteen of these species were modeled under the three scenarios as part of this study. Current management practices produce the greatest area of suitable habitat for most of these species, including sufficient amounts to preclude federal listing for a number of them. The exceptions were the Gulf Coast redflower pitcherplant and smallflowered meadowbeauty. For these two species, the no-management scenario provides slightly more area of suitable habitat. The no-base scenario severely reduces available habitat for all species. Figure E3 shows the comparison between the predicted species habitat areas.

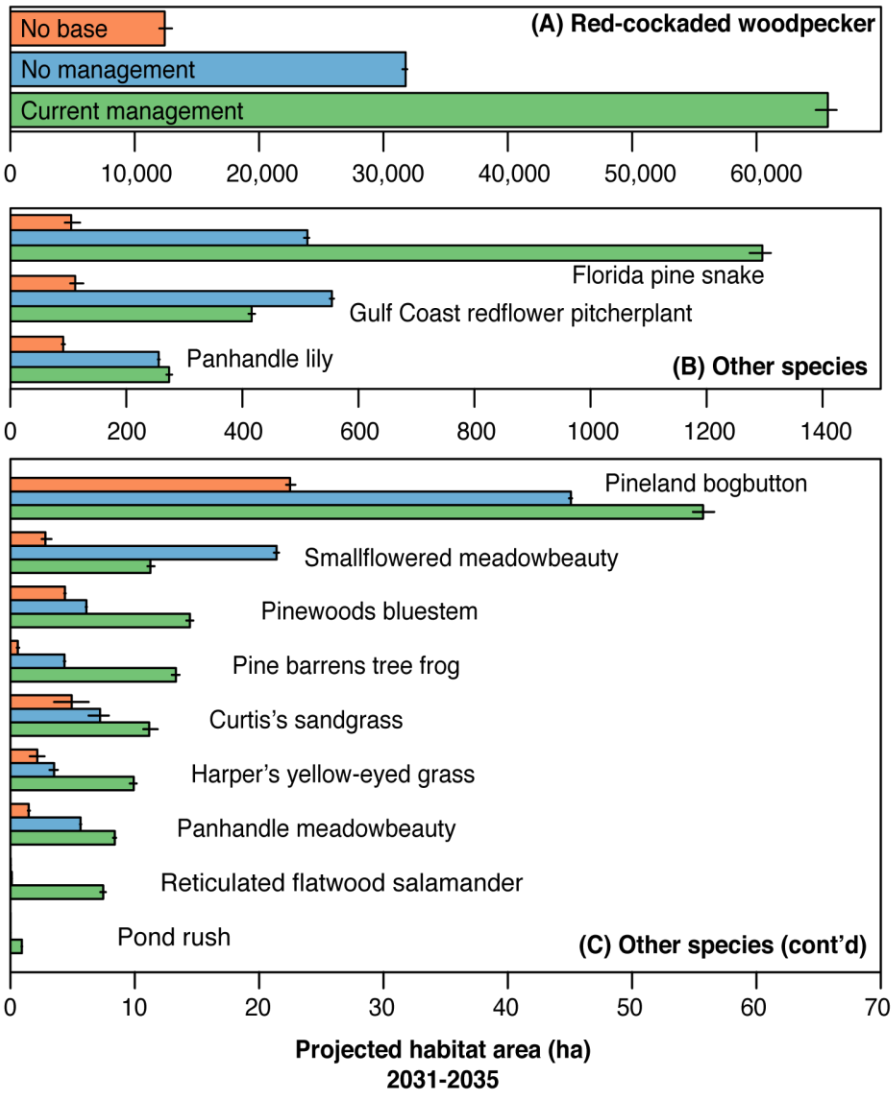


Figure E3. Habitat area available for key species under the three scenarios. Values plotted are based on projected distribution of vegetation in the period 2031–2035. Error bars are the 95% confidence interval.

5. Comparison of scenarios. Current management practices are associated with higher ecosystem service generation and lower value of flood risks than the no-base counterfactual. Conversely, the no-management counterfactual is associated with lower ecosystem service generation but also lower flood risks than current management. Taking account of these expected costs and benefits across scenarios, we find that the current management practices scenario produces significantly higher net benefits than either of the two counterfactuals (mean of $90.8 million and $40.5 million per year relative to no-management and no-base respectively)(Table E3).

Table E3. Modeled net benefits of current management compared to counterfactual no-management and no-base scenarios. Values displayed are means (95% CI)

Current management service provision improvement over		
Units	**No management**	**No base**
M$/yr [(a)]	90.8 (66.5–127.1)	40.5 (9.2–69.6)

[(a)] Annualized net present value over period 2020–2035 assuming a 5% discount rate and accounting for correlated uncertainties across individual services

Recommendations for Additional Research Needs

Aquatic ecosystem services. Because the most important services provided by Eglin Air Force Base were linked to the management of terrestrial ecosystems, in our pilot study we were not able to take advantage of some of the models and tools related to aquatic ecosystem services. At other bases, where aquatic systems and services are important, other models should be incorporated. The InVEST models have been tested and are simple to apply in many areas.

Water quality improvements. Similarly, research into water quality improvement related to both the ecosystem processes of nutrient removal, and the value of removed N and P for anything but waste water treatment would improve our model outputs.

Research into valuing species existence. Tradeoffs are most easily evaluated if different services can be measured in similar units, which is why economic valuation is so useful. Yet many base management activities on the pilot bases are focused on management of threatened, endangered or endemic species, as they provide critical habitat for them. The conservation or expansion of populations of at risk species represent important management outcomes.

More comprehensive assessment of economic values. We estimated economic values for many BRIs, but future research is needed to provide a more comprehensive assessment. Economic values for market goods are readily estimated because these goods have observable prices. For example, we computed economic values for timber and flood damage using market data on stumpage and real estate prices. Valuation of non-market goods is also possible using techniques such as the contingent valuation method. Non-market benefits quantified for Eglin include species preservation and carbon storage.

Conclusions

Since ecosystem services have become widely recognized as a useful tool for assessing the success of natural resource management actions, quantifying and reporting on these services is becoming part of good resource management practice. Our approach can help DOD natural resource managers show how they are enhancing the production of services, and how the existence of the base itself provides substantial ecosystem services benefits to people.

Our approach is unique in a number of ways. First, we use conceptual models as an intuitive transferable foundation for building base specific models across habitat types and management strategies. Second, we develop an assemblage of multiple models in an interactive probabilistic platform that can address trade-offs and interactions. Third, we explicitly use benefit relevant indicators (BRIs) as an alternative or additional measure to economic valuation.

Due to its modular framework, we have been able to take advantage of previous ecological assessment work available at many bases, but also have methods that apply where previous ecological modeling has not occurred. We have identified national models and datasets available for the contiguous 48 states. To use the approach in other regions, additional data and models would need to be identified. The methodology can be readily transferred to any large base anticipated to generate ecosystem services.

Ecosystem service outputs in the model are estimated in dollar values when possible, and also in valued benefits (benefit relevant indicators). Often benefit relevant indicators are more meaningful for stakeholders and are useful to communicate in addition to dollar values when both are available. Because most bases provide a diverse array of ecosystem services, and because some management decisions can reduce some services while increasing others, our methods combine this complex assemblage into a single, Bayesian model (MoTIVES) to integrate outputs and allow an evaluation of alternative management scenarios. This makes it possible for natural resource managers to evaluate how management for a particular habitat condition to support species or training will impact values for other services. Additionally, these management scenarios allow a comparison of different management choices as well as providing essential baseline comparisons needed to measure some ecosystem services such as flooding prevention.

The MoTIVES structure also allows it to take advantage of a broad array of available ecosystem assessment tools, broadening the ability to use the best data or model available for a particular base. A distinguishing feature of MoTIVES is the fact that it explicitly considers uncertainty in all aspects of the model and translates this uncertainty to model endpoints using Monte Carlo simulation. By using simulation to explore the range of possible consequences of management on ecosystem service values, we decrease the likelihood of later surprises or missed opportunities. This approach makes conclusions robust to questions about confidence in numerical answers. For example, despite wide confidence intervals, we are able to say with >95% confidence that net benefits of current management practices at Eglin Air Force Base are greater under current management than under plausible alternative scenarios considered.

The results from Eglin Air Force base show that current management provides very significant ecosystem service values, estimated at approximately $110 million dollars a year, much more than the same base not managed, or the same area if it had not become a base. It appears likely that similar results would result from this analysis at Fort Hood and most of the other large military installations.

1 Project Objectives

The objectives of this research are:

1. To develop a model that will provide a transferable and consistent foundation for assessing ecosystem service benefits from military installations including an understanding of cumulative effects, trade-offs, and uncertainty, and;
2. To provide a proof of concept for this model in an example military installation.

General conceptual models were developed for selected pilot inland and coastal bases that addressed all ongoing management activities, including training requirements, land stewardship, legal drivers, and coordination within and beyond installation boundaries. We explored how these generalized models could be specified to the needs of any individual base and form the foundation for qualitative assessments, quantitative models, and valuation. Starting with these conceptual models, we evaluated and compared available methods to include cumulative effects and interactions, while generating quantitative outputs of what is valued by people and, where possible, what those economic values are. The project proposes a transferable framework and design for an integrative modeling tool called MoTIVES (Model-based Tracking and Integrated Valuation of Ecosystem Services) to incorporate ecosystem services and benefits into decision making for large military installations in the U.S.

This project addresses the following three objectives from the SERDP Statement of Need:

1. Define and delineate the biological, physical and chemical services provided, including natural and nature-based features that provide benefit.
2. Understand cumulative effects, feedbacks and compensatory behavior of complex systems related to management of natural ecosystems and biological diversity.
3. Examine models that incorporate economic concepts and that may improve decision-making to evaluate trade-offs.

2 Project Background

Ecosystem services are the benefits nature provides to people such as recreational opportunities (e.g., fishing, boating, hiking, birdwatching), protection from natural disasters (e.g., flood protection, reduced risk of wildfire), provision of goods (timber, fish/shellfish, and contributions to crop production), as well as the sense of place, spiritual connection, and mental health benefits of being in nature and knowing it is there and healthy (Kumar 2010, MEA 2005). While the existence of healthy natural systems and species is often of sufficient importance to decision makers and the public that no further information is needed, in other cases it can be impactful to quantify the range of specific benefits that nature is providing. For example, it can be more meaningful to talk about whether people are allowed to swim in the water or whether it is healthy to eat shellfish from the water, than it is to talk about dissolved oxygen or pollutant levels. Information on the reduced risk of flooding provided by an upstream wetland can be meaningful to communities and their insurance companies (Watson et al. 2016). The knowledge that reducing wildfire within hundreds of miles can reduce negative respiratory health outcomes can be meaningful to vulnerable people (Liu et al. 2015). And knowing that recreational fish catch is declining in an area even though it appears healthy can also expand the information we have

available to manage these systems. In some cases, knowing these relationships can form the basis of conservation and management partnerships when one entity (a federal agency) is providing service to private landowners. For example, in Denver, the USFS is being paid via municipal water fees to manage their upstream forests to reduce wildfire and extreme sedimentation events that have huge costs for municipal water treatment.

In this project we are developing an integrated ecosystem services modeling framework that can be applied to any military base or DOD facility where natural resource management is ongoing. It can encompass a wide range of habitats and management actions that are typical of bases, and it will produce an assessment for a wide range of ecosystem services. For this initial modeling framework we have developed methods for evaluating two specific types of scenarios, in comparison to current conditions:

- **No management scenario**: In this scenario, we assume that the base continues all military operations but does not (currently or historically) manage for natural resources, with no prescribed fire or other management activity specific to natural resources.
- **No base scenario**: To assess the total ecosystem services being provided by the base, we created a counterfactual scenario in which the base does not exist and based projections on land use and land cover consistent with surrounding areas.

In this limited scope and duration project, we have developed a set of generic models and methods to be applied generally to any military base. We piloted our conceptual modeling approach at four bases, Eglin Air Force Base in Florida, Fort Hood Army Base in Texas, Camp Lejeune Marine Base in North Carolina, and Joint Base Lewis–McChord in Washington. We then applied the quantitative predictive model (MoTIVES) using specific data and relevant ecosystem services to Eglin Air Force Base, as an example of how it could be applied elsewhere.

3 Materials and Methods

3.1 Overview of the Approach

Our multi-step approach is as follows:

Step 1. Develop ecosystem services conceptual models for general habitat and management and facility types and then adapt them to individual bases and management actions. The project team first developed generalized habitat conceptual models for management of major habitat types (e.g., fire maintained forests, deserts, etc.). These generalized models can be combined to represent habitats for specific bases to form base-specific conceptual models of base management activities (e.g., prescribed fire, endangered species protections, training activities). These conceptual models incorporate ecosystem services and benefit-relevant indicators that include training requirements, land stewardship, and when possible legal drivers such as compliance with regulations or laws protecting natural resources. The modeling framework provided a foundation for predictive modeling of different management and regulatory scenarios, as well as modeling of cumulative effects and feedbacks.

Ecosystem service conceptual models visually display how a base management action can cause changes to biophysical aspects of an ecosystem and how these changes translate to benefit relevant indicators and, when applicable, their economic values (Figure 1). Such conceptual models form the basis of our subsequent quantitative modeling. Because there are common

habitat types that occur across DOD lands and there are often a defined set of management actions being taken within these habitats, we determined that we could formulate a limited set of **generalized habitat conceptual models** to be adapted and applied to any military base to then create a **base-specific model**. These base-specific models are then used as the framework for quantitative estimates of ecosystem services under specific base-relevant scenarios. Thus the conceptual framework creates consistency in ecosystem service assessment across bases, displaying how different elements of the system interact and providing a visual summary of the relevant ecosystem services being quantified at each base.

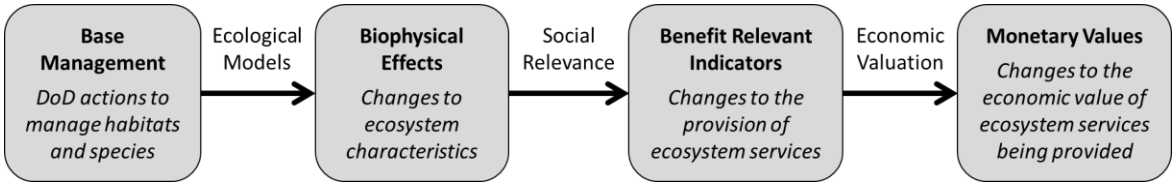


Figure 1. General structure of an ecosystem services conceptual model. The actual conceptual models include a detailed representation of each of the four stages shown here.

Step 2. Identify a suite of benefit-relevant indicators that can be used to monitor and report on ecosystem services outcomes of interest to DOD and their stakeholders (Tables 1 and 2). A minimal set of benefit-relevant indicators that can capture the outcomes valued by managers and other stakeholders were identified during the development of the conceptual models. We focused on indicators that capture outcomes relevant at individual bases but were also meaningful across bases. We intended these generalized models and benefit-relevant indicators to be specified to the needs of other bases and form the foundation for qualitative assessments, quantitative models, and/or monetary valuation.

We assessed methods to translate benefit-relevant indicators into monetary values. A key challenge is that many ecosystem services are not exchanged in traditional markets and as a result, direct information on how much people value them is lacking. There is a large literature in economics that provides alternative methods of valuing these non-market goods (Johnston and Russell 2011) through evidence of non-market values in related markets, or valuing ecosystem services using surveys. We evaluated the potential for applying these methods to benefits produced on bases as well as opportunities for transferring benefits estimates from existing studies.

Step 3. Identify relevant ecological, social and economic datasets and models that could be used to transform this conceptual model into a predictive modeling tool. There is a diverse set of computational tools available to analyze changes in the benefit-relevant indicators that occur when stewardship or management activities are implemented. There is an equally diverse array of tools to identify the location and quantity of ecosystem benefits being provided, including vegetation models, hydrologic models and flood risk models. We explored the types of tools that have been used to generate ecological outputs along with those linking people to benefits, and identify those best suited for the management questions important to military installations.

Step 4. Develop the design for a modular and transferable predictive modeling tool based on the general conceptual models that captures cumulative effects and feedback loops. The final step was to develop a design for a modular Bayesian network modelling tool (MoTIVES) based

on the generalized ecosystem services conceptual model frameworks and incorporating the ecological, social, and economic data and models identified in previous steps. Consistent with the conceptual modeling, Bayesian networks start with a graphical representation of the human/natural system being considered. Key variables are represented by nodes, and relations between nodes are represented by arrows. While Bayesian networks may be visually similar to flow charts or process diagrams, they are distinct in representing probabilistic dependence relations, rather than workflow or movement of materials and energy (Mavrommati et al. 2016).

Research goals: An important research aim of this project going forward will be to assess the transferability of the modules in our pilot models, given the diversity of facilities and associated natural resources. Another key research aim will be to develop and demonstrate methods for incorporating cumulative effects and feedbacks into the Bayesian network models. Such dynamic Bayesian networks have been developed in the academic literature but have only rarely been implemented in management practice.

The project has demonstrated a method to create a transferable framework and the design for a predictive modeling tool for incorporating ecosystem services and benefits into decision making for most of the large military installations in the United States (Figure 2). Developing a generalized model that can capture a broad range of overlapping actions in a specified location such as land stewardship actions, regulatory driven management, and off-site coordination, which are all relevant to DOD base management, remains a challenge. But this is a challenge we think now has a strategy and methodology for a solution, that allows stewardship and land use to be balanced.

In order to test the approach we develop here, we chose to pilot MoTIVES at Eglin Air Force base. Using the steps outlined above we developed a conceptual model for Eglin AFB, including only those services relevant at that site to act as a framework for applying only the relevant quantification tools and combining their results within MoTIVES. MoTIVES was applied to provide a scenario analysis that presents results comparing the ecosystem services outcomes of current ecosystem management of Eglin to a no management and no base scenario.

3.2 Conceptual Models of Ecosystem Services

As outlined in Step 1 of our approach, we began by building **ecosystem services conceptual models**. These conceptual models visually display how a management action causes changes to biophysical aspects of an ecological system and how those changes cascade to affect ecosystem services and, when appropriate, their economic values. Conceptual models form the basis of our quantitative modeling framework. Because there are common habitats that occur across DOD lands and there are a defined set of environmental management actions being taken within these habitats, we determined that it was possible to develop a set of **generalized habitat-based ecosystem services conceptual models** that could be adapted and applied to any military base, creating **base-specific models**. These base-specific models are then used as a framework for subsequent Bayesian network modeling that applies quantitative methods to produce estimates for ecosystem services outcomes. This conceptual framework is important as it helps to create consistency in modeling across bases, displays how different elements of the system are interacting, and provides a visual summary of the relevant ecosystem services being quantified at each base.

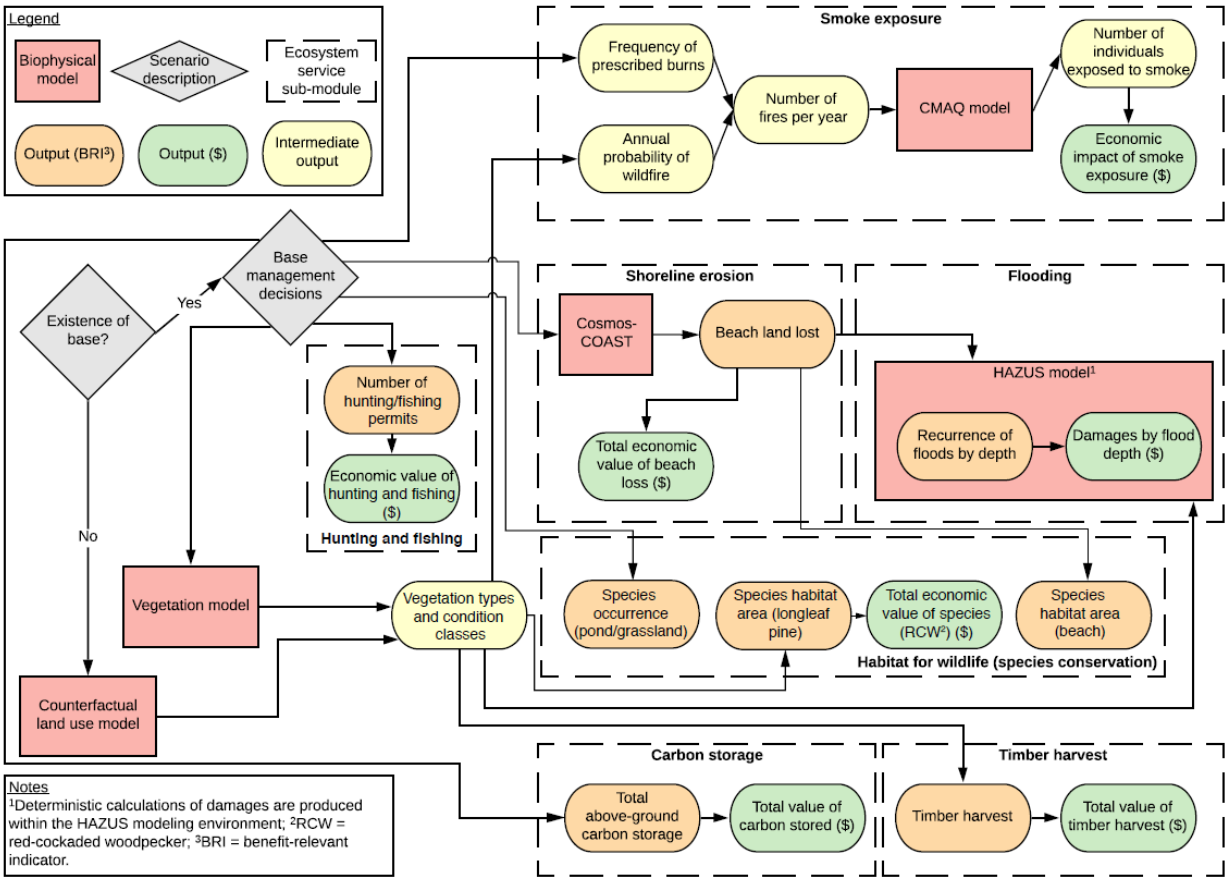


Figure 2. Schematic diagram of the major components of the MoTIVES integrated model for Eglin Air Force Base. Of the ecosystem service sub-models shown here, the Eglin case study in included carbon storage, wildlife habitat, flooding, hunting and fishing, but not shoreline erosion or smoke exposure.

3.2.1 Generalized Habitat Conceptual Models

The generalized habitat conceptual models identify ecosystem and management changes, and follow the outputs through a causal chain to link the flows from ecosystems to people. Different habitat types (e.g., northern deciduous forests, estuaries, deserts, and fire maintained forests) can provide a very different set of services, and many different services are generated by a single base. For efficiency, the number of generalized habitat models was kept as small as possible. Because some aspects of the habitats, including the biome type (forests, grasslands, deserts) and whether ecosystems are fire maintained or not, drive both the types of base management that occurs and the ecosystem services provided, a set of eight generalized habitats were identified. These models illustrate how natural resource management on bases results in changes to ecosystem services, and each model is distinguished by a certain habitat type (all models are available in Appendix 1). These generalized models represent common terrestrial and aquatic habitats that occur on bases all over the U.S., including:

- Fire maintained forests (Figure 3)
- Forests not maintained by fire (includes winter deciduous forests and some coniferous and mixed hardwood-conifer forests)

- Fire-maintained savannas, shrublands and prairies
- Savannas, shrublands and prairies not maintained by fire (alpine, tundra)
- Deserts
- Rivers, streams and riparian habitats
- Lakes, ponds, aquatic beds and wetland habitats
- Estuaries, saltmarsh, bays and shorelines, marine habitats

These generalized habitat conceptual models provided a template, making it easier to quickly generate base specific models while assuring that all of the major ecosystem services and their causal chains were identified.

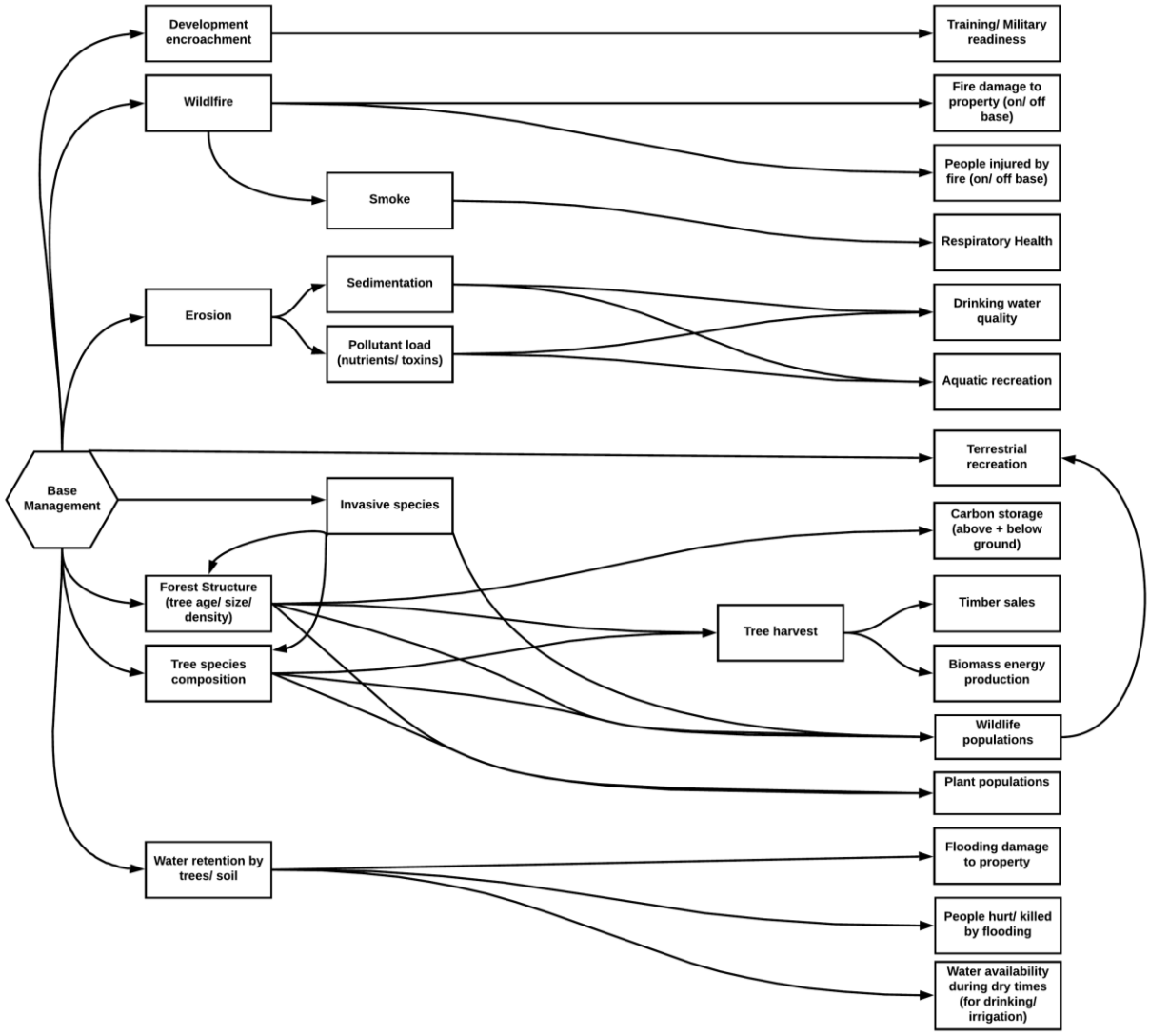


Figure 3. Generalized habitat conceptual model for a fire maintained forest type. This generalized model contains many potential ecosystem services that could be generated by this habitat type, and when applied at an individual base would be tailored to the services provided on the site.

However, when creating the base specific models, to be able to measure and value ecosystem services provided by the habitats, it is necessary to translate the generalized habitats into the specific vegetation types found at each base. To do this we identified a standard set of ecosystem types to use as the basis of our models.

In the process of identifying terrestrial ecosystems types to use for individual base analysis, it quickly became clear that the vegetation and habitat classifications individual bases used in their INRMPs to name and map these terrestrial and aquatic vegetation vary widely across the country. Installations often use the classification used by the state natural heritage program or the state fish and wildlife agency, federal classifications from the U.S. Fish and Wildlife Service (USFWS), NOAA Fisheries, the U.S. Geological Survey (USGS), and the U.S. Forest Service (USFS), or a combination of sources. For this project, to assure the framework could be used at all the bases, the team chose to crosswalk the habitats mapped at each base to a consistent hierarchical level in the National Vegetation Classification System (NVCS).

The NVCS classification was developed by the USGS and is maintained by NatureServe, and includes seven hierarchical levels, ranging from broad formations (e.g. forests, grasslands, shrublands) down to local plant associations (e.g. longleaf pine/wiregrass (*Pinus palustris/Aristida stricta*) or Douglas-fir – Pacific Madrone / salal (*Pseudotsuga menziesii-Arbutus menziesii/Gaultheria shallon*) forest). The macrogroup level in the NVCS was selected as the most appropriate level to link to BRIs because they are broad enough to represent similar ecosystems across the country, but fine enough to characterize the ecological functions and flows in a meaningful and measurable way. They also can be linked easily to the Ecological Systems Classification also developed by the USGS and NatureServe, which is the basis for the vegetation maps produced by the USGS, USFS, and the LANDFIRE project.

For marine and estuarine habitats, we used the Coastal and Marine Ecosystem Classification System (CMECS), which is the only comprehensive coastal and marine habitat classification in the U.S. The CMECS includes an aquatic setting and a biotic component, the latter used at the class level. Our team used the aquatic component at the system level, (Marine, Estuarine, Marine Nearshore and Marine Offshore) for the generic habitat models, and for use in the individual base models, the 11 biotic classes developed in the CMCS classification. For freshwater wetland habitats we could choose to use either the Cowarden classes (Forested, Shrub-Scrub, and Emergent wetlands) used in the National Wetlands Inventory (NWI) of the USFWS, or the NVCS macrogroup classification, depending on which wetlands classification was used by individual bases in their wetland maps. Lastly, for other aquatics, we used just two categories: 1) Rivers, streams and riparian habitat and 2) Lakes, Ponds and aquatic bed habitats.

3.2.2 Base-Specific Conceptual Models

Generalized habitat models can be adapted and combined to create unique base-specific models that reflect the service changes resulting from management on that base, across all the habitat types present. To build a particular base model, the user should select the habitat models relevant for the base and then remove all irrelevant pathways and outcomes from each habitat model. Generalized models have been built to include all *potential* ecosystem services outcomes, therefore some outcomes may not be applicable to the base of interest. To create a base-specific conceptual model, specific causal chains from the generalized conceptual models not relevant to the base if they are not produced or not used would be removed. Once each habitat model has been adapted to accurately reflect the base's context, these models should be overlaid to create a

base model that displays all relevant habitats and services. This then represents the quantitative modeling framework that can be used to quantify total service flows for the base (Figure 4).

The conceptual models reflect ways in which management decisions alter the individual ecosystems at the base, how these changes impact potential useful environmental outputs and then how these outputs are used. Often, the individual ecosystems managed are terrestrial ecosystems, which are usually described as a terrestrial or aquatic habitat type. Since actions specified in the Integrated Natural Resources Management Plan (INRMP) for each base are often organized by these habitat types, and vegetation maps are developed using habitat classifications, these are the best tools to use for analyzing the effects of management.

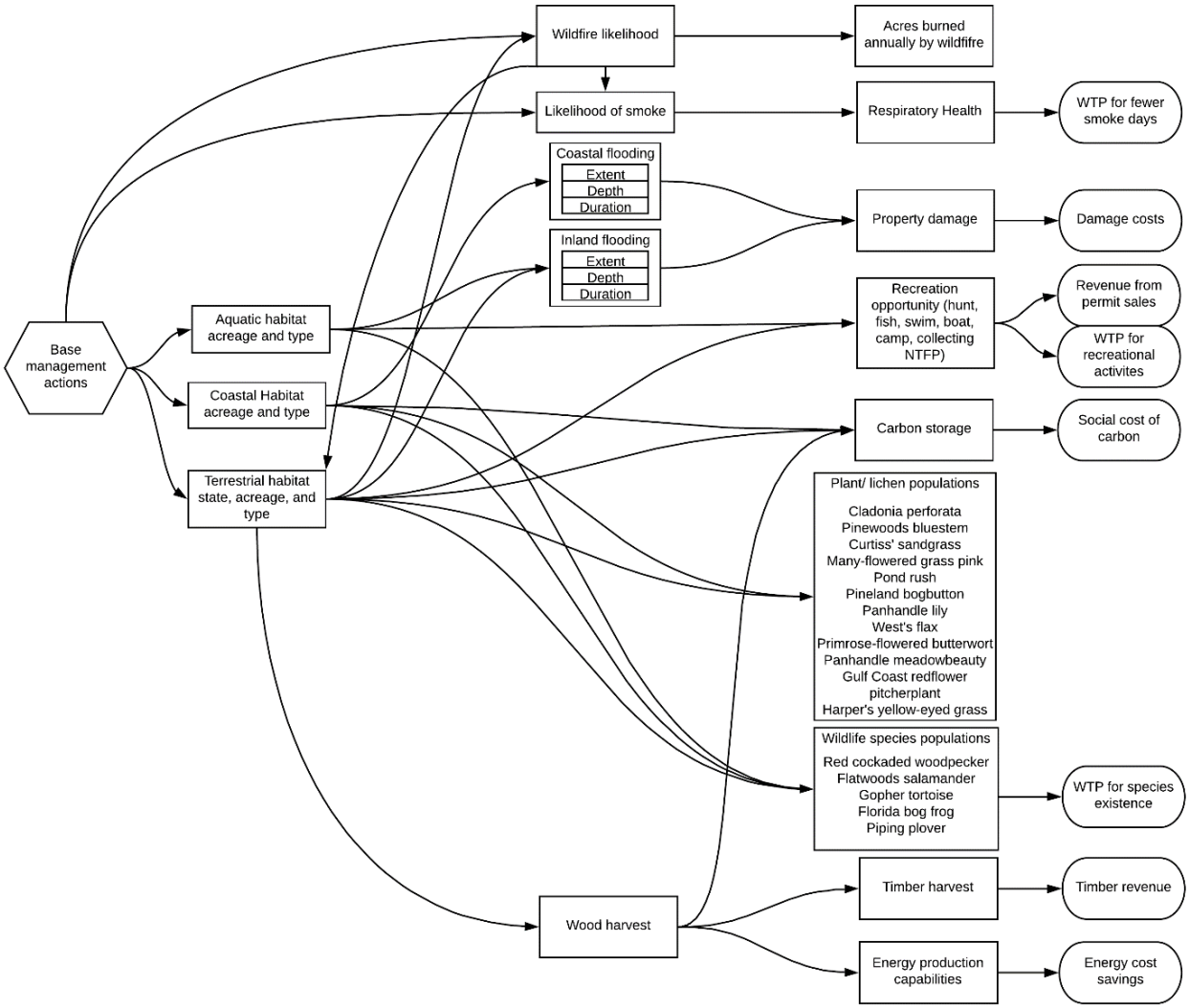


Figure 4. Military base-specific conceptual model for Eglin Air Force Base. This model combines the relevant habitat types at the base and includes management actions and services specific to the site.

3.3 Benefit Relevant Indicators (BRIs) and Economic Valuation

Step 2 of our approach involves identifying a suite of benefit-relevant indicators (BRIs) that can be used to monitor and report on ecosystem services outcomes of interest to DOD and their stakeholders. BRIs are the hand-off between ecological function and social impact, integrating the supply of benefits and the demand or reception of those benefits by people. For example, water storage capacity of a wetland is an ecological indicator, a 20% reduction in flooding risk resulting from that wetland to a downstream community with 100 homes and a population of 286 people is a benefit relevant indicator. BRIs are also the basis for economic valuation. The ecosystem services being evaluated will be presented as either benefit relevant indicators (BRIs), monetary values, or both (Table 2).

Table 1. Potential benefit relevant indicators (BRIs) and economic values for ecosystem services provided by military bases.

Model Endpoint	Benefit Relevant Indicator (BRI)	Economic Value
Wildfire damage	• Increased/decreased severity and/or extent of fire on and around base? (per acre)	• Avoided suppression costs • Avoided damage to property
Respiratory health (related to smoke)	• Number of people expected to experience increased smoke exposure/day	• Willingness to pay for reduced smoke exposure
Timber harvest	• Board-feet of timber harvested per year from the base	• Market value of timber
Energy production (from biofuels)	• Biomass energy production from the base	• Electricity cost savings for a base
Recreation opportunity	• User-days recreating on the base	• Willingness to pay for recreation
Carbon storage	• Mg C on the base	• Social cost of carbon
Federally-listed threatened and endangered species	• Acres of occupied habitat on the base • Population estimates • Population estimates on base relative to population over full range • Stream miles of occupied habitat • # of occurrences • # of occurrences on base relative to occurrences within species range	• Willingness to pay for species preservation
Endemic or locally important species	• Acres of occupied habitat on the base • Stream miles of occupied habitat • # of occurrences • # of occurrences on base relative to occurrences within species range	• Willingness to pay for endemic species preservation
Huntable wildlife species	• Number of hunting permits or tags from the base	• Willingness to pay for hunting
Harvestable fish	• Number of fishing licenses from the base	• Willingness to pay for fishing
Drinking water quality	• Tons of sediment per year exported from base for catchment, relative to proportion of waterways impaired in the catchment. • Sediment retention by land cover per year for catchment, relative proportion of waterways impaired in the catchment.	• Avoided water treatment and sediment removal costs • Value of improved fisheries

Model Endpoint	Benefit Relevant Indicator (BRI)	Economic Value
Flood damage to property (from coastal storm surge)	• Change in the probability of flooding downstream of base, due to base land cover (to estimate Number of properties/ facilities damaged per year)	• Avoided damage to property
Flood damage to property (from inland flooding)	• Water holding capacity of base uplands, wetlands and waterbodies during flood events in areas where downstream flooding impacts people and property	• Avoided property damage
Shoreline erosion	• Area of beach used by people, providing habitat for species, or protecting infrastructure.	• Cost of beach renourishment • Avoided damage to property
Water available for agriculture or industrial uses	• Water storage on the base and amount of water needed by farmers or industry downstream from the base or otherwise able to access base water.	• Cost of water rights or purchases

Where possible, BRIs were assigned an economic value. Economic or monetary valuation involves quantifying the net benefits (benefits minus costs) generated by an ecosystem service. Two methods are used for economic valuation of the BRIs:

1. The first is to construct measures using **data on the individual components of net benefits**. For example, to measure the net benefit from timber harvest on a base, we can identify the timber volume harvested and multiply this by the stumpage price for that timber type. The stumpage price measures the market value of the timber net of harvesting costs and so the product of stumpage price and harvest volume approximates the total net benefit from timber harvest.[1] This first approach is applicable to goods traded in markets, such as timber, energy production, and avoided property damage. Because these goods are traded in markets, it is possible to observe prices and costs of production in most cases.
2. The second approach is to apply **net benefit estimates from published studies**. This methodology is referred to as *benefits transfer* and is appropriate for goods not traded in markets (non-market goods), such as recreation and species preservation. Because prices cannot be directly observed for non-market goods, economists have developed a number of alternative methods to measure net benefits. To measure the value of recreation, such as a hunting trip or a visit to the beach, one can estimate how much a person spent on travel. The travel cost method provides a lower bound on the total benefit of the recreational experience if a person would only take the trip if the benefit exceeded the cost. In other cases, access to a non-market good will be reflected in the price of a market good, such as housing. As else equal, houses in areas with good air quality should sell for more than houses in areas with poor air quality. The price difference provides an estimate of the benefit from improved air quality. Valuation of non-market goods using housing price differentials is referred to as the hedonic property value approach.

   In the case of recreation and air quality, people interact directly with the non-market good. This need not be the case, such as when people derive benefits from the preservation of

[1] Economists measure the net benefit of a market good as the sum of consumer and producer surplus. The net benefit measure for timber equals producer surplus. Including consumer surplus requires a detailed market analysis to estimate the demand function for the good.

endangered species. Even if they never interact with the species, people may derive an existence value simply from the knowledge that the species is preserved. To measure benefits in this case, economists often use survey methods to elicit hypothetical willingness to pay for the non-market good. One common approach is referred to as the contingent valuation method.

Hundreds of studies have been conducted to estimate benefits from recreation, species preservation, and other non-market goods. Benefits transfer involves applying benefit estimates from one or more studies to a new setting, making adjustments for the factors such as demographic characteristics of the population. The USGS Benefit Transfer Toolkit (https://my.usgs.gov/benefit-transfer/) summarizes benefits estimates from a large number of U.S. studies on recreation and species preservation, and water quality. Estimates can be tailored to specific regions, recreational activities types, and land ownership.

3.4 Biophysical Models of Landscape Change

Step 3 of our approach (*Identify relevant ecological, social and economic datasets and models that could be used to transform the conceptual model into a predictive modeling tool)* involves identifying ecological datasets and models that provide ways to quantitatively assess how military base management affects changes in habitat type and landcover that are represented in our conceptual models. Once a base-specific conceptual model framework for a particular base has been created, quantitative methods must be applied to approximate the flows of ecosystem services through the system (Duggan et al. 2015). The first step requires quantifying the varied biophysical effects of habitat condition, which is affected by base management actions or the mere existence of a base. These models are used to quantify the connections between habitat type, condition, or extent and other ecological outcomes at each base. Three types of biophysical models were used to quantify landscape change, and to compare with change anticipated with the current management plan:

1. Current Management: Vegetation condition models to quantify changes in condition classes based on current management practices over the next 20 years.
2. No Management: Vegetation condition models to quantify changes in condition classes based on the military not managing the base for anything but training between base establishment and 20 years from now.
3. No Base: Land use land cover (LULC) change model of major ecosystem types assuming there were no military base, and evaluation of services provided by this alternative landscape.

Below, we describe the ecological models that were selected for quantifying landscape change. Each model includes a description of its relevant application, and then an explanation of how the model was applied at our pilot site, Eglin Air Force Base. Other biophysical models, such as those related to water, recreational, or attributes not directly linked to terrestrial land cover, are included below under the section for the relevant ecosystem service.

3.4.1 No-Base Scenario

To quantify ecosystem services produced by a base as compared to a scenario where no base exists requires developing a plausible estimate of what this land would be if it were not a base (a

plausible counterfactual). To develop this, a modeling technique was used that uses existing land use and cover around the base.

To generate infilled maps of potential land use / land cover patterns which are consistent with the surrounding area, we employed the direct sampling algorithm (Mariethoz and Renard, 2010; Meerschman et al., 2013), a probabilistic approach in which we subsample from training data to generate a plausible counterfactual. In effect, this algorithm samples from a conditional distribution over possible infills by identifying existing patches of training data which are consistent with the partial observation.

In practical terms, the direct sampling approach requires iteratively matching partially-filled regions with completely filled regions which are close matches. This matching process is achieved by defining a distance function between image subregions and searching for a sufficiently close match in the existing data. In this instance, we used the edit distance, defined as the number of entries in each pair of compared patches which differ in their values.

A key advantage of this approach is that it allows us to sample from high-dimensional distributions over the geometry and prevalence of different land use / land cover patches without enumerating an explicit probability model as done when employing universal kriging or Markov random fields. The resulting output is either a map, or a set of probable land use / land cover values, which can be averaged over a number of runs. These values were used as the starting current conditions of a no base scenario to determine ecosystem service values using our biophysical models and BRIs. Because of how differently public and private forest lands are managed in the US, the forested lands in the Counterfactual No-Base scenario were separated into public and private forest classes, using the direct sampling approach to other land use / land cover classes.

3.4.2 Vegetation Condition Models

3.4.2.1 Terrestrial Vegetation Models

Terrestrial ecosystems are comprised of complex vegetation communities that are shaped by climate, external events such as windstorms and fire, plant and animal species interactions, and management such as fire management or timber harvest. For instance, a longleaf forest can be composed of 500-year old, widely spaced large longleaf pines with a native wiregrass understory that is maintained by frequent ground fires and provides high quality habitat for many species. Alternatively, this same forest type can be a 50-year old, closed canopy forest of slash and sand pine with a thick, fire resistant understory. These forests can also be harvested for timber, leaving few or no mature trees. These three very different conditions or “states” of the same forest type each provide very different services.

State-and-transition models characterize dynamic vegetation systems by combinations of vegetation composition and structure (boxes), and transitions that cause change such as disturbances (e.g., wildfire) or management activities (e.g., prescribed fire) (arrows). These models can be parameterized with probability values for each transition type to form state-and-transition simulation models (STSMs) that project changes in vegetation condition over time (Daniel et al. 2016). We used STSMs to project the effects of vegetation succession and growth, disturbances such as wildfire and insect outbreaks, and management actions such as prescribed fire and timber harvest on future vegetation condition. The LANDFIRE Project has developed STSMs describing historic conditions for all the terrestrial ecosystem types in the U.S., along

with maps of biophysical settings, existing condition maps, and other data on fire risk and fuels. These STSMs can be modified to capture current conditions and incorporate the effects of management actions. The open source ST-Sim software then simulates future conditions through Monte Carlo simulations. Where ecosystem services are tied to vegetation condition, these future outputs can then be used to measure the available services provided under a certain scenario or suite of management actions.

While STSMs are the tool we used to characterize changes in services tied to terrestrial vegetation condition, the MoTIVES integrated ecosystem services modeling framework is general enough that if a military installation has access to alternative or more complex vegetation models linking management to ecological outcomes, these can be used to replace STSMs. For example, the Landis-II forest landscape model (Scheller et al. 2007) has been applied at Fort Lewis-McChord in Washington and Fort Bragg in North Carolina. Landis is a complex forest vegetation model which requires more calibration than STSMs, but which generates more sophisticated outputs related to forest species composition, carbon, timber, and species habitat.

STSMs provide outputs describing the amount of area occupied by each state or vegetation condition type on a bases under a set of management actions. These area estimates can be tied to certain ecosystem services such as species habitat that is dependent on vegetation condition, and thus can be used to derive a subset of the BRIs provided on a base. When run under alternative management scenarios (e.g., no management or current management), outcomes can be compared to determine the value of management on the base.

Although they are useful for comparing management scenarios and require minimal parametrization, STSMs are very generic models that simplify complex vegetation communities into a few states. Information required to parameterize these models often comes from expert judgment, as data are usually not available to define transition probabilities across large landscapes. Linking vegetation states to conditions such as wildlife habitat or carbon is similarly difficult to define quantitatively and often relies on expert judgment.

3.4.2.1.1 Longleaf Pine Vegetation Condition Model for Eglin Air Force Base

Most of the land base on Eglin consists of sandhill and flatwood longleaf pine forests or woodlands, covering more than three quarters of the base (148,600 hectares). The longleaf pine ecosystem has been well studied, and vegetation dynamics of the longleaf pine ecosystem were simulated using a STSM adapted from Costanza et al (2015) (Figure 5). This STSM captures growth and succession, wildfire, prescribed fire and other management activities under contemporary conditions, modified from a LANDFIRE model representing historic conditions. The STSM contains five state classes varying in age and stand closure. As described in the vegetation modeling section, the STSM simulates change over time based on transition probabilities of different events, including management such as prescribed fire. Modifications were made to the model to adapt it to Eglin, including reducing wildfire to 10% of historic probabilities based on fire data supplied by the base, reducing the effectiveness of prescribed fire in closed stands based on discussions with the Eglin fire ecologist, and eliminating management practices not used at Eglin (e.g., clearcutting, conversion from plantations). Due to the relatively small size of most riparian forests at Eglin, these were not modeled using STSMs.

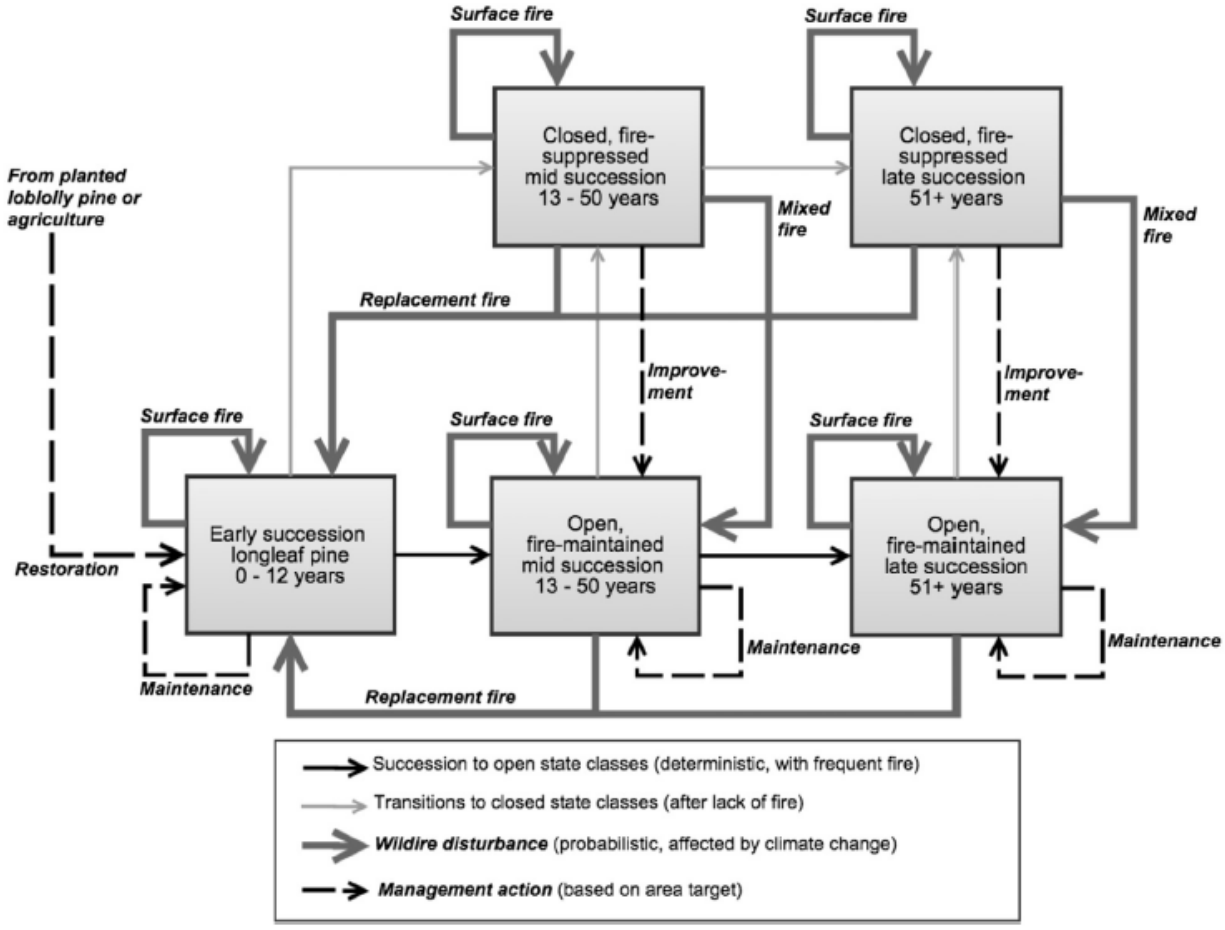


Figure 5. Conceptual diagram of the longleaf pine STSM used for Eglin Air Force Base, from Fig. 3 in Costanza et al (2015). Boxes represent state classes of vegetation condition, including age ranges from early (young) to late successional (old), and canopy cover (open or closed). Arrows represent processes like succession, fire and management that are assigned probabilities to simulate future condition. The lower right box representing open, late successional conditions is the primary desired state.

3.4.2.2 Aquatic Condition Models

Ecosystem services derived from freshwater and estuarine aquatic ecosystems, which we define as wetlands, streams, rivers and freshwater lakes and ponds, are estimated using hydrological models. These models address several BRIs, including flood amelioration, storm surge protection, nutrient (nitrogen and phosphorus) removal, sediment delivery, water provision for drinking, agriculture or industrial uses, and the provision of fish or other aquatic animals and plants of interest. Each of these service types are measured or modeled independently, and many of these are addressed individually in the Ecosystem Services Quantified section, below. These are more directional services, so can often be measured using linear spatial hydrological modeling tools in ArcGIS (ARC Hydro) to define areas where management actions such as floodplain, riparian or wetlands restoration have reduced peak flows. InVEST has hydrological models available to use for many services, but for some services or bases that have high resolution data available, modeling these individually can provide more meaningful results. The Institute for Natural Resources at Portland State University has developed methodology that

relies on high resolution DEMs to define local wetland basins, the area in and around wetlands that can hold water during floods, is available for nutrient control, and can provide late season water for multiple uses. These wetland basins are attributed with data on the catchment area, forest cover of the basin, soils, geology, distance from rivers and streams, as well as the slope (Blackmore and Chang 2015); all of which can be used in the individual service models.

STSMs were not used or recommended for use in riparian areas. There are very limited examples of management-focused STSMs for riparian habitats. As a result, directly modeling ecosystem conditions for aquatic habitats requires an evaluation primarily of the type and size of these ecosystems, and has limited ability to include habitat conditions and management actions. However, since aquatic habitats are so important in providing valuable ecosystem services, modeling individual services based simply on the area and type of riparian or aquatic habitat present is sufficient to measure and value most of the benefits these habitats provide on military installations.

3.5 Quantifying and Valuing Ecosystem Services

Step 3 of our approach also includes identifying additional ecological, social, and economic datasets and models that can be used to quantify how landcover change affects the delivery of the BRIs outlined in step 2. The outputs of biophysical models describing the state, extent, and status of various habitat types on a base represent the information required to quantify ecosystem services. Ecological model outputs can be translated into BRIs and economic values using the approaches summarized in Table 2 and detailed below in individual sections for each service.

Many of the ecosystem services models embedded in this framework use nationally available databases that can be applied to any base in the 48 contiguous states. Other data will need to be identified for the other states, territories and international bases. The other ecosystem services estimates are based upon base specific data that most bases should have on hand. Therefore, it should be relatively easy to collect and input the data needed to run the integrated MoTIVES model for any base. However, many bases have more localized datasets that can be used in base-specific models.

Table 2. Summary of potential approaches for benefit-relevant indicators and economic valuation for a range of ecosystem services that may be provided at military bases. See text for each ecosystem service in the Ecosystem Service Valuation section, below. The right column indicates whether each service was quantified at Eglin Air Force Base.

Ecosystem Service	BRI quantification approach(es)	Economic valuation approach(es)	Modeled at Eglin?
Wildfire risk reduction or damage	State-and-transition simulation model (STSM); Fire behavior models (e.g. FSim)	Market values of structures to estimate avoided damages to property based on mean parcel values in nearby counties	No
Respiratory health protection	Community Multiscale Air Quality (CMAQ) model	Estimates of WTP for reduced smoke exposure based on Richardson et al. study	No
Timber harvest	Data on timber harvest obtained from bases	Calculated from estimated volume of timber harvested and stumpage price	Yes

Ecosystem Service	BRI quantification approach(es)	Economic valuation approach(es)	Modeled at Eglin?
Energy Production	Data on biomass energy production obtained from bases	Avoided costs of purchasing electricity estimated as the product of electricity produced and local electricity price	No
Recreation opportunity	Data on permit numbers sold for recreation obtained from bases	WTP estimates from USGS benefits transfer toolkit; permit numbers and prices	No
Carbon storage	STSM; Century model; Landis-II; NatCARB	Multiplying the social cost of carbon (SCC) by the amount of carbon stored at the base	Yes
Persistence of endemic, listed, or important species	STSM; Estimates of population increases or decreases based on area occupied.	WTP estimates for survival of specific species; general value of species derived from USGS benefits transfer toolkit	Yes
Huntable or harvestable species	Data on permit numbers sold for hunting and fishing obtained from bases	WTP for hunting and fishing opportunities from USGS benefits transfer toolkit	Yes
Flood damage	Hazus	Market values of structures to estimate avoided damage to property	Yes
Storm surge protection	SLOSH storm surge models, NOAA	Market values of structures to estimate avoided damage to property	No
Drinking water quality	InVEST sediment delivery model	WTP for clean drinking water estimates	No
Water availability for agriculture or industry	Modeling water storage capacity using a modified hydrologic engineering approach, and calculating the number of downstream beneficiaries.	In regions where water is scarce, benefits from water production can be quantified if there are local water markets or if published estimates from hedonic property value studies exist	No

The following sections detail the datasets and models identified to quantify each ecosystem service, and national datasets to inform this quantification. If the service was relevant at Eglin Air Force base, we include details on how the identified models were used to quantify services for the Eglin case study.

3.5.1 Wildfire Risk and Damage

3.5.1.1 Introduction

Most terrestrial ecosystems are fire-adapted or experience at least some wildfire. Wildfire presents risks to human infrastructure and respiratory health, and can lead to loss of life when fires escape suppression or burn into the wildland-urban interface. However, wildfire also has ecosystem benefits in many places where risk to humans is low; and some ecosystems are fire-dependent and rely on fire for reproduction.

3.5.1.2 National Datasets or Models Available

Wildfire monitoring via satellites is carried out across the US by multiple agencies. The Monitoring Trends in Burn Severity (MTBS) program monitors wildfire perimeters and estimates burn severity within wildfire areas, which can be viewed through an interactive map or downloaded. Other sources of national data include the GeoMAC Wildland Fire Support web portal and National Interagency Fire Center. Many state forestry or natural resource agencies also track fire starts, even if fires are not large enough to be mapped using satellites.

There are many modeling platforms that simulate wildfire behavior and effects. A variety of landscape simulation models such as ST-Sim and LANDIS-II have been used to simulate landscape effects of wildfire, along with other processes such as vegetation succession and management activities. More detailed fire behavior modes such as FSim (Finney et al. 2011) and FARSITE can simulate the behavior and severity of a wildfire without accounting for changing vegetation condition or management actions. The LANDFIRE program also has developed models and maps of fire risk and fuels across the country, which are readily available online.

3.5.1.3 Generation of BRIs and Economic Values

Market values of structures are used to estimate the avoided damage to property from wildfires. Average property values in an area are estimated by local assessors and available in a national proprietary database from CoreLogic. In some cases, management of bases will resulted in avoided wildfire suppression costs. Regional estimates of suppression costs can be derived from Situation Reports to the National Wildfire Coordinating Group.

3.5.1.4 Models and Data Used at Eglin Air Force Base

Most military bases have high-quality, accurate records of wildfire within the military installation. At Eglin, base natural resource personnel provided records of acres burned on the base over the last 20 years. The average over the recorded period was considered the current level of wildfire on the base and used to adjust the probability of wildfire in the vegetation condition models. Over the period of 2009-2018, an average of 3206 ha burned in wildfires per year at Eglin (not including prescribed fire, which far exceeded this total).

3.5.2 Respiratory Health

3.5.2.1 Introduction

Wildfire smoke is a major source of air pollution in many areas of the country, particularly in fire maintained or fire prone ecosystems of the southeast, south central and western U.S. where many military bases occur. Because fires can be so damaging to people, their property, and the fiber, fuel, livestock forage, or wood products they can generate, wildfires have been suppressed wherever possible for almost 100 years. As a result, many of the forests have had excessive fuels build up, increasing the potential for catastrophic damages as were seen in California in 2018, and massive wildfires, such as those in British Columbia, Idaho and Washington that created air quality problems in all of the major metropolitan areas along the west coast. The combination of fuels removals, thinning, and prescribed burns are used by managers to reduce the wildfire risk, as well as to reduce the fire damages and smoke released from wildfires that occur.

Prescribed burns can reduce the risks of wildfire on the base and the risk of property damage from wildfires. However, the constituents of the smoke from both prescribed burns and wildfires,

including carbon monoxide, nitrogen oxides, volatile organic compounds, particulate matter, sulfur dioxide, and ammonia, can cause respiratory issues for residents of the communities surrounding the base. The risk of smoke-related respiratory impacts can be valued using the reported willingness to pay to reduce exposure to poor air quality days from the smoke.

3.5.2.2 National Datasets or Models Available

Some of same national datasets as listed under the Wildfire Risk and Damage section, above, are relevant to respiratory health associated with wildfires and prescribed fires. Other resources such as the National Oceanic and Atmospheric Administration (NOAA) Smoke Forecasting System may also be used, but limited options are available for longer-term modeling as needed for scenario analysis.

3.5.2.3 Generation of BRIs and Economic Values

Recent research has suggested a value of $84.42 per person per day impacted by wildfire smoke (2012 $) (Richardson et al. 2012). Past work suggested a range of $36 to $129 for a variety of related symptoms such ranging from mild cough to severe asthma, though this work was not specific to the context of wildfires and related smoke exposure (1997 $) (Johnson et al. 1997). We would then actualize these values to 2018 $ and consider a triangular distribution (min: 56.32; max: 201.82; mode: 92.33) of dollars per person per day of smoke exposure.

3.5.2.4 Models and Data Used at Eglin Air Force Base

Wildfires and prescribed burns impact an uncertain number of people as a function of local population density and smoke plume shape and direction. Plume characteristics in turn depend on meteorological variables which vary throughout the year. We consider the number of people impacted by a given fire to be a randomly distributed variable calculated by simulating fires throughout the year and overlaying plume shape with local Census data (United States Census Bureau 2018). We consider impacted populations to be those exceeding EPA reference doses for particulate matter (US EPA 2016). To predict the extent and composition of potential smoke plumes, we will use the BlueSky framework and the Community Multiscale Air Quality (CMAQ) model (US EPA 2019). The BlueSky framework establishes emissions based on vegetation-specific emission factors. For these, we use the values from the STSM model of vegetation condition.

We consider the valuation described in Section 3.5.2.3: 56.32 (range: 92.33–201.82) $/exposed person/day.

By running these numerical models within a probabilistic environment, we can characterize ranges of impacts over meteorological conditions and explore sensitivity in valued outcomes to underlying physical parameters. For example, past work has suggested that CMAQ may underestimate plume height and overestimate impacts (Liu et al. 2010). Our analysis can quantify the implications for ecosystem service valuations of such model uncertainties. While the Community Multiscale Air Quality (CMAQ) model (US EPA 2019) was identified for use at Eglin, but the limited project timeline did not allow the team to parameterize and run the model and include the results in the final report.

3.5.3 Timber Harvest

3.5.3.1 Introduction

Many of the forested bases have programs to manage the forest resources, either to restore ecosystems supporting at-risk species or wildlife, to maintain conditions suitable for training, or to provide timber to support local mills and generate revenue. Many types of timber products result in trees being cut and sold, providing jobs for the community, material to generate wood products, paper or biofuel. All of these are ecosystem services which can be measured and valued.

3.5.3.2 National Datasets or Models Available

A variety of landscape simulation models such as ST-Sim and LANDIS-II have been used to simulate scenarios of varying timber harvest across large forested areas, along with other processes such as vegetation succession and wildfire. Other simulation models such as the Forest Vegetation Simulator model tree growth and harvest prescriptions at the stand scale.

Almost all forested bases have vegetation maps, and many have detailed Light Detection and Ranging (LiDAR) maps, which together generate comprehensive information on the cover and size of the forest resources at the bases. In addition, all bases track timber sales and permits to remove trees and forest products, as well as the income generated.

3.5.3.3 Generation of BRIs and Economic Values

Net benefits from timber harvests are estimated as the product of timber volume and stumpage price. A stumpage price measures the market value of timber net of harvesting costs. Region- and species-specific estimates are available from U.S. Forest Service and state-level reports as well as proprietary databases (e.g., TimberMart-South).

3.5.3.4 Models and Data Used at Eglin Air Force Base

At Eglin, timber harvest was simulated in the STSM as a restoration activity, but not for revenue generation. Instead, records from the base were used to determine the volume of timber being harvested under current base management. The no management scenario assumes that no timber management or timber sales would occur at the base, so no timber value is generated.

For the no base scenario, the forest landcover was identified as either private or public forest lands. The majority of lands were privately owned, managed as industrial private timberlands, while the small areas of public forest lands were assumed to be parks or natural areas with no management. The amount and value of the timber generated by the private industrial forest lands was determined based on Susaeta and Gong (2019), who provide a methodology for estimating the income generated by intensive loblolly pine timber production on longleaf pine habitat in the southeastern U.S. The paper notes that timber production varies extensively based on the site productivity as defined by the site index, which ranged from 19 for the least productive longleaf pine sites, to 35 for the most productive. We used a moderate site index of 27, as the soils are quite sandy, typical of longleaf sandhills,

3.5.4 Renewable Energy Production

3.5.4.1 Introduction

Bioenergy and solar power are produced at many bases, while wind energy is generated at a few. All of the energy generated reduces the power needs for base operations, and at a few bases in desert ecosystems solar power produced by bases can provide power needed for nearby communities. Because of the significant benefits of increased renewable energy production, these are important ecosystem services, which can be readily measured.

3.5.4.2 National Datasets or Models Available

The same models used to describe tree growth and forest management can be used to model the generation of materials to use in bioenergy facilities. Currently, models to evaluate the potential of lands to generate solar or wind power have been developed locally, but due to tradeoffs related to competition for other land uses, or impacts to birds and wildlife, these are not available nationally or even regionally.

3.5.4.3 Generation of BRIs and Economic Values

The benefit of bioenergy generated on a base is the avoided costs of purchasing electricity from the grid. The benefit can be estimated as the product of electricity produced and the local electricity price, which is available from https://www.electricitylocal.com/states/.

3.5.4.4 Models and Data Used at Eglin Air Force Base

All bases generating bioenergy or solar energy track the amount of the energy produced, and the benefits in energy savings or sales that result from this generation. At Eglin, a bioenergy facility is currently under construction, but since it is not operational yet we did not include it in any of our scenarios.

3.5.5 Hunting and Fishing

3.5.5.1 Introduction

Hunting and fishing recreational opportunities are provided by many military installations, and are often easily tracked and valued. All of the four bases evaluated in this study allowed some access for both hunting and fishing, and the INRMP or management documents indicated extensive use, in spite of permit requirements and their associated costs.

3.5.5.2 National Datasets or Models Available

In general, hunting and fishing are managed by state fish and wildlife agencies. Federal agencies that manage lands generally work with their state agency to track hunting and fishing, and often to establish license fees. Individual states and bases all post these fees, and most track usage.

3.5.5.3 Generation of BRIs and Economic Values

Willingness to pay estimates are available from published studies on the value of hunting and fishing and assembled in the USGS Benefits Transfer Toolkit. These estimates can be applied to specific locations of bases and recreational activities. Alternatively, data on the number of hunting and fishing permits issued, the cost of each of these obtained from reasonably up-to-date

INRMPs for most bases, which can be used directly as a measure of the willingness to pay for this type of recreation.

Regardless of whether the USGS Benefits Transfer Toolkit, or actual information from INRMP or base natural resources management staff, the base information needed is the number and cost individual permits issued each year. The value of these permits is the lower bound value, and does provide an estimate of the revenue provided to the base. It can also be used to provide an indication of the number of recreational days spent on the base hunting and fishing, which can be multiplied times the Benefits Transfer value for these activities and translated into a willingness to pay. If both the permits and willingness to pay are used, it is important to disaggregate them into relevant types of recreation, such as permit revenue and where possible estimate willingness to pay for hunting different species or fishing.

3.5.5.4 Models and Data Used at Eglin Air Force Base

Hunting opportunities are permitted activities, and every base tracks the number of permits and the income these permits generates. This information is usually included in base INRMP documents. At Eglin, we estimated the annual value of deer hunting and fishing from base records. In 2018, approximately 8700 hunting and 6600 fishing permits were sold. We used the number of permits as a proxy for the number of individuals who hunted and fished. The permits alone generated approximately $262,680 per year to support base management, based on an average hunting permit cost of $26.40 and fishing permit cost of $5.00.

Florida deer hunters spend an average of 22 days per year hunting, and fishers spend an average of 19 days per year according to U.S. Fish and Wildlife data. A study by Aiken (2009) finds a willingness to pay of $207 per person per day for deer hunting in Florida and $86 per person per day for fishing. This translates into total annual benefits of $40 million for hunting and $11 million for fishing at Eglin.

Only the special use permits and camping permits are not specifically designed to support hunting and fishing, and it is likely that some of the camping that occurs is hunting or fishing related. As a result, these benefits are quite a bit more easily measured and valued then is beach use, hiking or bird watching.

3.5.6 Recreation Opportunity

3.5.6.1 Introduction

Other recreation opportunities besides hunting and fishing (see above) are often supported by military installations, including hiking, horseback riding, wildlife viewing, boating and bicycling. Coastal bases often provide opportunities for swimming, sun bathing, and other beach activities.

3.5.6.2 National Datasets or Models Available

Every state generates a state comprehensive outdoor recreation plan which describes the state's plan for meeting its outdoor recreation needs. These reports often include information on the values and benefits of outdoor recreation, and often consider military bases as recreational lands, as Florida's SCORP plan does with Eglin.

3.5.6.3 Generation of BRIs and Economic Values for Recreation

Willingness to pay estimates are available from published studies on the value of recreational activities and assembled in the USGS Benefits Transfer Toolkit. These estimates will be applied to specific locations of bases and recreational activities.

3.5.6.4 Models and Data Used at Eglin Air Force Base

Almost all bases track and permit recreational uses. The major recreation activities on many bases are hunting and fishing, which can be tracked and valued based on permits and tags provided (see section above). Other recreation types, particularly activities such as biking, hiking, bird watching, swimming, canoeing or kayaking can be more difficult to monitor and value. However, we were unable to quantify these non-hunting or fishing recreational activities at Eglin under the time constraints of this project.

3.5.7 Carbon Storage

3.5.7.1 Introduction

Many military bases provide broad areas with natural vegetation, which may provide substantial carbon storage potential. Carbon can be stored in live vegetation, dead vegetation and soils, and carbon storage potential varies widely across vegetation types and climate zones. Carbon storage can also vary with management actions and vegetation condition – for instance, old, structurally complex forests store more carbon than young stands. In many ecosystems there is a trade-off between long-term carbon storage in the ecosystem and removal of carbon from management activities such as timber harvest, or disturbances such as wildfire. Carbon storage is one benefit of intact natural ecosystems that is important to quantify for military bases.

3.5.7.2 National Datasets and Models Available

A number of maps and models are available to estimate carbon storage across large landscapes. Some of these estimate ecosystem total carbon storage, including above-ground, below-ground, live and dead pools of carbon, and others estimate only above-ground carbon. Nation-wide efforts such as the NATCARB project from the US Department of Energy and LandCarbon project from the USGS provide nationally consistent maps of carbon storage based primarily on broad approximations of land use/land cover or vegetation type. Nationally, the InVEST has developed a carbon storage and sequestration model tying land use maps and other carbon pools to estimate the amount of carbon stored in an area at any given time for both terrestrial carbon and blue carbon in marine and coastal systems. For terrestrial habitat types, LANDFIRE also has data and models with links to above ground carbon outputs. However, these approximations generally do not account for growth, and compare changes based largely on land use changes.

The CENTURY model can be used to simulate changes in above- and below-ground carbon, and forms the basis for some of the other landscape-scale models that simulate soil carbon (e.g. some modules of Landis-II model). Since the largest terrestrial carbon stores tend to occur in forests, much of the focus of carbon modeling has been directed to reforestation, forest management, or protection. LiDAR can be used to determine detailed structural attributes of forested vegetation, and is increasingly available across the country. For some regions (e.g., the Pacific Northwest), maps of forest structure based on imputation of US Forest Service forest inventory data are available and account for detailed differences in forest structure and composition (Ohmann and Gregory, 2002; Bell et al. 2018).

All of these models are limited by the quality of the data that informs the model, as well as be research that reflects growth rates of different vegetation types, particularly forests, in varied locations. There are very few studies that characterize how soil carbon levels vary with management, and since the few studies that measure carbon indicate that there may be as much or more carbon in the soils than is found in the canopy, not including this information decreases the utility of the analysis. In addition, most models have limited ability to predict above ground biomass increases over time, using linear growth rates to calculate change over time, rather than the more complex curves that reflect actual increases of carbon for regenerating forests. More generalized carbon maps or models will be sufficient for assessing tradeoffs in more generalized scenarios (e.g., presence of a base vs no base) but may not be optimal for assessing the impacts of base management, which largely changes the composition and structure of the vegetation.

3.5.7.3 Generation of BRIs and Economic Values

Carbon dioxide (CO_2) is a global pollutant, which implies that the value of reducing atmospheric concentrations of CO_2 is the same regardless of where carbon storage occurs. Global damages of carbon emissions have been valued using the "Social Cost of Carbon" (SCC), which we adopt to value the benefits of carbon sequestration at Eglin. The U.S. Interagency Working Group on Social Cost of Greenhouse Gases has estimated the SCC at $12 (95% confidence interval: $1–$43) per metric ton of CO_2 for the year 2020 and assuming a discount rate of 5%. We adopt this valuation to quantify the benefits of carbon sequestration at Eglin.

3.5.7.4 Models and Data Used at Eglin Air Force Base

Many bases have a relatively recent LiDAR dataset which provides detailed information on vegetation structure that is more convertible to above ground carbon and will reflect changes to vegetation structure and composition based on management. At Eglin, we used the STSM vegetation condition models to determine the structure and composition of longleaf pine forests across the base under each scenario, and used published literature (Becker 2011, Samuelson et al 2014) to estimate the carbon storage in each model state based on stand age and structure. We only captured change in above-ground carbon storage at Eglin.

As mentioned above, the vast majority of carbon in longleaf pine is stored underground in soils, but we did not have good information on how soil carbon would change under varying land uses in the no base scenario, so we did not include soil carbon in the analysis. Recent studies (Samuelson et al. 2017) provide details on above ground and soil carbon for military bases in longleaf pine habitats in the southeastern under various conditions. These studies have generated complex models which, in a longer term project, could be incorporated into MoTIVES by linking them into our STSM models. We also did not capture "blue carbon" at Eglin, carbon that is stored in coastal and wetland habitats. See the section above for more information on models that can capture these carbon stores, such as InVEST.

3.5.8 Listed, Endemic or Locally Important Species

3.5.8.1 Introduction

Management to protect or restore habitat for at-risk species is an important part of the natural resources management plans at many bases. Military installations often provide critical habitat for threatened and endangered species and the large buffers needed to protect surrounding communities from live fire training often also provide important habitat for a variety of plant and

animal species. Bases often occur in areas that would otherwise be developed for housing, agriculture or industry, making them refuges for declining species. The US values endangered species sufficiently to have created strong laws to assure their protection and to allocate resources for their recovery. As a result, most bases have permanent biologists to monitor populations of at-risk species and assure there is biology expertise available to help make natural resources management decisions.

Additionally, many more common species have significant value to people in communities near the bases, as many military bases allow for hunting, fishing and recreation to occur in non-sensitive areas. As bases almost always require permits for hunting and fishing, and often charge for these permits, for this project, species value is measured by the actual revenues obtained from those hunting and fishing on each bases. This also applies to use of fungi, or the rare allowable collection of common plants for various uses.

3.5.8.2 National Datasets or Models Available

Information on listed, threatened and endangered species, and other at-risk species, is often available from state natural heritage programs or the state of fish and wildlife departments. NatureServe (http://www.natureserve.org) is a national non-profit organization that has integrated this information across the country, and can provide national scale data if needed to work across multiple states. NatureServe has worked with the DOD, and is currently undertaking an effort in partnership with ESRI and The Nature Conservancy to create more accurate species distribution models for all at-risk species in the U.S. These models, or the individual maps of at-risk and threatened and endangered species occurrences, both can serve as the needed base data for this ecosystem service assessment.

If population numbers of species are tracked by base, these numbers can be used to both report on the productivity of existing management and to link species numbers to existing habitat conditions. However, models are needed to identify how well the base would supports populations of the species of interest at each base without any base management, or if the area had never been a base. There are a few bases in which at-risk species have been studied sufficiently that a population viability model or an occupancy model has been developed. Where they exist, they can be used as a source of information for at-risk species production at the base, and tied directly to management scenarios.

Most rare, endemic or threatened and endangered species found on bases will not have occupancy or inductive habitat suitability models available, but will be inventoried and mapped on the base. The observations or occurrences developed from these inventories can be used to measure to the contribution any base makes to the relative viability of each species, based on the percentage of occurrences for each species on and off the base. Assessing the actual “existence” value for a rare or threatened species or for biodiversity overall is difficult, but has been the focus of research (Richardson and Loomis 2009).

There are many important wildlife species that have not been well studied and are not able to be linked to a specific STSM state. For these species, basic deductive models developed by the USGS Gap Analysis Program are available to provide an estimate of where the species are likely to occur. These models, which have been developed for all terrestrial wildlife species occurring in the conterminous U.S., are a simple, presence or absence model based on a wildlife habitat relationship. For habitats, these models use the “Ecological Systems” vegetation classification,

which are now nested within the Macrogroup category within the NVC. Therefore acres of habitat for all amphibians, reptiles, birds and mammals are available. While these models do not predict the habitat suitability of the habitats on bases where they occur, an average number of individuals per area can be estimated from them. And in many parts of the country, more detailed habitat suitability indices have been developed and mapped for all wildlife species, and where these are available, they would be used to provide a more accurate estimate of the wildlife each base provides to nearby communities and the public at large.

For at-risk species, individual bases generally track individual populations of all federally listed and nationally significant, and many state important species. The locations of these local populations, called "element occurrences" by most programs, provide an estimate of the area occupied by current and historic populations. In many cases, bases have data on overall population numbers, which then provide average occupancy rates. Additionally, most base natural resource programs monitor especially federally listed species, and carefully track areas occupied and species health. Additionally, NatureServe, some bases, some natural heritage programs, and some state and national fish and wildlife management agencies have developed species distribution models to predict occupied areas, which often are suitable for linking to base habitat models.

3.5.8.3 Generation of BRIs and Economic Values

Willingness to pay estimates are available from published studies on the value of species preservation and assembled in the USGS Benefits Transfer Toolkit. These estimates can be applied to the species found at bases.

3.5.8.4 Models and Data Used at Eglin Air Force Base

At Eglin, we quantified ecosystem service benefits provided by listed, endemic or locally important species in two ways:

1. Species habitat (longleaf pine): For species that occur in longleaf pine habitats, we used the STSM to simulate vegetation conditions and linked the area of habitat for species of interest to each of the states in the STSM. A straightforward example of this is the red cockaded woodpecker (RCW), a species listed as threatened under the U.S. Endangered Species Act. RCW requires mature, fire-maintained, open pine forests (Jackson et al 1979, Wilson et al. 1995), as captured in the longleaf pine STSM (Figure 5). We captured this relationship by overlaying species occurrence data or high resolution species distribution models from the Florida Natural Inventory with our map of longleaf pine vegetation condition classes at Eglin, and calculating the proportion of the species occurrence areas found in each of the five longleaf pine STSM states. The results of this analysis, the area of occupied habitat for each of these species, is shown in Table 3.

Table 3. Species modeled as a function of vegetation condition in the STSM state classes, consisting of vegetation age (early, mid, late), and structure (open and closed canopy).

Common Name	Scientific Name	Habitat provided by condition class (ha)				
		Early	Mid-closed	Mid-open	Late-closed	Late-open
Reticulated flatwoods salamander	*Ambystoma bishopi*	0	0	1	1	5
Red-cockaded woodpecker	*Dryobates borealis*	1,797	527	8,534	7,119	38,576
Pineland bogbutton	*Lachnocaulon digynum*	0	0	0	1	9
Gulf Coast redflower pitcherplant	*Sarracenia rubra ssp. gulfensis*	2	4	4	59	169
Panhandle lily	*Lilium iridollae*	0	0	0	5	6
Harper's yellow-eyed grass	*Xyris scabrifolia*	0	0	1	1	9
Pond rush	*Cladium mariscoides*	0	0	0	0	1
Curtiss' sandgrass	*Calamovilfa curtissii*	2	1	2	10	34
Panhandle meadowbeauty	*Rhexia salicifolia*	6	0	1	1	6
West's flax	*Linum westii*	0	1	0	1	1
pinewoods bluestem	*Andropogon arctatus*	0	0	0	0	5

2. Species habitat (beach): For species not tied to longleaf pine habitat, there was no ecosystem model analogous to the STSM to simulate effects of management on species persistence. For these species, we made simple assumptions about whether or a not a species was likely to persist under the three management scenarios. Because nesting turtles and the endangered sand lichen are rarely ever survive long-term without active protection, both the no management and no base scenarios assume that no management of natural resources occur, and these species disappear. The assumption for the current management is that Eglin managers continue to restrict visitation when turtles nest, and maintain habitat for the lichen, and that the amount of habitat remains constant over time. In this case, broad generalizations about presence or absence of a species were deemed appropriate.

3. Species occurrence (pond and grassland): At Eglin, we were only able to provide a monetary valuation for red-cockaded woodpeckers (RCWs), although many other species occur on the base and the base provides important habitat. A study by Reaves et al. (1999) found a willingness to pay of $22.36 per year per household to ensure the survival of RCW in South Carolina. Chadwick (2005) estimates the South Carolina population of RCWs at 669 in 2000. This implies an annual per individual per household value of about $0.03. Transferred to the 7.5 million households in Florida, this yields an annual value of $251,036 per individual species member. We assumed that this willingness to pay was for an individual RCW over its lifetime. To assess an annual value, we assumed an average lifespan of 7 years for the species, based on Wilson et al. (1995), which reduces the annual value to $35,862. While this number seems high, the fact that the productivity of RCW at Eglin is a major factor likely to lead to the delisting of at least the Florida population of RCW is evidence that the value of this regulatory relief to other private forest landowners would be at least this high.

3.5.9 Flood Damage and Risk

3.5.9.1 Introduction

Inland and coastal flooding can cause significant financial losses and deaths. Annual flood risk is a function of random meteorological events (e.g., precipitation duration and intensity, strong winds at high tide, etc.) and local physical attributes (e.g., ground cover, land use, topography). Vegetated coastal environments can dissipate kinetic energy from storm surges, reducing wave height and insulating inland properties from flood risks (Shepard et al. 2011). Additionally, vegetation offers enhanced drainage and buffering capacity, relative to paved or developed surfaces, to reduce inland flood risks (Wheater and Evans 2009). Our framework calculates and values flood hazards for each scenario. This valuation accounts for the probability distribution of flood events of various magnitudes.

Every year, damage from floods causes major impacts to communities across the country. Measuring overall flood risk and economic impacts can be extremely complex (Koks et al 2015). However, as aquatic ecosystems producing floods generally have linear and directional flows, we have chosen to evaluate changes in peak flows produced by management on bases, combined with some measure of the value of this protect to the beneficiaries of these reduced flows (Jones et al. 2018). In each base, areas in which riparian, wetland and aquatic habitats have been restored or enhanced are analyzed using the data the set of actions in an area. The data attributed for each wetland basin is combined with climate and storm information to estimate the amount of flood reduction provided by accumulated base actions. Vulnerable properties downstream from bases or the cost of past flood damage would be used to assess the value of this flood reduction.

3.5.9.2 National Datasets or Models Available

In general, flood hazards can be evaluated using statistical models based on past occurrence of floods or physical-process models, which calculate flood risks mechanistically as a function of relevant physical characteristics of the site under study. Examples of these are the Storm Water Management Model (SWMM) developed by the EPA, site-specific models developed for unique geographies, and the Hazus Flood Model (FEMA 2018). We have elected to use the Hazus Flood Model because it supports user inputs through a GIS interface (ABS Consulting 2011) and directly interfaces with national databases to produce site-specific risk estimates based on local hydrologic and land-use variables. Therefore, the model developed here can easily be adapted to characterize risks under alternative scenarios (e.g., different land use assumptions) at the same site or to characterize risks at different sites in a way that is straightforward and user-friendly compared to alternative approaches.

FEMA flood risk maps are available nationally and provide data on vulnerable properties or communities located downstream from military installations. The wetlands, water bodies, and upland vegetation on bases provide water-holding capacity reducing downstream flood damage. The water holding capacity of habitats can be modeled as described below.

3.5.9.2.1 Wetland Flood Attenuation

Wetlands have been demonstrated to capture water in ways that reduce flooding (Acreman and Holden 2013). Flood attenuation benefits of individual wetlands can be estimated by 1) modeling wetland water storage using a modified hydrologic engineering approach that incorporates spatially-accurate, high-resolution elevation, wetlands and streams data, 2) calculating the number of downstream beneficiaries, and 3) combining the two values per wetland.

Following the above approach, water storage capacity per wetland can be generated from the following variables: catchment runoff rate, wetland water residence time, and distance to the nearest stream. Wetland catchments can be derived using ESRI's ArcHydro toolset to model water flow and accumulation across the project area while assuming that wetland polygons behave as sinks (or modified sinks in the cases where streams intersect wetlands). Key data sources for deriving wetland catchments include a high-resolution LIDAR-derived digital elevation model (DEM), stream hydrography that match the DEM, and spatially-accurate wetland polygons.

Once wetland catchments have been created, catchment runoff rates (i.e., the potential amount of overland water flow into a wetland over a given time) can be calculated using a modified version of the Rational Method (Novotny 2003, LMNO, Ltd. 2015). Instead of the runoff coefficients usually associated with the Rational Method (which are solely based on ground cover type), runoff curve numbers (NRCS 1986) per wetland catchment can be chosen based on the most prevalent hydrologic soil complex and ground cover types. Next, wetland water residence time can be calculated from wetland volume and catchment runoff. Wetland volume is estimated by multiplying wetland area by an average wetland depth that is assigned by Cowardin code (e.g., a palustrine wetland with an aquatic bed is assumed to have a greater water storage volume than a palustrine emergent wetland) and a correction factor to account for sloping edges. Finally, wetland distance to the nearest stream can be determined using the Flow Distance tool from the ArcGIS Hydrology toolset, a process that incorporates the streams data and flow direction dataset generated while deriving wetland catchments.

Given a dearth of readily available high-resolution spatial data of human populations (e.g., number of residents per structure), tax lots can be used as a proxy for wetland flood attenuation beneficiaries. The number of tax lots located in floodplains (of various temporal/spatial resolutions) downstream of each wetland can be calculated to derive the total number of beneficiaries per wetland. Relating this number to each wetland's water storage capacity would yield a final measure of wetland attenuation benefits provisioned per wetland.

3.5.9.2.2 Riparian Flood Attenuation

Modeling potential flood attenuation benefits of riparian areas would follow a similar procedure to that used for wetlands; however, the process of identifying riparian areas that should be treated as individual units (rather than long contiguous reaches across varied terrain) and modeling the catchments that feed them needs to be carefully considered. Most states environmental quality agencies have developed stream water quality assessment units, which are often attributed with current water quality information, and can be tied to restoration actions.

Much of the base data required for these models, including high resolution DEMs, updated stream and wetland spatial data, and high quality vegetation and climate data, is available from most bases. However, these data need to be developed individually. Alternatively, FEMA floodplain maps are available at almost all bases, although the resolution of these vary widely nationally.

3.5.9.3 Generation of BRIs and Economic Values

Market values of structures are used to estimate the avoided damage to property from floods. Average property values in an area are estimated by local assessors and available in a national proprietary database from CoreLogic.

3.5.9.4 Models and Data Used at Eglin Air Force Base

At Eglin Air Force Base, flood risk was modeled for the three scenarios. Ground elevation and flood regions for analysis are derived from digital elevation maps (USGS 2018) and Flood Insurance Rate Maps (FEMA 2019). Default values for a variety of flood analysis parameters (e.g., stream drainage area, velocity, and flow regulation) were used in the present analysis as a proof of concept. A full-scale characterization of ecosystem services across bases will present sensitivity analysis for key parameters as part of the overall uncertainty analysis. Similarly, in this draft, we have presented interim deterministic results for the economic value of flood risks for each scenario. MoTIVES characterizes the propagation the influence of various uncertain variables through model sub-modules including flood damages.

HAZUS measures the flood hazard, or the annual chance of inundation at specific flood depths. Inland flood risk (recurrence period of certain flood depths) is calculated as a function of local riverine discharge, frequency, and surrounding topology. Coastal flood risk (recurrence period of wave heights and flood depth) is calculated as a function of local elevation, shoreline characteristics, and regional wave parameters. Corresponding losses are calculated as a function of buildings, facilities, and other assets in the study area, which must be specified. The HAZUS General Building Stock provides census block level data based on the 2010 census and specifies the location, size, and data on the replacement cost for buildings nationwide. In future studies, building data can be integrated with the Army Core of Engineers building data to improve the accuracy of site-specific data (Shultz 2017).

At Eglin, results were calculated by deriving a relationship between the economic damage of a flood event and its occurrence probability using HAZUS. 1,000 hypothetical timelines were simulated, where each timeline sees a randomly generated sequence of flood events. These hypothetical timelines were in turn valued (according to a 5% discount rate), and the distribution of the economic values is recorded. Topographic and hydrologic parameters corresponding to the current-management scenario were used to run HAZUS simulations and calculate damage estimates for various flood events. For each flood event, HAZUS returned economic valuations for multiple land-use categories (e.g., residential, agricultural). To calculate economic values for the no-base scenario, we scaled the valuations of flood events simulated for current-management by land-use characteristics. For the no-management scenario, we took account of the expected higher infiltration of older growth forests. In the setting of a full project execution, we plan to use available time and computational resources to simulate each scenario independently in HAZUS in order to also account for varying hydrologic and topographic parameters not accounted for in the present proof-of-concept.

3.5.10 Water Available for Agriculture or Industry

3.5.10.1 Introduction

In many parts of the country, particularly the western and southeastern states, water resources are limited, creating competition for water. Some lands, particularly wetlands, rivers, streams and floodplains, have sufficient water holding capacity that they provide additional downstream water at low flows. Restoration of these habitats will increase these downstream flows, often making water available to farmers, industrial users, and water treatment plants, reducing costs or making agriculture possible. In assessing flood risk, the water holding capacity information for wetlands and streams provides the exact data needed to measure the ability of these habitats to

provide additional water to these users. While groundwater is often a source of agricultural and industrial water, links between land management and volume of these water sources have not been clearly developed.

3.5.10.2 National Datasets or Models Available

Most states have water rights information available from the state Water Resources, Environmental Protection or similar agency. Some have excellent maps of over-allocated streams, rivers and lakes, information needed to map the BRI. Unfortunately, this type of data is not available nationally.

3.5.10.3 Generation of BRIs and Economic Values

In regions with plentiful water supplies, water pricing is typically used to recover the costs of infrastructure for conveyance. In cases where water is not a scarce resource, additional water production on a base is not a quantifiable benefit. In regions where water is scarce, benefits from water production can be quantified in some cases if there are local water markets or using published estimates from hedonic property value studies (e.g., Buck et al. 2014). No water availability estimates were produced for Eglin.

3.5.10.4 Models and Data Used at Eglin Air Force Base

Eglin does not provide significant water for agriculture or industry, and thus this service was not included in the model.

3.5.11 Drinking Water Quality

3.5.11.1 Introduction

Providing clean drinking water for communities is an important ecosystem service provided by many public lands in the country. There are two primary sources of drinking water, groundwater or above ground (stream and water body). Some habitats, particularly wetlands and riparian floodplains, have the ability to improve water quality. They do this by some combination of providing shade, if excessive temperature is a problem, as it is in the west; by removing excessive nutrients, particularly nitrogen and phosphorus; or by preventing excessive sedimentation. Land managers can either protect or restore these habitats, leading to additional provision of ecosystem services.

3.5.11.2 National Datasets or Models Available

Multiple approaches are available to model drinking water quality, which generally correspond to the source of drinking water, and the factors that impair water quality from lakes and streams. For groundwater, most states have maps of groundwater resources, as well as locations where communities access aquifers for their drinking water. Aquifer recharge areas are often mapped and linked to drinking water availability.

Most data and models for drinking water are focused on streams and waterbody impacts, particularly sedimentation, nutrient control, and temperature control; each which are modeled separately.

3.5.11.2.1 InVEST Sediment Model

The InVEST sediment delivery model calculates annual sediment delivery to waterways based on soil loss from each pixel draining to a waterway and a sediment delivery ratio representing the proportion of that soil loss that will reach the waterway (Sharp et al. 2018). Annual soil loss is calculated from the revised universal soil loss equation, based on rainfall, soil, slope, and management factors (a C factor reflecting the effect of land management practices on erosion rates, and a P factor that reflects the effect of cropping practices on water runoff). The sediment delivery ratio is calculated from a connectivity index for each pixel, which is based on upslope and downslope topography and land cover factors. Sediment export from a given pixel to the waterway is the annual soil loss multiplied by the sediment delivery ratio, and total catchment sediment export (or sediment delivery to the waterway) is the sum of exports for all pixels in the catchment. Both are reported in tons of sediment per hectare per year.

The model automatically calculates sediment retention, defined as the sediment loss avoided by the current land cover compared to bare ground. Analysis of sediment retention under different scenarios can be accomplished by running the model with different land use/land cover input layers or by changing the management factors for each land use type. Valuation of the difference in sediment delivery between scenarios is possible using avoided cost, replacement cost, or willingness to pay methods, depending on how sedimentation affects the end user of the water (Sharp et al. 2018). Due to limitations described in more detail below, valuation should only be done when the model has been calibrated to the specific context.

Data required to run the InVEST model include digital elevation model, rainfall erosivity index, soil erodibility, and land use/land cover rasters, all of which are readily available in the United States. A table identifying C and P management factors by land use type is also required; these must be estimated from literature. The InVEST user's guide provides references that may be useful for estimating these factors (Sharp et al. 2018). An optional drainage layer can be used to identify pixels artificially connected to streams; this is most likely to be relevant in developed areas. Several model parameters are also required: a threshold flow accumulation (determined by comparison with a known stream network for the study area), the maximum sediment delivery ratio (representing the fraction of topsoil particles finer than 1000 um, 0.8 is the default), and the k and IC calibration parameters (it is recommended to use the default values for initial analysis and to adjust the k parameter if needed to calibrate to observed data). Model outputs can be compared with observations from sediment accumulation in a reservoir or with a time series of total suspended solids concentrations (concentration data first need to be converted to annual sediment loads using other software, as in Hamel et al. 2015).

Several important limitations constrain the usefulness of the InVEST model for valuation based on absolute sediment delivery. Because soil loss is calculated from the revised universal soil loss equation, which only represents rill and inter-rill erosion processes, other types of erosion, including gully, streambank, and mass erosion, are not included in the sediment yield estimates (Sharp et al. 2018). Therefore, sediment delivery will be underestimated in areas where other types of erosion make up a large proportion of the total sediment budget. The model is very sensitive to the k parameter, which is not physically based; calibration studies have found that k parameters vary widely by individual location (Hamel et al. 2015). A recent assessment of six applications of the InVEST model found that it performed better than global statistical models of sediment delivery, even without calibration, but that calibration was very important for reducing model bias (Hamel et al. 2017). Uncalibrated model results should be used with caution, and

valuation is only recommended when the model has been calibrated (Hamel et al. 2017, Sharp et al. 2018).

3.5.11.2.2 Nutrient Removal Model

Wetlands and riparian floodplain vegetation have been demonstrated to remove nutrients (Verhoeven et al. 2006), and are often constructed to address wastewater treatment plants (Vymazal, 2007). Modeling nutrient removal as an ecosystem service requires and assessment of three factors. First, that nutrient removal is necessary at the wetlands or streams potentially providing the service; second, the capacity of the habitats to remove N or P, and lastly the downstream drinking water use. The first of these are modeled from agricultural and residential P and N loading accumulated from upstream areas. The second from a combination of the water holding capacity, runoff curve numbers, soils and the vegetation present. These can provide results for individual wetlands or combined results for watersheds or managed areas, however the science behind the model results needs additional work (Thorslund et al. 2017).

3.5.11.3 Generation of BRIs and Economic Values

Estimates for the generation of BRIs and values are available from published studies on WTP for clean drinking water (Johnston and Thomassin 2010, Polyzou et al. 2011).

3.5.11.4 Models and Data Used at Eglin Air Force Base

Most military bases have well mapped wetlands and riparian habitats, high resolution DEMs and high quality soils data available to determine if and where drinking water protection is needed. However, because no drinking water is being generated by Eglin streams, we did not model drinking water at the base and did not attach an economic value.

3.5.12 Shoreline Erosion

3.5.12.1 Introduction

Management to protect shoreline erosion is an important feature of a natural resource management plan at military bases. Many methods are currently available to address shoreline erosion, with most methods intended to protect beachfront property at risk. The four major categories of methods to address erosion are: 1) Manage land use 2) Vegetate 3) Harden and, 4) re-nourish or trap sand.

Military bases are known to use a combination of various methods to protect shorelines with the most common methods being to either re-nourish the sand or harden the shoreline by using seawalls. Depending on the geomorphology of the coast however, seawall construction is not always possible and other management actions are required to protect the shoreline. For example, the Naval Air Station Key West is located entirely on low-lying keys and is thus unprotectable by seawalls or levees. Training and operations can significantly be impacted by sea level rise and alternate management actions like more frequent re-nourishment or vegetation may be necessary to protect the shoreline.

3.5.12.2 National Datasets or Models Available

Cosmos-COAST is a hybrid physics based numerical model to simulate long-term shoreline evolution. The model by itself is a numerical combination of a set of ordinary and partial differential equations representing several physical processes. Its main governing equation is a

partial differential equation composed of three process based models – 1) alongshore transport one-line model, 2) a cross shore equilibrium shoreline model, and 3) a sea level driven shoreline erosion model. Various management actions can be implemented as scenarios within the model to evaluate their impacts on storm surge protection and future shoreline erosion. These can include building of sea-walls and determining the rate of future re-nourishments. Other inputs to the model include scenarios of future sea level rise, wave conditions and other physical characteristics that determine the beach slope in addition to historical shoreline observations. Currently this model has been applied to coasts in southern California but its structure makes it usable to other regions of the world as long data for input variables is available. Usable outputs of the model are future shoreline projections from which estimates of average beach width can be obtained.

3.5.12.3 Generation of BRIs and Economic Values

Willingness to pay measures can be developed for tourism, recreation, education as well as research. These measures are likely to scale with the beach width and can be related to the management actions being implemented at the beach. The BRI in this case would be the area of the beach restored and that is used by people for tourism, recreation, education, or research. Additionally, beaches provide wildlife protection. Willingness to pay estimates are available from published studies on values associated with preserving various species. These can be found in the USGS Benefit Transfer Toolkit and applied to the particular species found at the shoreline. The BRIs can be generated by evaluating the area of wildlife habitat protected on restoration as an outcome of the management action undertaken.

Market values of structures can also be used to estimate the avoided damage to property from shoreline erosion. Average property values in an area are estimated by local assessors and available in a national proprietary database from CoreLogic.

3.5.12.4 Models and Data Used at Eglin Air Force Base

To characterize shoreline erosion at Eglin, we modeled beach erosion and nourishment as a dynamic capital accumulation problem (Smith et al 2009) in which benefits are derived as a function of beach width. The model assumes a linear background erosion rate plus an exponentially decaying rate at which the proportion of the nourished width erodes. This is due to the along-shore (lateral) and cross-shore movement of sand due to wave action. Hence, over time, sand is not only spread across the shore but also towards the shelf/ocean floor. McNamara et al (2015) expand upon the model of Smith et al (2009), adding the possibility of storms that remove the entire nourished portion of the beach with a Poisson-distributed probability.

3.5.13 Storm Surge Protection

3.5.13.1 Introduction

Management to protect shoreline erosion is an important feature of a natural resource management plan at military bases. Many methods are currently available to address shoreline erosion, with most methods intended to protect beachfront property at risk. The four major categories of methods to address erosion are: 1) Manage land use 2) Vegetate 3) Harden and, 4) re-nourish or trap sand.

Military bases are known to use a combination of various methods to protect shorelines with the most common methods being to either re-nourish the sand or harden the shoreline by using

seawalls. Depending on the geomorphology of the coast however, seawall construction is not always possible and other management actions are required to protect the shoreline. For example, the Naval Air Station Key West is located entirely on low-lying keys and is thus not protectable by seawalls or levees. Training and operations can significantly be impacted by sea level rise and alternate management actions like more frequent re-nourishment or vegetation may be necessary to protect the shoreline.

3.5.13.2 Generation of BRIs and Economic Values

Market values of structures are used to estimate the avoided damage to property from storm surges. Average property values in an area are estimated by local assessors and available in a national proprietary database from CoreLogic.

3.5.13.3 Models and Data Used at Eglin Air Force Base

Storm surge protection was not modeled at Eglin, and no monetary valuation estimates were produced.

3.6 Integrated Ecosystem Services Model

Step 4 of our approach involves joining all the various biophysical models, service quantifications, and economic valuations described in the previous subsections into a single integrated ecosystem services model (MoTIVES) in the R statistical modeling software environment. This integrated modeling approach is advantageous compared to parallel assessment of individual habitats and ecosystem services because it allows for holistic consideration of interactions, including co-benefits and offsets. This is especially important when accounting for uncertainty or potential site-to-site variability in assessment results.

This is illustrated schematically in Figure 6. Economic valuations of the changes in an ecosystem service caused by some management decision are subject to cascading variability and uncertainty from the uncertain effect of the intervention on the biophysical system, variability in the natural system, an uncertain or variable relationship between the biophysical system and the related ecosystem services, and uncertainty or variability in the economic value of these services. Where changes in ecosystem services result from changes in the same biophysical system, these changes are likely to be correlated. For example, decisions about prescribed fire will affect the distribution of ages and types of vegetation present on military bases, reflected in the vegetation model component. This effect then propagates to other components such as wildfire occurrence, carbon storage, or productivity of red cockaded woodpeckers, each of which have their own economic contributions. For instance, an unusually old distribution of tree ages suggests a greater risk of wildfire occurrence (negative economic impact) but also has a greater carbon-storage potential (positive economic impact). Thus, “extreme” conditions in biophysical systems may not necessarily produce the highest total economic values.

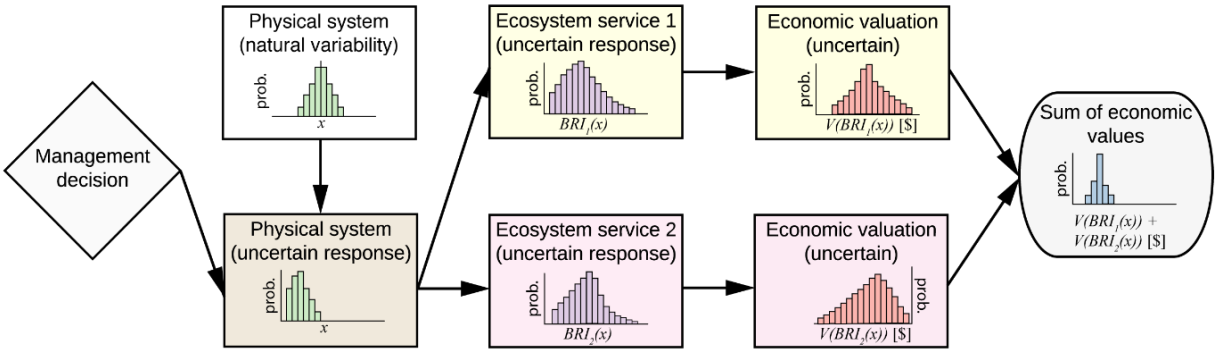


Figure 6: The effects of cascading variability and uncertainty in integrated economic valuation of ecosystem services associated with management decisions. At the left, a management decision generates an uncertain or variable response in a biophysical system property (quantity x) which has an uncertain or variable effect on subsequent benefit-relevant indicators (BRI) 1 and 2. These BRIs then translate to uncertain or variable economic values ($V(BRI_1)$ and $V(BRI_2)$). If unusually high values $V(BRI_1)$ derive from the same conditions as unusually low values of $V(BRI_2)$, then the sum of the values will be less uncertain and less variable than either value $V(BRI_1)$ or $V(BRI_2)$ individually.

In general, correlations among model components may either counterbalance one another, resulting in a smaller overall change than expected, or may reinforce one another, resulting in a larger-than-expected change. Tracking correlations ***within*** scenarios is therefore essential for correctly calculating the differences in economic values ***between*** scenarios. Our MoTIVES framework accounts for the correlations across biophysical and economic models to provide a more robust and realistic comparison of ecosystem service values.

The MoTIVES framework is applied to alternative scenarios, given alternative sets of assumptions about management decisions and modeling their impacts on potential future provision of ecosystem services. Scenarios are essential to address a number of ecosystem services, especially those such as wildfire or flooding effects, which occur infrequently or randomly and that need a comparison to assess value. The value of a wetland, a functioning floodplain, or a beaver dam to prevent flooding is only a value relative to a condition in which these features are not present. Scenarios are also needed because most ecosystem service models need to be attributed with starting conditions which generally are only available when the models are developed, in our project usually using vegetation or land cover data from 2016 to2018. This means even evaluating current management plans can require modeling how these plans impact service provision in the near future.

For Eglin Air Force Base, we chose three scenarios (current management, no management, and no base), and reported on the ecosystem services provided by each of these in the near future. This is described in greater detail below.

4 Results and Discussion

In this section we present a proof of concept for Eglin Air Force Base. We obtained data from Fort Hood and demonstrated that the methods and models can be applied to any base where current management can be mapped and modeled, and management goals can be identified. However, the results and discussion is limited to the results of the Eglin models.

4.1 Eglin Site Description

At 188,000 hectares (464,000 acres), Eglin Air Force Base is the largest forested military base in the United States. It is located on the Gulf Coast of Florida in four counties, between Pensacola and Panama City, about 150 miles west of Tallahassee (Figure 7). The base supports the largest remaining mature longleaf pine (*Pinus palustris*) forest in the world, made up of both sandhill and flatwood habitats. It also includes much of a barrier island, major rivers and streams. The base provides important habitat for more than eight federally listed and sixteen state listed threatened or endangered species.

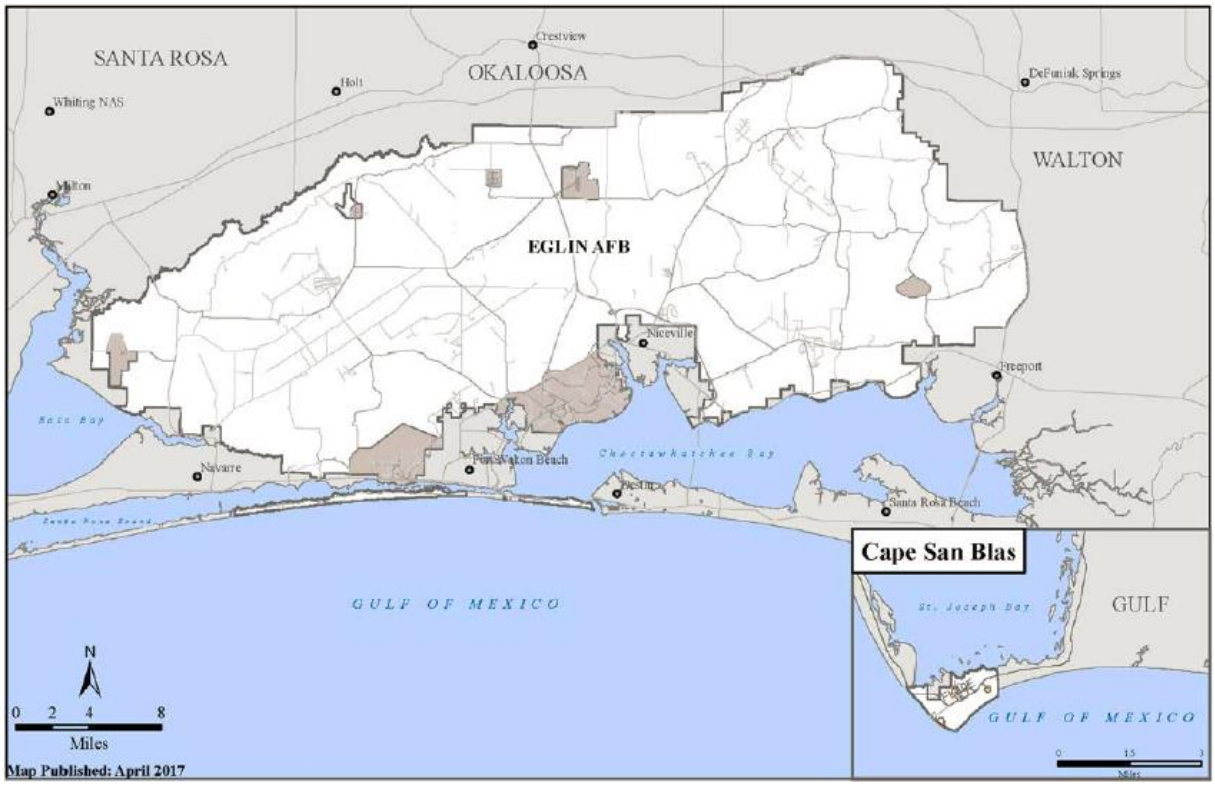


Figure 7: Map of Eglin Air Force Base and surrounding landmarks from the Eglin INRMP.

According to the 2017 Eglin INRMP, management "integrates and prioritizes wildlife, fire and forest management activities to protect and effectively manage the Complex's aquatic and terrestrial environments". Management includes a major program to use prescribed and wild fires to restore and maintain the extensive longleaf pine forests, and to recover species that have become threatened and endangered, while assuring that rare and endemic species found primarily on the base do not require endangered species act. This program provides wood to produce

biofuels and some timber products, along with the improved habitat for threatened and endangered species.

Eglin also supports extensive freshwater and estuarine wetlands, ponds and riparian meadows, supporting two species of endemic frogs, an endemic salamander, managed by the natural resources staff for the many benefits they provide. The base has a number of coastal streams and bays that support at-risk fish, along with desirable fishing locals. The base allows access for fishing and boating in all appropriate areas. Much of the eastern portions of Santa Rosa Island, a Gulf of Mexico barrier island, is part of Eglin, supporting turtle nesting, habitat for endangered shorebirds and a sand adapted threatened lichen, along with providing protection from storm surges and coastal flooding to the communities of Fort Walton Beach and Navarre. The parts of Okaloosa Island where beach use is compatible with the conservation of the shorebirds, lichen and sensitive species are open for beach access. The base supports recreation, hunting, and fishing, while providing the necessary infrastructure for its primary training mission.

4.2 Scenarios Evaluated at Eglin

We used the MoTIVES model to evaluate three specific scenarios for Eglin Air Force Base:

1. Current Management: The baseline scenario describes continuing current management at Eglin. As a baseline, we assumed that current natural resource management on the base would continue as specified in the Eglin INRMP. This includes a program of forest restoration using prescribed burning to create the open conditions favorable to longleaf pine and associated wildlife species. Vegetation maps depicting stand age and forest stand type provided by the base were used to define initial conditions for the vegetation model, represented as proportion of the longleaf pine area in each of the five state classes. MoTIVES was used to simulate current management from current conditions (circa 2015) to 20 years in the future.

2. No Management: In this scenario, we assumed that the base continued all military operations, but without historical, current, or future natural resource management. Therefore, we assumed that no prescribed fire or other management activity specific to natural resources occurred at all on the base. MoTIVES was used to simulate 60 years of no base management, from roughly 40 years ago when base natural resource management began to 20 years in the future.

3. No Base: To assess the total ecosystem services being provided by the base, we created a "counterfactual" scenario in which we assume that the base never existed. To do this, we generated hypothetical LULC maps for the current base footprint to be consistent with surrounding LULC. We employed a probabilistic approach in which we iteratively sampled from the conditional distribution of the surrounding LULC classes using a direct sampling algorithm. This is a version of approximate Bayesian computation that fills in an empty base footprint using logical combinations of surrounding LULC pixels (Mariethoz et al. 2010). As a result, the no base scenario models are run from current times (circa 2015) to 20 years in the future.

4.3 Proof of Concept: Eglin Air Force Base Results

4.3.1 Vegetation Condition

The longleaf pine STSM for Eglin captures forest growth and succession, wildfire, prescribed fire, and timber harvesting (both thinning and clear-cutting). Old forest with open

canopy conditions (referred to as late open) generally provide the high quality wildlife habitat for many wildlife species, and must be maintained through prescribed burning. Currently, late open conditions cover roughly half of the forested area at Eglin (roughly 77,000 ha). Under the current management scenario (consisting of continuing large-scale prescribed burning), the area of late open forest is expected to increase to roughly 115,000 hectares, covering the majority of the base (Figure 8). Conversely, under the no management scenario (without any prescribed burning either currently or historically), the base would likely contain very little (<5%) older, open longleaf pine and largely consist of older, closed forest. Closed canopy forests burn rarely, tend to become invaded by sand pine, and provide low quality wildlife habitat. Under the no base scenario, we expect ~50,000 hectares of conversion from forest to other land use types, and of the remaining forest, very little is projected to remain in late open conditions due to frequent clear-cutting and dense replanting on private timberlands (Figure 8). Estimates for the types of management occurring on private timberlands and timber values were based on Susaeta and Gong (2019).

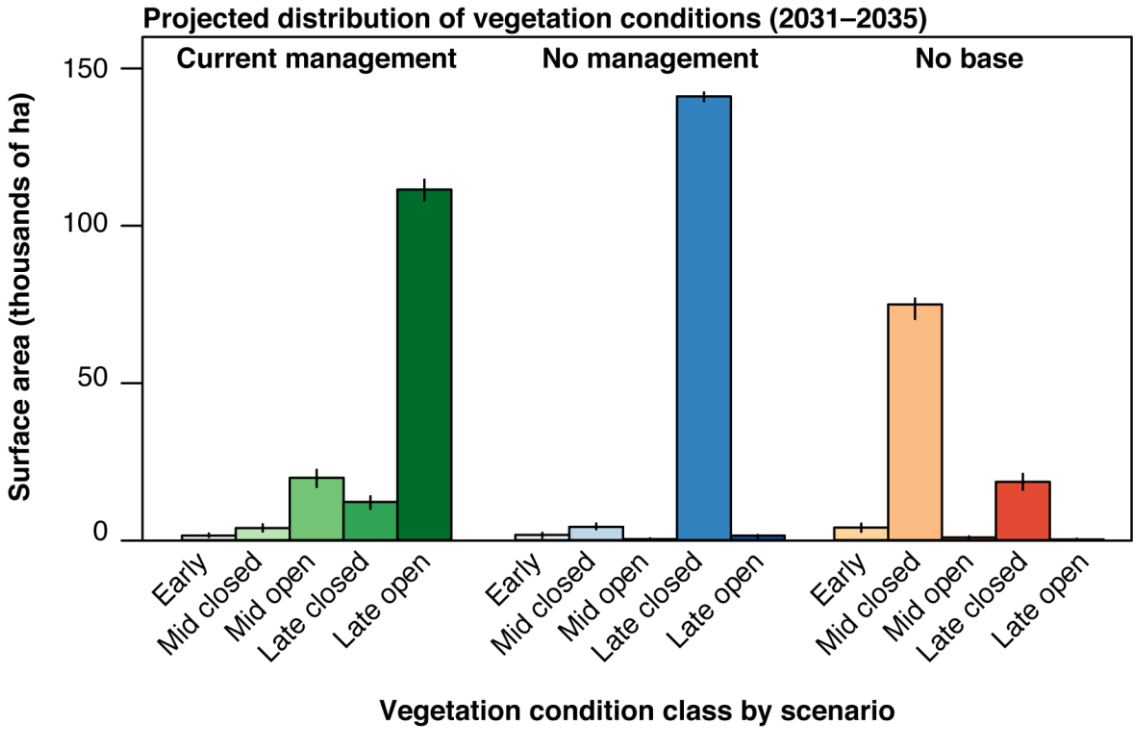


Figure 8. Projected longleaf pine forest condition classes at Eglin Air Force Base across the current management, no management and no base scenarios in years 2031-2035. Without active management of longleaf pine through prescribed fire under the current management scenario, condition degrades from open (desirable) to closed (undesirable) canopy conditions.

4.3.2 Flood exposure and protection

Table 4 displays the results of flood risk simulations for each of the three scenarios. Under current management, expected losses from flood events over the period 2020–2035 average $610.4 million per year for the three counties surrounding Eglin Air Force Base. Under no-management and no-base scenarios, these losses are expected to be $579.8 million per year and

$637.3 million per year respectively. Therefore, on average, current management practices reduce the expected value of future flood damages by roughly $27 million per year as compared to the no-base scenario. However, increased density of old-growth trees under the no-management scenario means that this counterfactual scenario would be associated with flood risks roughly $31 million per year lower than with current management conditions. Estimates for present value of future flood risks are quite uncertain given the wide range of possible distributions of future flood events. For example, the present value of future flood events under current management practices may range between $251 million per year and $1.7 billion per year (95% confidence interval).

Table 4. Modeled valuations of future flood risks (damages) by scenario over period 2020–2035. Values displayed are means (95% CI)

Units	Current management	No management [(a)]	No base [(a)]
M$/yr [(b)]	610.4 (251.7–1,689.2)	579.8 (239.1–1,604.7)	637.3 (262.8–1,763.6)

[(a)] Flood risks for no-management and no-base scenarios calculated using hydrologic simulation from current-management simulation scaled according to the land-use patterns of each scenario (described in Section 3.4).
[(b)] Future flood risks are modeled by simulating multiple future horizons with different floods occurring at different times according to the probability of each. These risks are valued by calculating the annualized net present value (5% discount rate) for each simulation. Results presented here are the mean (95% CI) of the valuations of 1,000 individual simulations of future flood occurrence. The relationship between flood occurrence probability and economic damage was derived from HAZUS (described Section 3.5.9).

4.3.3 Monetized ecosystem services

Table 5 summarizes the monetized ecosystem services provided by Eglin Air Force Base. Current management practices generate ecosystem service benefits that are most often greater than the benefits associated with counterfactual no-base and no-management scenarios. However there are a few trade-offs worth noting. Flood risk may be lower with no base. Timber harvest would likely be greater with no base. And above ground carbon storage is greatest with a base that is not managed for natural resources. Overall, current management tends to be better both for services that are monetized and for non-monetized habitat area for key species.

Table 5. Modeled ecosystem service values under three scenarios. Values displayed are means (95% confidence interval in parentheses where modeled probabilistically)

	Current management	No management	No base
	Monetized services (M$/yr)[(a)]		
Timber harvest	1.0	0	39 (24–48)
Recreational hunting	36	0	0
Recreational fishing	11	0	0
Carbon storage	1.6 (0.7–3.5)	3.1 (1.4–6.7)	1.2 (0.6–2.6)
Red-cockaded woodpecker value	56 (35–70)	30 (18–36)	11 (6.8–14)
Total monetized services[(b)]	**109 (87–123)**	**33 (20–40)**	**51.2 (32–63)**

Figure 9 displays the distribution of ecosystem service benefits generated by Eglin Air Force Base under current management practices and for the counterfactual no-management and no-base scenarios for the period 2020–2035. While under the no-base scenario, the likely timber harvest is greater than under current management practices, this is outweighed by smaller population abundance of red-cockaded woodpecker and an absence of recreational hunting and fishing. In the no-management scenario, all monetized ecosystem services are smaller than in current-management with the exception of carbon sequestration, but this is a small contribution to overall ecosystem services.

Overall, current management practices are estimated to generate $57.8 million more per year (95% CI: $31.8 million–$82.5 million per year) in ecosystem services than the no management scenario and $75.6 million more per year (95% CI: $55.3 million–$96.1 million per year) than the no-base scenario.

The ecosystem service benefits are quantified here for each scenario independently. We note that another service provided by current management practices derives from flood protection. However, the flood protection service can only be valued by comparing two scenarios together: we calculate it based on the difference in net present value of future flood risks between scenarios. We account for the flood protection service (along with the services presented here) in our calculation of the net benefits of current management in comparison to alternative scenarios (Section 4.3.5).

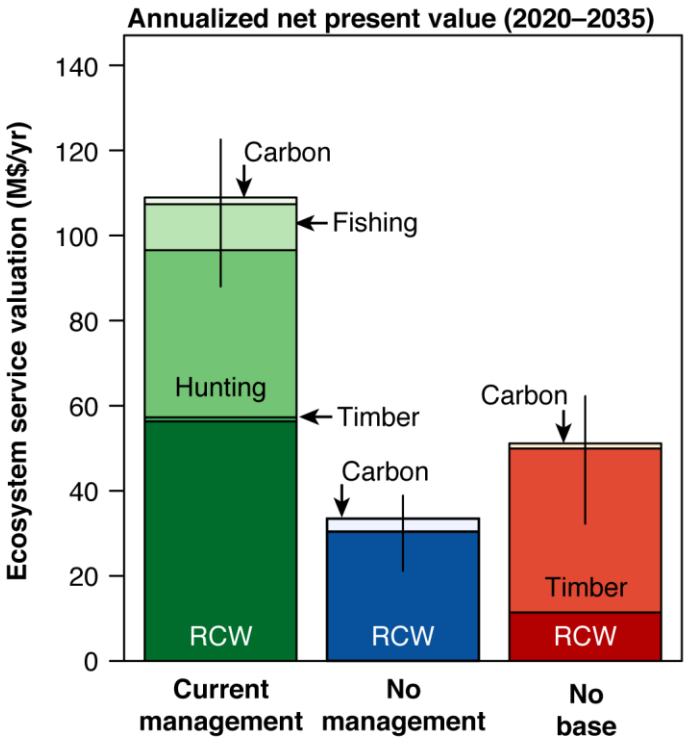


Figure 9. Monetized ecosystem services from Table 5. Values plotted are annualized net present value (assuming a 5% discount rate) over the period 2020–2035. Error bars correspond to 95% confidence interval for the sum of the services for each scenario.

4.3.4 Habitat of critical species

Eglin Air Force Base provides habitat for a number of key species (Table 3, Table 5). Current management practices produce the greatest area of suitable habitat for all species other than Gulf Coast redflower pitcherplant and smallflowered meadowbeauty. For these two species, the no-management scenario provides slightly more area of suitable habitat.

The no-base scenario severely reduces available habitat for all species. Habitat area for each species and each scenario is based on projected distribution of vegetation state classes (2031–2035) and is summarizes in Table 5 and plotted in Figure 10. Estimates for red-cockaded woodpecker species habitat area are in turn converted into species abundance and economic value (Table 5).

Table 6. Species habitat, non monetized modeled ecosystem service values under three scenarios. Values displayed are means (95% confidence interval in parentheses where modeled probabilistically)

	Current management	**No management**	**No base**
	Habitat area of key species (ha)[(c)]		
Curtis's sandgrass	55.7 (54.9–56.6)	45.1 (44.9–45.2)	22.5 (22.2–22.9)
Florida pine snake	1,296 (1,274–1,311)	512 (506–515)	105 (94–120)
Gulf Coast redflower pitcherplant	273 (269–279)	256 (254–257)	91 (89–94)
Harper's yellow-eyed grass	14.4 (14.2–14.7)	6.1 (6.06–6.14)	4.4 (4.33–4.43)
Panhandle lily	11.3 (11.0–11.6)	21.4 (21.2–21.6)	2.8 (2.5–3.3)
Panhandle meadowbeauty	11.2 (10.7–11.8)	7.2 (6.3–7.9)	4.9 (3.5–6.3)
Pine barrens tree frog	416 (410–422)	554 (550–557)	112 (103–126)
Pineland bogbutton	13.3 (13.0–13.6)	4.35 (4.30–4.40)	0.59 (0.51–0.69)
Pinewoods bluestem	7.5 (7.2–7.7)	0.1 (0.05–0.11)	0.01 (0–0.03)
Pond rush	0.92 (0.89–0.94)	0.012 (0.006–0.014)	0.002 (0.001–0.004)
Red-cockaded woodpecker	65,700 (64,800–66,400)	31,800 (31,500–31,900)	12,400 (12,000–13,000)
Reticulated flatwood salamander	8.4 (8.2–8.5)	5.6 (5.6–5.7)	1.5 (1.4–1.6)
Smallflowered meadowbeauty	9.9 (9.6–10.2)	3.5 (3.1–3.8)	2.2 (1.6–2.7)

[(a)] Annualized net present value over period 2020–2035 assuming a 5% discount rate
[(b)] Total adjusts for correlated uncertainties and may not equal arithmetic sum of individual services
[(c)] Based on projected distribution of vegetation state classes over period 2031–2035

These species habitats outputs represent the set of modeled benefit relevant indicators (BRI) considered to be of sufficient value to be a primary focus of the INRMP at Eglin. Figure 10 shows the comparison of these modeled ecosystem service BRI values under three scenarios.

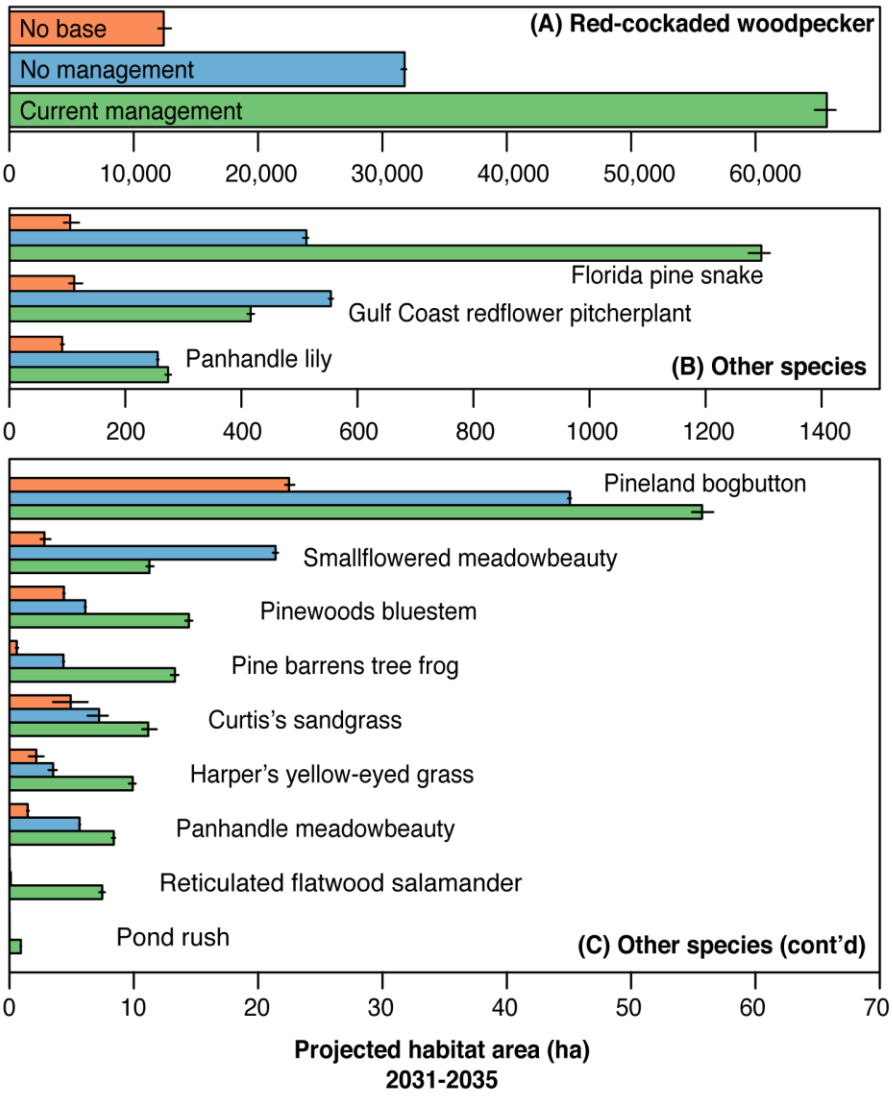


Figure 10. Habitat area available for key species from Table 5. Values plotted are based on projected distribution of vegetation in the period 2031–2035. Error bars are the 95% confidence interval.

4.3.5 Comparison of scenarios

We have compared management scenarios in terms of average value of future flood risks (Section 4.3.2) and in terms of active generation of ecosystem services for which there is an available economic quantification method (Section 4.3.3). Here, we evaluate the net benefits of current management conditions in comparison to counterfactual no-management and no-base scenarios accounting for both active generation of ecosystem services and differences in flood risk.

Current management practices are associated with higher ecosystem service generation and lower value of flood risks than the no-base counterfactual. Conversely, the no-management counterfactual is associated with lower ecosystem service generation but also lower flood risks than current management. Taking account of these expected costs and benefits across scenarios, we find that the current practices scenario produces higher net benefits than either of the two counterfactuals (mean of $90.8 million and $40.5 million per year relative to no-management and no-base respectively). Furthermore, this finding is robust when considering the uncertainties inherent in the underlying modeling methods (both 95% confidence intervals for net benefits of current management practices are far from 0). Table 7 displays the results of this analysis.

Table 7. Modeled net benefits of current management compared to counterfactual no-management and no-base scenarios. Values displayed are means (95% CI)

Current management service provision improvement over		
Units	**No management**	**No base**
M$/yr [(a)]	90.8 (66.5–127.1)	40.5 (9.2–69.6)

[(a)] Annualized net present value over period 2020–2035 assuming a 5% discount rate and accounting for correlated uncertainties across individual services

5 Conclusions and Implications for Future Research and Implementation

5.1 Evaluation of the Approach

Since ecosystem services have become widely recognized as a useful tool for assessing the success of natural resource management actions, quantifying and reporting on these services is becoming part of good resource management practice. Our approach can help DOD natural resource managers show how they are enhancing the production of services, and how the existence of the base itself provides substantial ecosystem services benefits to people.

The model we developed includes several components:

- generalized ecosystem service **conceptual models** for habitat types and specific military bases that form the foundation for the quantitative models
- biophysical **ecological models** to characterize ecological condition underlying the provision of services
- ecosystem services production function models that link the ecological conditions to **benefit relevant indicators (BRIs)** of ecosystem service provision and estimates of the **economic value** of the services where possible, and
- an **integrated ecosystem services model (MoTIVES)** to quantitatively model cumulative effects, co-benefits, feedbacks, and compensatory behavior across multiple scenarios that consider uncertainty.

Because of our modular approach linking models and datasets, we are able to take advantage of the previous ecological assessment work done at many bases when it is available, and use generic models and data where it is not. We have identified national models and datasets available at almost all locations within the 48 contiguous states. As a result, the methodology can be readily expanded to any large base anticipated to generate ecosystem services. To expand to

bases outside the 48 states or in other countries new data and models would need to be collated and incorporated.

Ecosystem services are expressed as benefit relevant indicators (BRIs) whenever possible. BRIs link the ecological changes in systems to the benefits received by people, often including metrics that include the number of people or properties affected. We convert the BRIs from physical units to dollars values when the economic data is available. BRIs tend to be intuitive measures that communicate well to stakeholders and decision makers. Although useful on their own, expressing BRIs in dollars terms allows direct comparison of different ecosystem services.

Because bases provide a diverse array of ecosystem services, and because some management decisions can reduce some services while increasing others, our methods combine this complex assemblage of models into a single, Bayesian model (MoTIVES) to integrate outputs and allow an evaluation of trade-offs and co-benefits. It also allows us to run different management scenarios and cumulative effects. MoTIVES structure also allows it to take advantage of a broad array of available ecosystem assessment tools, broadening the ability to use the best data or model available for a particular base. MoTIVES can also be used with spatially explicit data to help managers target those areas providing the largest or most valuable services, and to direct potentially damaging training activities to those providing the fewest benefits.

A distinguishing feature of our approach is the fact that we explicitly consider uncertainty in all aspects of the model related to ecosystem outputs and benefit relevant indicators, and translate this uncertainty to model endpoints using Monte Carlo simulation. Predicting the response of a natural system to management actions is a highly uncertain task and the actual outcome can never be perfectly known in advance. Regardless of the quality of the biophysical or economic models used, there will always be residual uncertainty due to natural variability, measurement error in underlying data, or misspecification of ecological processes. This means that most models underrepresent the natural dynamics and variation in a system, leading to management actions that have unanticipated consequences. By using simulation to explore the range of possible consequences of management for ecosystem service values, we decrease the likelihood of later surprises or missed opportunities.

5.2 Additional Research Needs to Improve This Approach

Because the most important services provided by Eglin Air Force Base were linked to the management of terrestrial ecosystems, in our pilot study we were not able to take advantage of some of the models and tools related to aquatic ecosystem services. At other bases, where aquatic systems and services are important, other models should be incorporated. The InVEST models have been tested and are simple to apply in many areas. For example, in the MoTIVES framework, InVEST can be useful in exploring management tradeoffs between sediment removal and other terrestrial land management decisions. We acknowledge that the InVEST model is simplified and more detailed hydrological models may give better results. However, the detailed hydrologic models have only been piloted in a few small watersheds, and only the flood control models have been carefully tested. These more intensive and time consuming models could be useful for bases because each individual wetland or stream segment on a base can be assessed for the specific services they provide. Including this aquatic detail in MoTIVES would allow base natural resources staff to target restoration and conservation considering both terrestrial and aquatic systems.

Similarly, research into water quality improvement related to both the ecosystem processes of nutrient removal, and the value of removed N and P for anything but waste water treatment would improve our model outputs. Research is underway a to develop high resolution decision support tools for assessing the value of nutrients that individual wetlands, stream segments and floodplain vegetation can remove or prevent these from reaching downstream streams (Kadlec 2006). Access to high resolution, Lidar based DEMs, hydrologic modeling tools, along with data linking wetland basin size, condition and vegetation to sediment removal, makes assessment of BRIs for nutrients possible for bases where water provision is important. Fortunately, the ability of MoTIVES to provide information on uncertainty allows our methods to be useful with whatever are the best available data and models.

Tradeoffs are most easily evaluated if different services can be measured in similar units, which is why economic valuation is so useful. Yet many base management activities on the pilot bases are focused on management of threatened, endangered or endemic species, as they provide critical habitat for them. The conservation or expansion of populations of at risk species represent important management outcomes. We provide estimates of the existence values associated with species conservation for a single species only (red cockaded woodpecker), although we recognize that the values obtained depend critically on how estimates from focused studies are transferred to larger human populations. Research into valuing species existence would significantly improve any methods to evaluate this important ecosystem service (Olander et al. 2017).

We estimated economic values for many BRIs, but future research is needed to provide a more comprehensive assessment. Economic values for market goods are readily estimated because these goods have observable prices. For example, we computed economic values for timber and flood damage using market data on stumpage and real estate prices. Valuation of non-market goods is also possible using techniques such as the contingent valuation method. Non-market benefits quantified for Eglin include species preservation and carbon storage. Economic values were not provided because:

1. preliminary analysis indicated negligible benefits,
2. economic value estimates were available but could not be linked to BRIs, or
3. economic value estimates were unavailable.

An example of the first case is respiratory health protection, which we determined to be a negligible impact. Drinking water quality is an example of the second case. There are willingness-to-pay estimates for clean drinking water, but the output from a sediment delivery model (soil loss) is not what is directly valued in the economic studies. In the third case, there are endemic species found at Eglin for which contingent valuation estimates are unavailable. Future research can address these last two cases by developing ways to align model outputs with available economic estimates or to develop new estimates to match the BRIs produced by the models.

5.3 Pilot Base Application

Eglin Air Force Base served as a useful pilot because it provides many important services, and because many of these services exist primarily as a result of two decades of intensive management by Eglin staff. This intense management is coincident with very high quality data, allowing more accurate predictions of services such as carbon, endangered species, and stream

water quality improvement. And the scenario evaluation demonstrates how important base management has been and will be in relation to the value of services provided, both when compared to the no base scenario and the no management scenario. The initial pilot studies indicate that there appear to be no limitations as to where our approach can be applied. However, the time and cost to implement this at another base will depend on several factors, including the availability of ecosystem process models for the primary ecosystems at the base, quality of data related to ongoing base management, and usable valuation protocols for the services of interest.

Although we did not apply MoTIVES at Fort Hood, our work there was important for understanding how variation in management, habitats and data would affect the time, cost and effectiveness of implementing this methodology across all of the large bases. Unlike Eglin, Fort Hood occurs in an ecological transition including prairies typical of the Midwest, oak-juniper woodlands typical of Texas, and some shrublands characteristic of the southwest; requiring multiple habitat models each linking to different ecosystem services. At Fort Hood the team was able to compare national, regional and local vegetation datasets to evaluate if they would be suitable for use in our models – and they generally were. Although the local datasets were much more useful for identification of ecosystems states, and to assess the values of benefit relevant indicators for the relevant services.

5.4 Feasibility Assessment of Future Expansion of this Work

Our approach can be applied widely, although the time and cost to implement it at any given base will depend on a number of factors. These include:

1. The availability of ecosystem process models for the primary ecosystems at the base. The primary ecosystem type at Eglin AFB, longleaf pine, happens to both be a well-studied ecosystem type and one that dominates at least ten other large bases from Virginia south to Florida and west to Mississippi. Existing models are available for many ecosystem types in the western US, particularly where the USFS has developed and used STSMs for their forest planning, locations of the Integrated Landscape Assessment Project. Models are also available at Fort Lewis and Fort Bragg and the forested landscapes in the upper Midwest and New England where other models such as Landis have been developed and applied.
2. The availability of base-specific ecosystem and use data. Our methodology requires an understanding the natural resources management objectives of each base. The team found that implementing this project was much more straightforward when working at military installations with INRMP documents produced within the last five years. These tended to include comprehensive information on recreational, hunting, livestock and other uses, endangered species management, and other relevant information.
3. The availability of state, university or other partners with expertise on natural systems at the base. For bases with this information available, it was possible to apply models without a major time commitment from base staff, which is important if the methodology is to be more widely implemented. For bases with older or out of date INRMP documents, the involvement of base staff is critical. In addition, where threatened and endangered species are an issue, the availability of state Natural Heritage Program or state Fish and Wildlife agency staff with experience at the base can significantly reduce the effort required while improving the results.

Based on the initial project, it is clearly feasible to apply this methodology across bases in the US. Although we did not apply MoTIVES at Fort Hood, our work there was important for understanding how variation in management, habitats and data would affect the time, cost and effectiveness of implementing this methodology across all of the large bases. Unlike Eglin, Fort Hood occurs in an ecological transition, including prairies typical of the Midwest, oak-juniper woodlands typical of Texas, and some shrublands characteristic of the southwest, requiring multiple habitat models each linked to different ecosystem services. At Fort Hood, the team was able to compare national, regional and local vegetation datasets to evaluate whether they would be suitable for use in our models, and they generally were. While the local datasets were much more useful for identification of ecosystems states, and would therefore come up with more accurate estimates of the services provided, available data will work in MoTIVES and provide reasonable estimates of the value of the ecosystem services any base provides.

Our proposal to move this process forward would be for Duke University to take the lead on this effort, working with researchers at the University of California Santa Barbara. The most efficient way to complete this work would be to employ PhD students and Post-Doctoral researchers over a four-year time period, which would cost approximately $2.8 million. The project would both address the key research questions listed above and implement this methodology at 12-16 geographically large or ecologically significant bases in the country, selected jointly between DOD and our project team. Any bases, both international and domestic, could be evaluated. However, our initial recommendations as to the most important places to do this work include the following 20 bases located in the conterminous United States:

Fort Hood, Texas (to be completed)
Joint Base Lewis – McChord, Washington (to be completed)
Camp Lejeune, North Carolina (to be completed)
Dugway Proving Ground, Utah
Camp Pendleton, California
Fort Benning, Georgia
Fort Bragg, North Carolina
Fort Campbell, Kentucky and Tennessee
Fort Huachuca, Arizona
Fort Jackson, South Carolina
Fort Knox, Tennessee
Fort McCoy, Wisconsin
Fort Pickett, Virginia
Fort Stewart, Georgia
Nellis AFB, Nevada
Pacific Fleet Training Center, Arizona
Twentynine Palms, California
Vandenberg AFB, California
White Sands Missile Range, New Mexico
Yakima Firing Center, Washington

6 Literature Cited

ABS Consulting (2011). "Flood Information Tool User Manual". Arlington, VA.

Acreman, M. and J. Holden (2013). "How wetlands affect floods" in *Wetlands* 33 (5): 773-786.

Aiken, R. 2009. "Net economic values of wildlife-related recreation in 2006: Addendum to the 2006 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation." Report 2006-5. Washington, DC: U.S. Fish and Wildlife Service

Becker, Kathryn E. (2011). "Variability of carbon stock in Florida flatwoods ecosystems undergoing restoration and management" (MS Thesis). Orlando, FL: University of Central Florida.

Bell, D.M., M.J. Gregory, V. Kane, J. Kane, R.E. Kennedy, H.M. Roberts, M. Simpson and Z. Yang (2018). "Multiscale divergence between Landsat- and LIDAR-based biomass mapping explained by regional variation in canopy cover and composition" in *Carbon Balance and Management* Vol. 13(15).

Blackmore, D.S. and H. Chang (2015). "A Geospatial tool for wetland prioritization at the watershed scale" (Report to U.S. EPA). Portland, OR: Institute for Natural Resources, Portland State University. Available: https://pdxscholar.library.pdx.edu/naturalresources_pub/31/

Buck, S., M. Auffhammer, and D. Sunding (2014). "Land Markets and the Value of Water: Hedonic analysis using repeat sales of farmland." in *American Journal of Agricultural Economics* Vol. 96(4): 953-969.

Costanza, J.K., A.J. Terando, A.J. McKerrow, and J.A. Collazo (2015). Modeling climate change, urbanization, and fire effects on *Pinus palustris* ecosystems of the southeastern U.S. 2015. Journal of Environmental management 151: 186-199.

Chadwick, N. (2005). "Red-cockaded woodpecker". Charleston, SC: South Carolina Department of Natural Resources, US Fish & Wildlife Service. Available: http://www.dnr.sc.gov/cwcs/pdf/Redcockadedwoodpecker.pdf

Daniel, C.J., L. Frid, B.M. Sleeter and M.J Fortin (2016). "State-and-transition simulation models: a framework for forecasting landscape change" in *Methods in Ecology and Evolution*, Vol. 7(11):1413-1423.

Duggan, J.M, B.A. Eichelberger, S. Ma, J.J. Lawler and G. Ziv (2015). "Informing management of rare species with an approach combining scenario modeling and spatially explicit risk assessment" in *Ecosystem Health and Sustainability*, Vol. 1(6): 1-18.

Eglin Air Force Base (2013). "Final Environmental Impact Assessment for Integrated Natural Resources Management Plan Activities" https://apps.dtic.mil/dtic/tr/fulltext/u2/a616715.pdf

Federal Emergency Management Agency (FEMA) (2018). "Hazus Flood Model User Guidance." Washington, DC.

Federal Emergency Management Agency (FEMA) (2019). "FEMA Flood Map Service Center." Retrieved 2019-05-16 from https://msc.fema.gov/portal/home.

Finney, M.A., C.W. McHugh, I.C. Grenfell, K.L. Riley, and K.C. Short (2011). "A Simulation of wildfire risk components for the continental United States" in *Stochastic Environmental Research and Risk Assessment* Vol. 25(7): 973-1000.

Galik, C.S., R.C. Abt, G. Latta, A. Méley and J.D. Henderson (2016). "Meeting renewable energy and land use objectives through public–private biomass supply partnerships" in *Applied Energy*, Vol. 172: 264-274.

Hamel, P., R. Chaplin-Kramer, S. Sim and C. Mueller (2015). "A New approach to modeling the sediment retention service (InVEST 3.0): case study of the Cape Fear catchment, North Carolina, USA" in *Science of The Total Environment*, Vol. 524:166-177.

Hamel, P., K. Falinski, R. Sharp, D.A. Auerbach, M. Sánchez-Canales and P.J. Dennedy-Frank (2017). "Sediment delivery modeling in practice: comparing the effects of watershed characteristics and data resolution across hydroclimatic regions" in *Science of the Total Environment*, Vol. 580: 1381-1388.

Jackson, J.A., M.R. Lennartz, and R.G. Hooper (1979). "Tree age and cavity initiation by red-cockaded woodpeckers" in *Journal of Forestry*, Vol 77(2): 102-103.

Johnson, F.R., E.E. Fries and H.S. Banzhaf (1997). "Valuing morbidity: an integration of the willingness-to-pay and health-status index literatures" in *Journal of Health Economics*, 16(6), 641-665.
Johnston, R.J. and M. Russell (2011). "An Operational structure for clarity in ecosystem service values" in *Ecological Economics*, Vol. 70(12):2243-2249.
Johnston, R.J. and P.J. Thomassin (2010). "Willingness to pay for water quality improvements in the United States and Canada: considering possibilities for international meta-analysis and benefit transfer" in *Agricultural and Resource Economics Review*, Vol 39(1): 114-131.
Jones, C.N., G.R. Evenson, D.L McLaughlin, M.K Vanderhoof, M.W. Lang, G.W. McCarty, H.E. Golden, C.R. Lane, and L.C. Alexander (2018). "Estimating restorable wetland water storage at landscape scales" in *Hydrological Processes*, Vol. 32:305-313.
Kadlec, R.H (2006). "Free surface wetlands for phosphorus removal: the position of the Everglades Nutrient Removal Project" in *Ecological Engineering*, Vol. 27(4): 361-379.
Koks, E.E., M. Bočkarjova, H. de Moel, and J.C.J.H. Aerts (2015). "Integrated direct and indirect flood risk modeling: development and sensitivity analysis" in *Risk Analysis*, Vol. 35(5): 882-900.
Kumar, P. (Ed.) (2010). *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*. Abingdon-on-Thames, UK: Routledge.
Liu, Y., G.L. Achtemeier, S.L. Goodrick and W. A. Jackson (2010). "Important parameters for smoke plume rise simulation with Daysmoke" in *Atmospheric Pollution Research* 1(4): 250-259.
Liu, J.C., G. Pereira, S.A. Uhl, M.A. Bravo and M.L. Bell (2015). "A systematic review of the physical health impacts from non-occupational exposure to wildfire smoke" in *Environmental Research*, Vol. 136: 120-132
LMNO Engineering, Research, and Software, Ltd. (LMNO) (2015). "Rational Equation Calculator" retrieved 2019-05-16 from https://www.lmnoeng.com/Hydrology/rational.php.
Mariethoz, G., and P. Renard, (2010). "Reconstruction of incomplete data sets or images using direct sampling" in *Mathematical Geosciences*, Vol. 42: 245–268.
Mariethoz, G., P. Renard, and J. Straubhaar (2010). "Direct sampling method to perform multiple-point geostatistical simulations" in *Water Resources Research*., 46(11).
Mavrommati, G., M.E. Borsuk and R.B. Howarth (2016). "A Novel deliberative multicriteria evaluation approach to ecosystem service valuation" in *Ecology and Society*, Vol. 22(2):39.
McNamara, D.E., S. Gopalakrishnan, M.D. Smith and A.B. Murray (2015). "Climate adaptation and policy-induced inflation of coastal property value" in *Plos One* 10(3): e0121278.
Meerschman, E., G. Pirot, G. Mariethoz, J. Straubhaar, M. Van Meirvenne and P. Renard (2013). "A Practical guide to performing multiple-point statistical simulations with the direct sampling algorithm" in *Computers & Geosciences*, Vol. 52: 307–324.
Natural Resources Conservation Service (NRCS) (1986). *Urban Hydrology for Small Watersheds* (Technical Release 55). Washington, D.C. Available: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf.
Novotny, V (2003). *Water Quality: Diffuse Pollution and Watershed Management* (Second Edition). New York: John Wiley & Sons, Inc.
Ohmann, J.L. and M.J. Gregory (2002). "Predictive mapping of forest composition and structure with direct gradient analysis and nearest-neighbor imputation in coastal Oregon, USA" in *Canadian Journal of Forest Research*, Vol. 32(4): 725-741.
Olander, L., S. Polasky, J.S. Kagan, R.J. Johnston, L. Wainger, D. Saah, L. Maguire, J. Boyd, and D. Yoskowitz (2017). "So you want your research to be relevant? Building the bridge between ecosystem services research and practice" in *Ecosystem Services*, Vol. 26(A): 170-182.
Polyzou, E., N. Jones, K.I. Evangelinos, and C.P. Halvadakis (2011). "Willingness to pay for drinking water quality improvement and the influence of social capital" in *Journal of Socio-Economics*, Vol. 40(1): 74-80.
Reaves, D.W., R.A. Kramer and T.P. Holmes (1999). "Does question format matter? Valuing an endangered species" in *Environmental and Resource Economics*, Vol. 14: 365-383.

Richardson, L. and J. Loomis (2009). "The Total economic value of threatened, endangered and rare species: An updated meta-analysis" in *Ecological Economics*, Vol 68(5): 1535-1548.
Richardson, L.A., P.A. Champ and J.B. Loomis (2012). "The Hidden cost of wildfires: economic valuation of health effects of wildfire smoke exposure in southern California" in *Journal of Forest Economics*, Vol. 18(1), 14-35.
Samuelson, L.J., T.A. Stokes, J.R. Butnor, K.H. Johnsen, C.A. Gonzalez-Benecke, P.H. Anderson, J. Jackson, L. Ferrari, T.A. Martin, and W.P. Cropper, Jr (2014). "Ecosystem carbon stocks in Pinus palustris forests" in *Canadian Journal of Forest Research*, Vol. 44: 476–486.
Samuelson, L.J., T.A. Stokes, J.R. Butnor, K.H. Johnsen, C.A. Gonzalez-Benecke, T.A. Martin, W.P. Cropper, Jr, P.H. Anderson, M.R. Ramirez, and J.C. Lewis (2017). "Ecosystem carbon density and allocation across a chronosequence of longleaf pine forests" in *Ecological Applications*, Vol. 27: 244–259.
Scheller, R.M., J.B. Domingo, B.R. Sturtevant, J.S. Williams, A. Rudy, E.J. Gustafson and D.J. Mladenoff (2007). "Design, development, and application of LANDIS-II, a spatial landscape simulation model with flexible temporal and spatial resolution" in *Ecological Modelling*, Vol. 201: 409– 419.
Sharp, R., H.T. Tallis,T. Ricketts, A.D. Guerry, S.A. Wood, R. Chaplin-Kramer, E. Nelson, D. Ennaanay, S. Wolny, N. Olwero, K. Vigerstol, D. Pennington, G. Mendoza, J. Aukema, J. Foster, J. Forrest, D. Cameron, K. Arkema, E. Lonsdorf, C. Kennedy, G. Verutes, C.K. Kim, G. Guannel, M. Papenfus, J. Toft, M. Marsik, J. Bernhardt, R. Griffin, K. Glowinski, N. Chaumont, A. Perelman, M. Lacayo, L. Mandle, P. Hamel, A.L. Vogl, L. Rogers, W. Bierbower, D. Denu and J. Douglass (2018). "InVEST 3.6.0 user's guide." (Collaborative publication by The Natural Capital Project, Stanford University, the University of Minnesota, The Nature Conservancy, and the World Wildlife Fund). Stanford, CA: Stanford University.
Shepard, C.C., C.M. Crain and M.W. Beck (2011). "The Protective role of coastal marshes: a systematic review and meta-analysis" in *PLoS One* 6(11): e27374.
Shultz, S. (2017). "Accuracy of HAZUS General Building Stock Data" in *Natural Hazards Review*, Vol. 18(4): 04017012.
Smith, M.D., J.M. Slott, D. McNamara and A.B. Murray (2009). "Beach nourishment as a dynamic capital accumulation problem" in *Journal of Environmental Economics and Management*, Vol. 58(1): 58-71.
Susaeta, A. and P. Gong (2019). "Economic viability of longleaf pine management in the southeastern United States" in *Forest Policy and Economics*, Vol. 100, 14-23.
Stevens, T.H., J. Echeverria, R.J. Glass, T. Hager and T.A. More (1991). "Measuring the existence value of wildlife: what do CVM estimates really show?" in *Land Economics*, Vol. 67(4): 390-400.
Thorslund, J., J. Jarsjö, F. Jaramillo, J.W. Jawitz, S. Manzoni, N.B. Basu, S.R. Chalov, M.J. Cohen, I.F. Creed, R. Goldenberg, A. Hylin, Z. Kalantari, A.D. Koussis, S.W. Lyon, K. Mazih, J. Mård, K. Persson, J. Pietron, C. Prieto, A. Quin, K. Van Meter, and G. Destouni (2017). "Wetlands as large-scale nature-based solutions: status and challenges for research, engineering and management" in *Ecological Engineering*, Vol. 108: 489-497.
United States Census Bureau (2018). "S0101 – Age and Sex." American Community Survey: 2013-2017 American Community Survey 5-Year Estimates.
United States Environmental Protection Agency (US EPA) (2016). "Particulate Matter (PM) Standards: Table of Historical PM NAAQS." Retrieved 2019-05-31 from https://www3.epa.gov/ttn/naaqs/standards/pm/s_pm_history.html.
United States Environmental Protection Agency (US EPA) (2019). "Community Multiscale Air Quality Modeling System (CMAQ): About CMAQ." Retrieved 2019-05-31 from https://www.epa.gov/cmaq/cmaq-models-0.
United States Geological Survey (USGS) 2018. "Wetland Restoration in the San Francisco Bay Delta and Pacific Northwest." Retrieved 2019-01-24 from https://www.usgs.gov/centers/werc/science/wetland-restoration-san-francisco-bay-delta-and-pacific-northwest.

United States Department of the Interior, U.S. Fish and Wildlife Service, U.S. Department of Commerce and U.S. Census Bureau (2011). *National Survey of Fishing, Hunting, and Wildlife-Associated Recreation*. Washington, D.C.

Verhoeven, J.T.A., B. Arheimer, C. Yin, and M.M. Hefting (2006). "Regional and global concerns over wetlands and water quality" in *Trends in Ecology and Evolution*, Vol. 21(2): 96-103.

Vymazal, J (2007). "Removal of nutrients in various types of constructed wetlands" in *Science of the Total Environment*, Vol. 380: 48-65.

Watson, K.B., T. Ricketts, G. Galford and S. Polasky (2016). "Quantifying flood mitigation services: the economic value of Otter Creek wetlands and floodplains to Middlebury, VT" in *Ecological Economics* 130: 16-24.

Wheater, H. and E. Evans (2009). "Land use, water management and future flood risk" in *Land Use Policy*, Vol. 26: S251-S64.

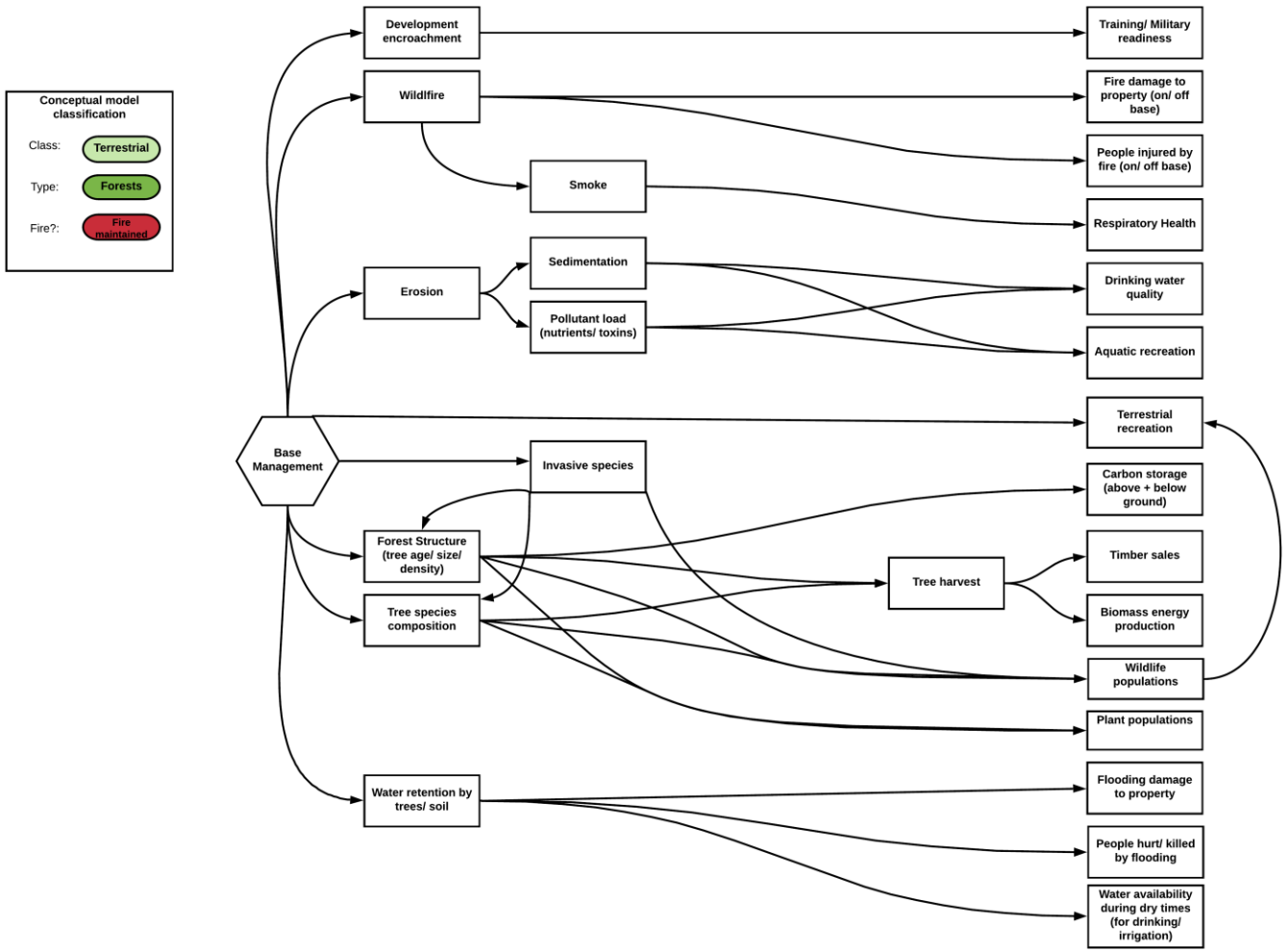
Wilson, C.W. R.E. Masters and G.A. Bukenholfer (1995). "Breeding bird response to pine-grassland community restoration for red-cockaded woodpeckers" in *Journal of Wildlife Management*, Vol. 59 (1): 55-67.

Withers, P.J.A. and H.P. Jarvie (2008). "Delivery and cycling of phosphorus in rivers: a review" in *Science of the Total Environment*, Vol. 400(1-3): 379-395.

7 Appendices

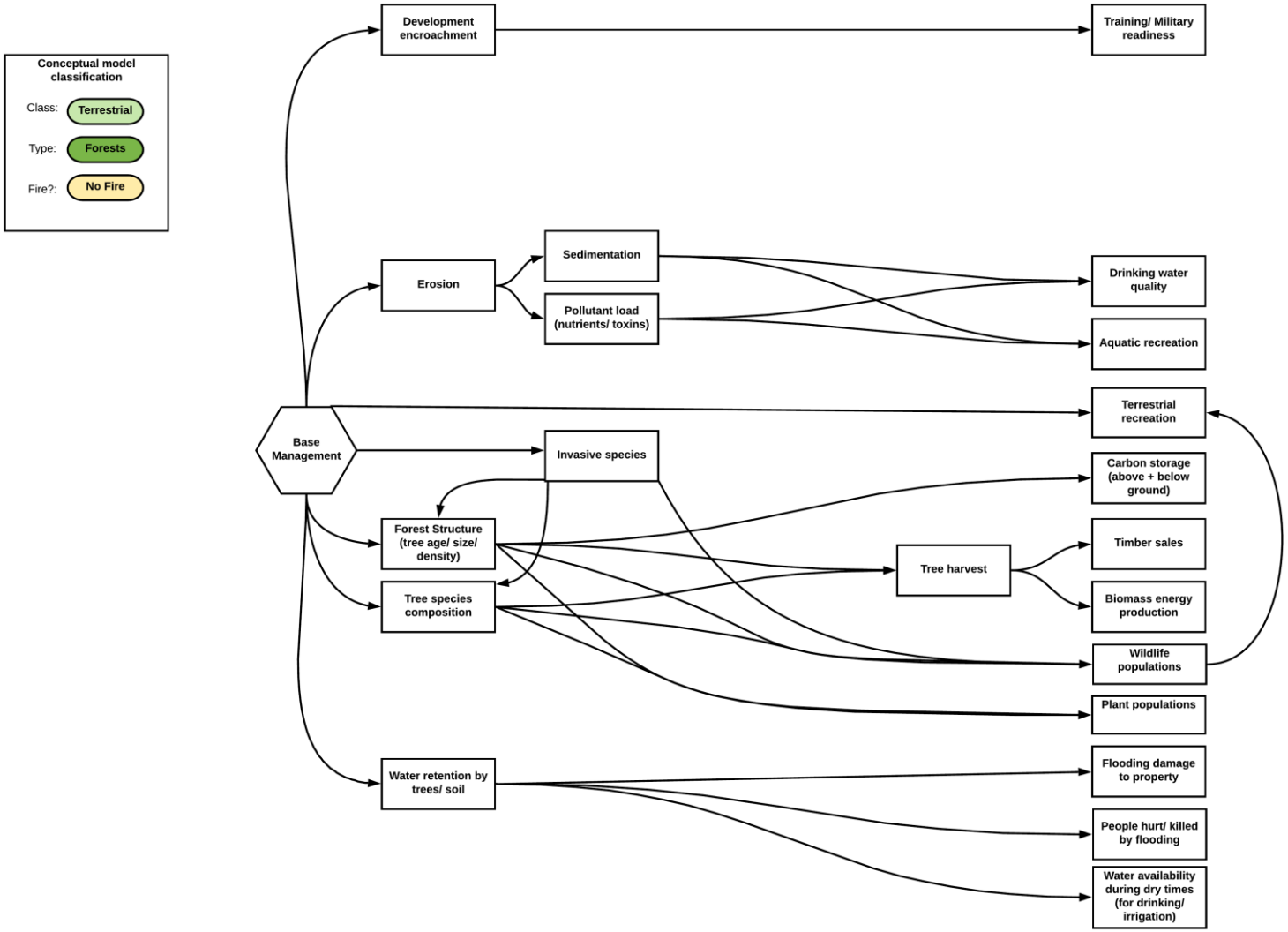
7.1 Appendix 1. Generalized habitat conceptual models

Fire maintained forests

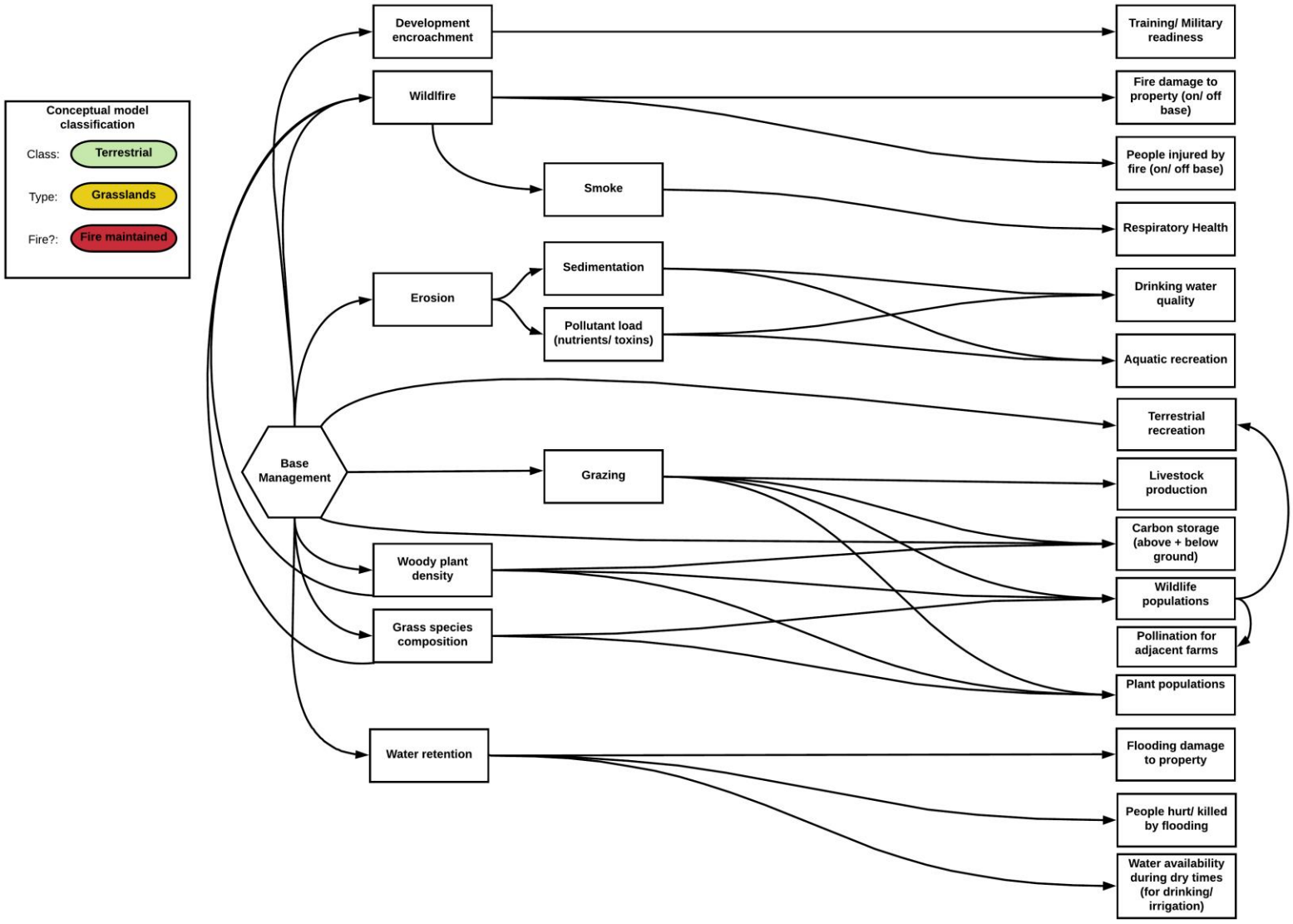


Forests not maintained by fire

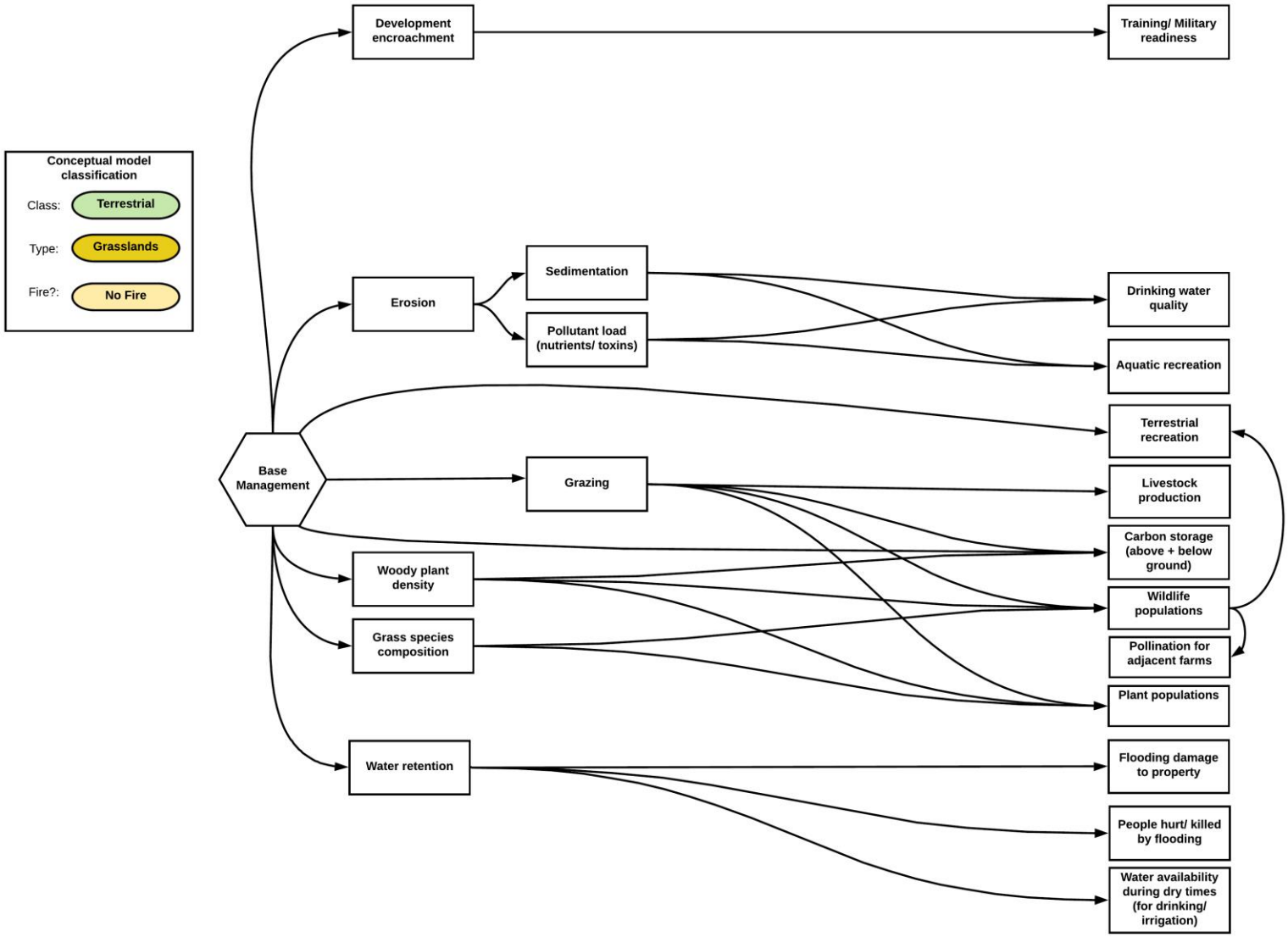
This category includes winter deciduous forests and some coniferous and mixed hardwood-conifer forests



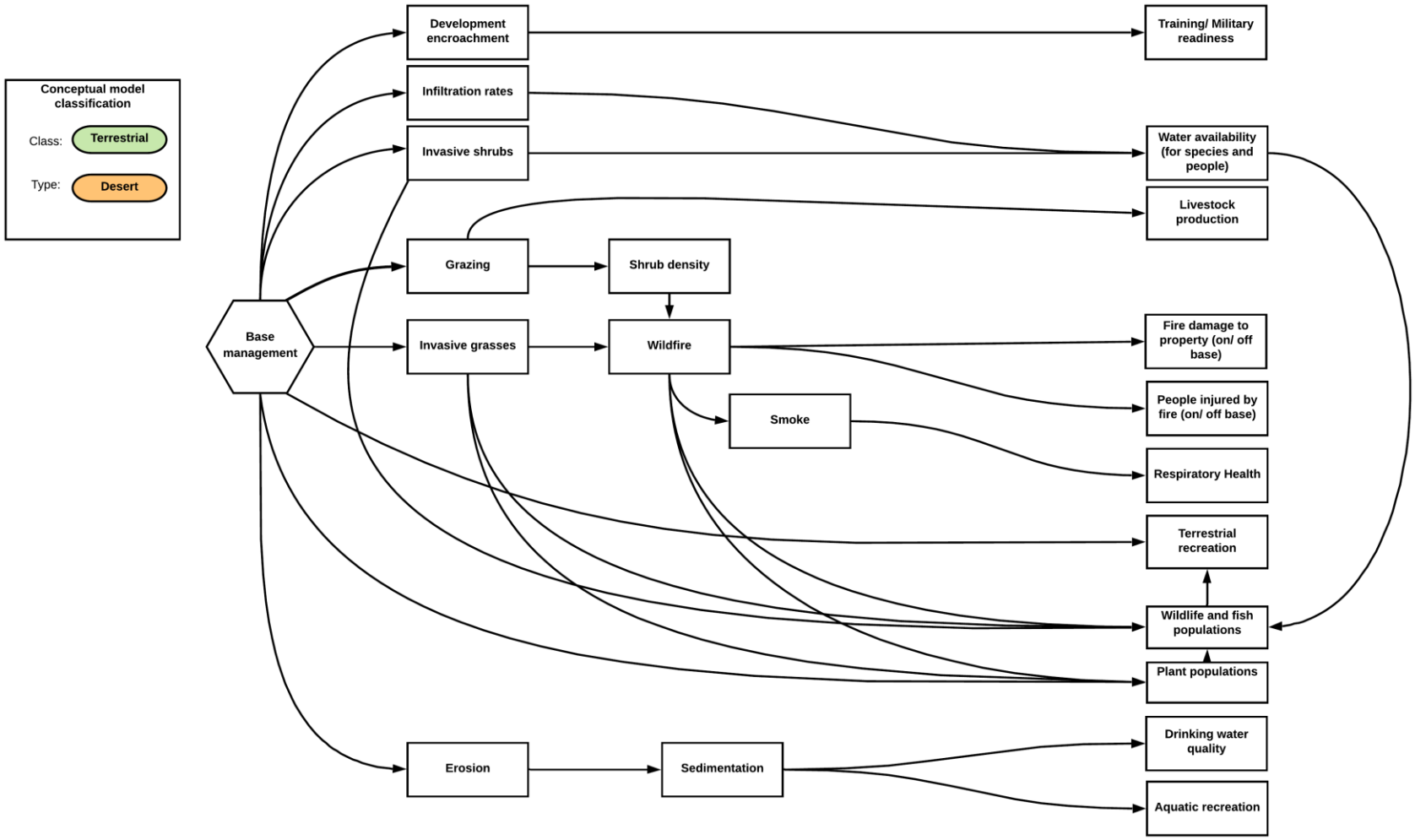
Fire-maintained savannas, shrublands and prairies



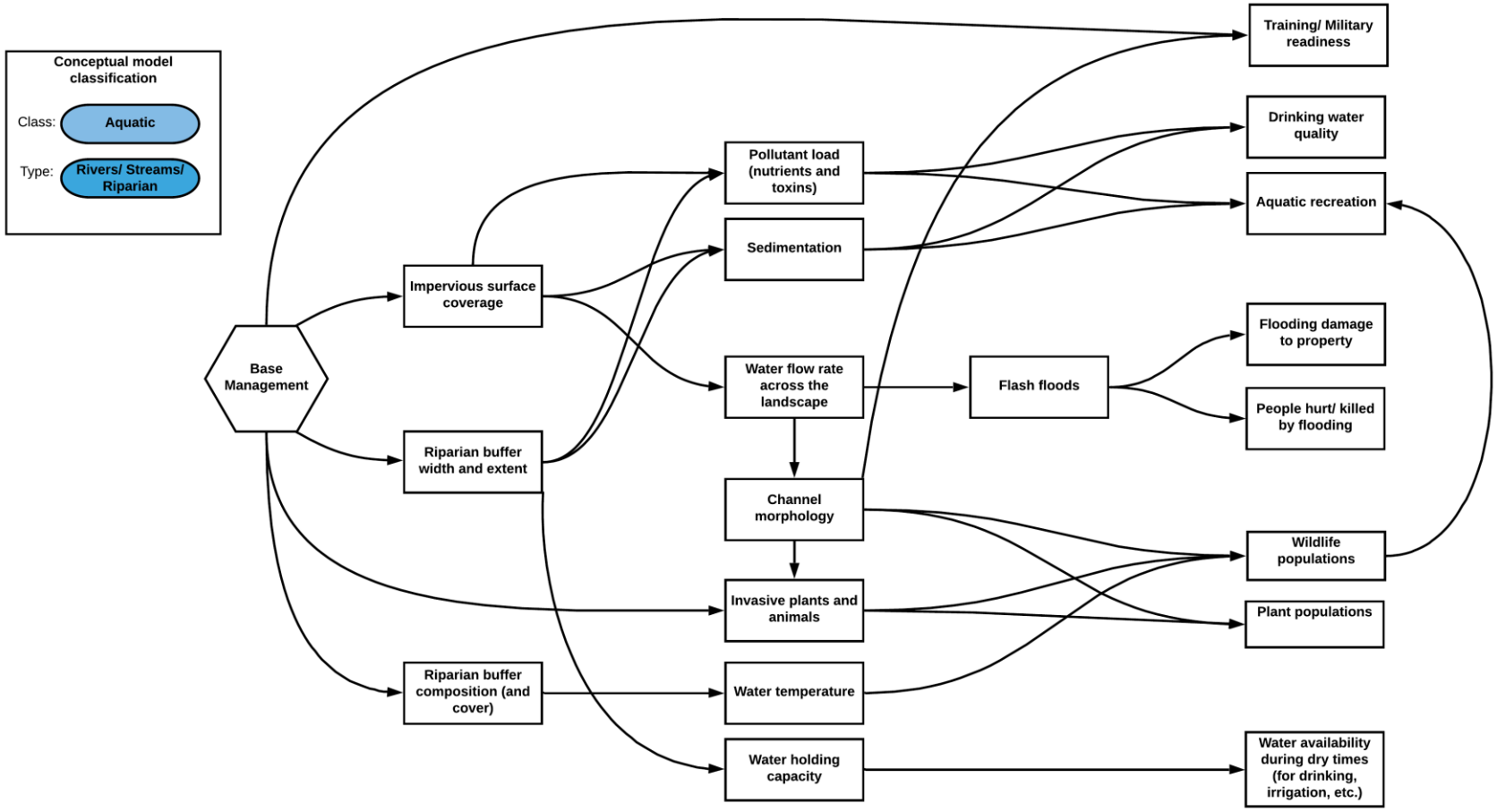
Savannas, shrublands and prairies not maintained by fire (alpine, tundra)



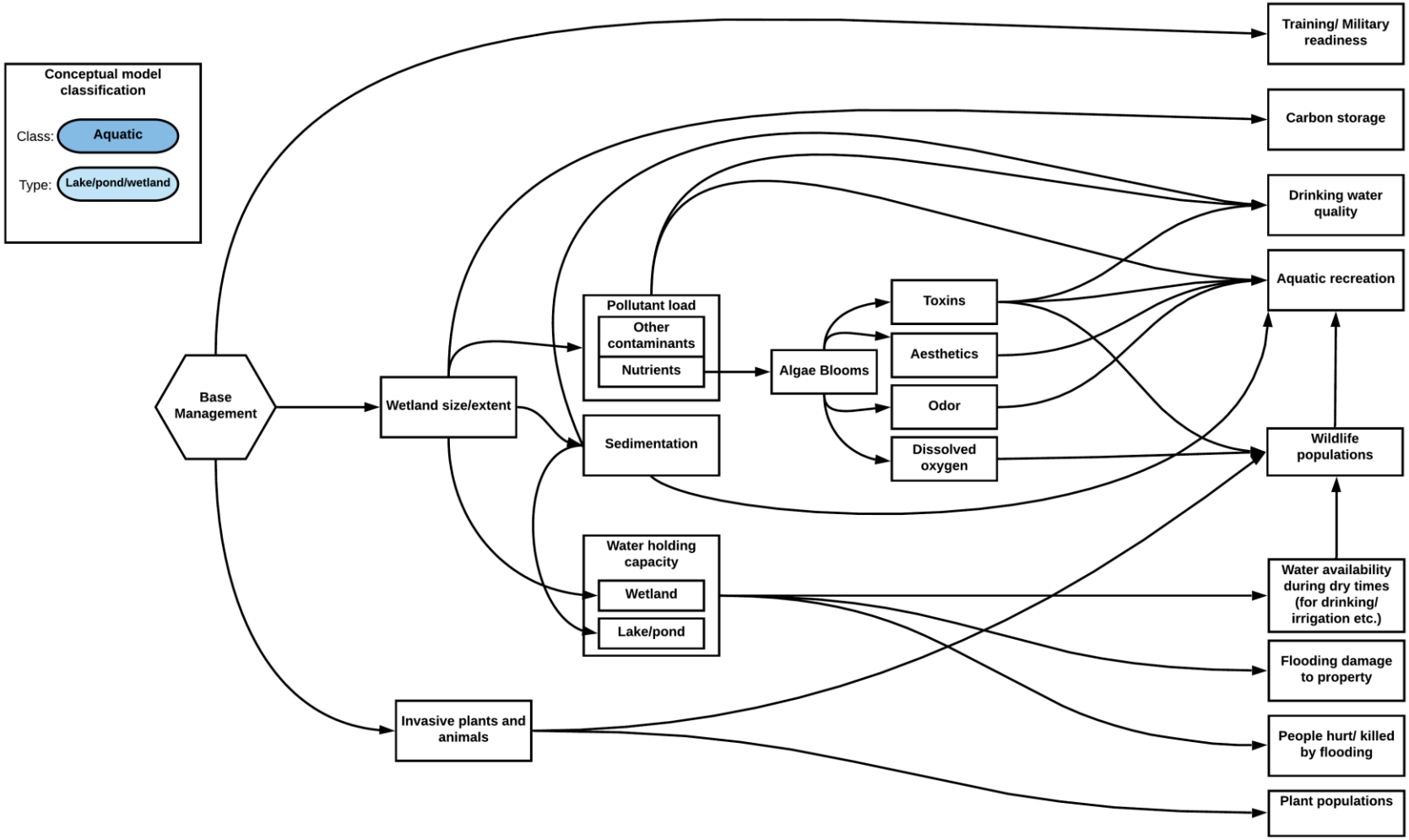
Deserts


Conceptual model classification
Class:
Terrestrial
Type:
Desert
Base management
Development encroachment
Infiltration rates
Invasive shrubs
Grazing
Shrub density
Invasive grasses
Wildfire
Smoke
Erosion
Sedimentation
Training/ Military readiness
Water availability (for species and people)
Livestock production
Fire damage to property (on/ off base)
People injured by fire (on/ off base)
Respiratory Health
Terrestrial recreation
Wildlife and fish populations
Plant populations
Drinking water quality
Aquatic recreation

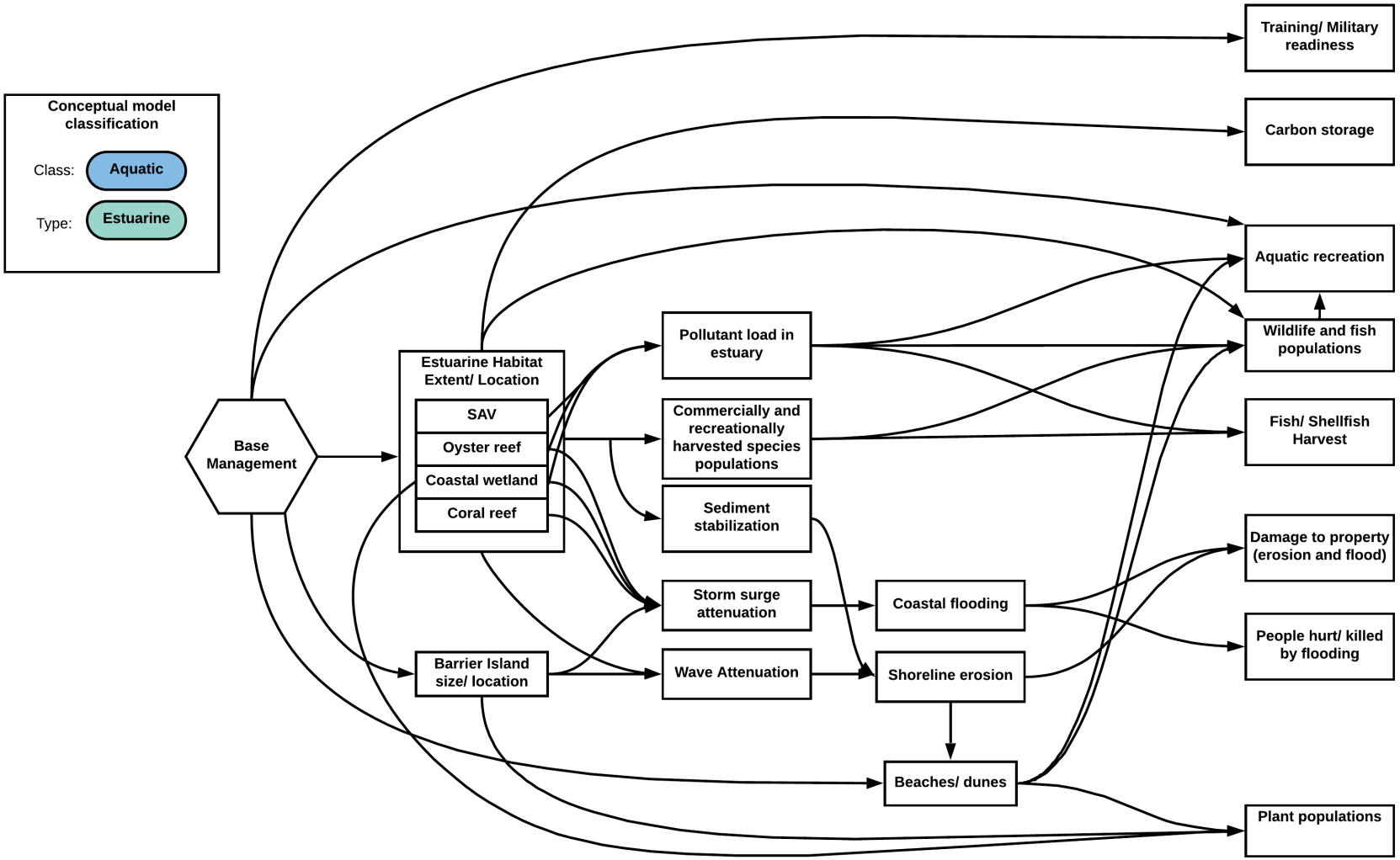
Rivers, streams and riparian habitats



Lakes, ponds, aquatic beds and wetland habitats

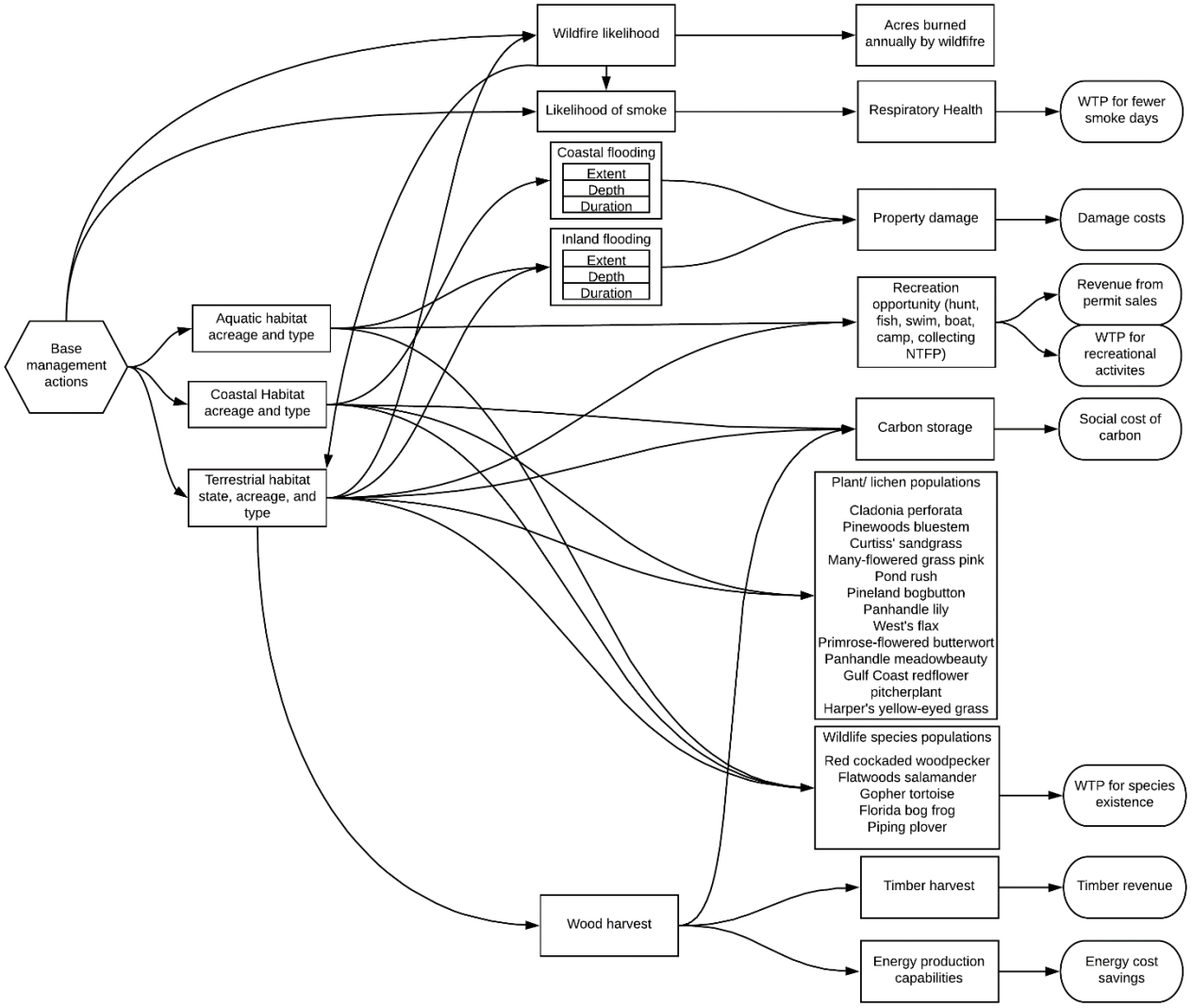


Estuaries, saltmarsh, bays and shorelines, marine habitats

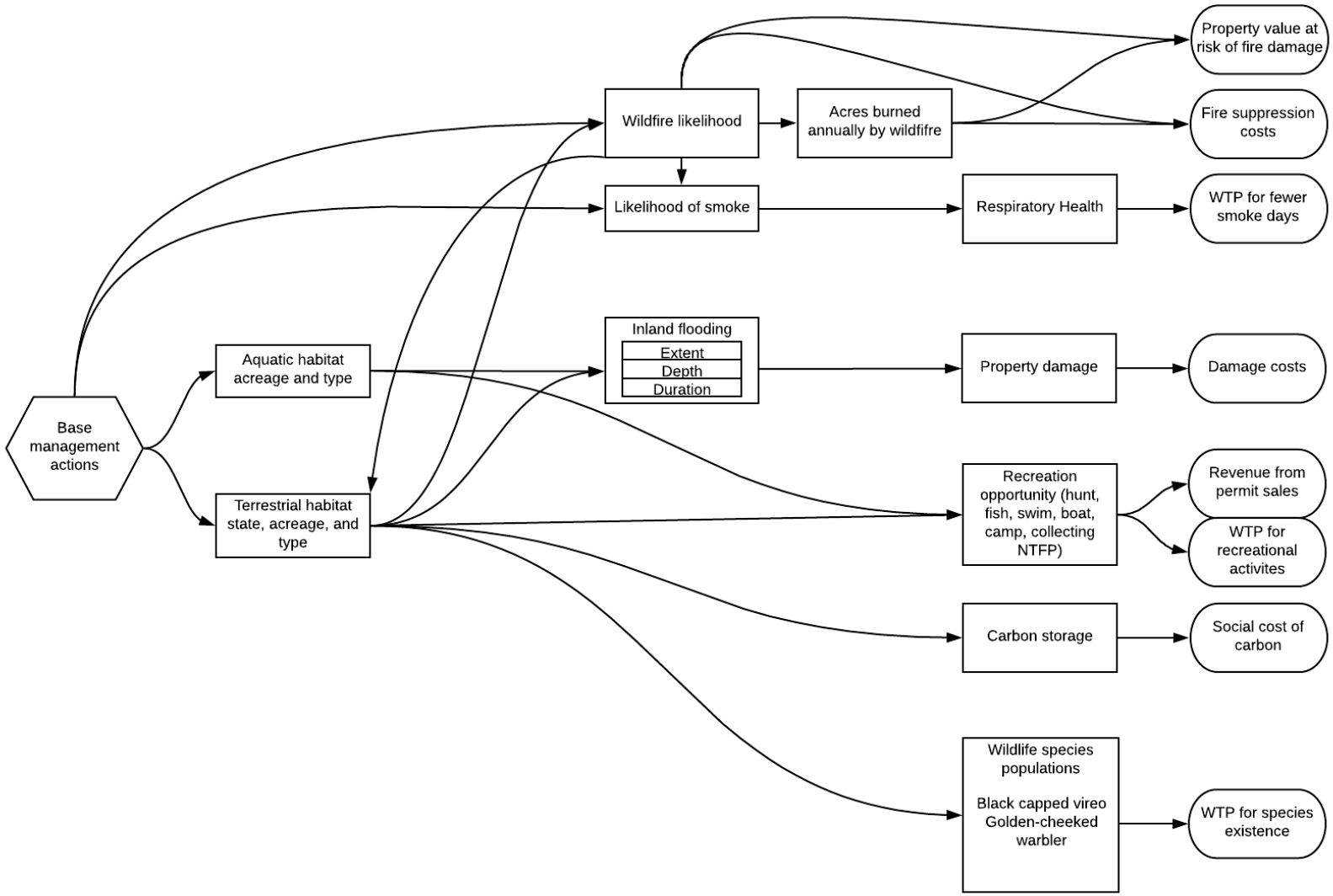


7.2 Appendix 2. Military base-specific conceptual models.

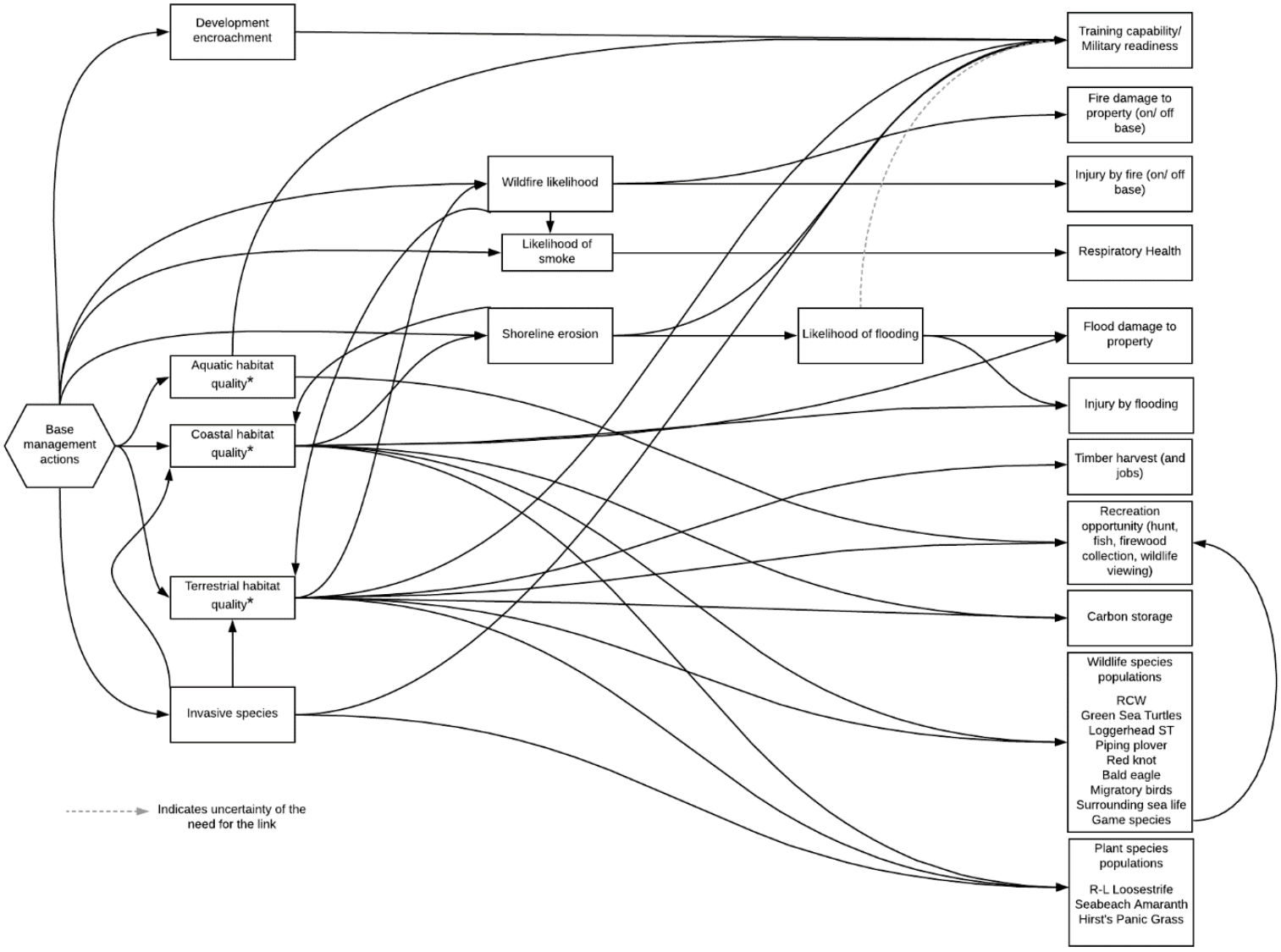
Eglin Air Force Base, Florida



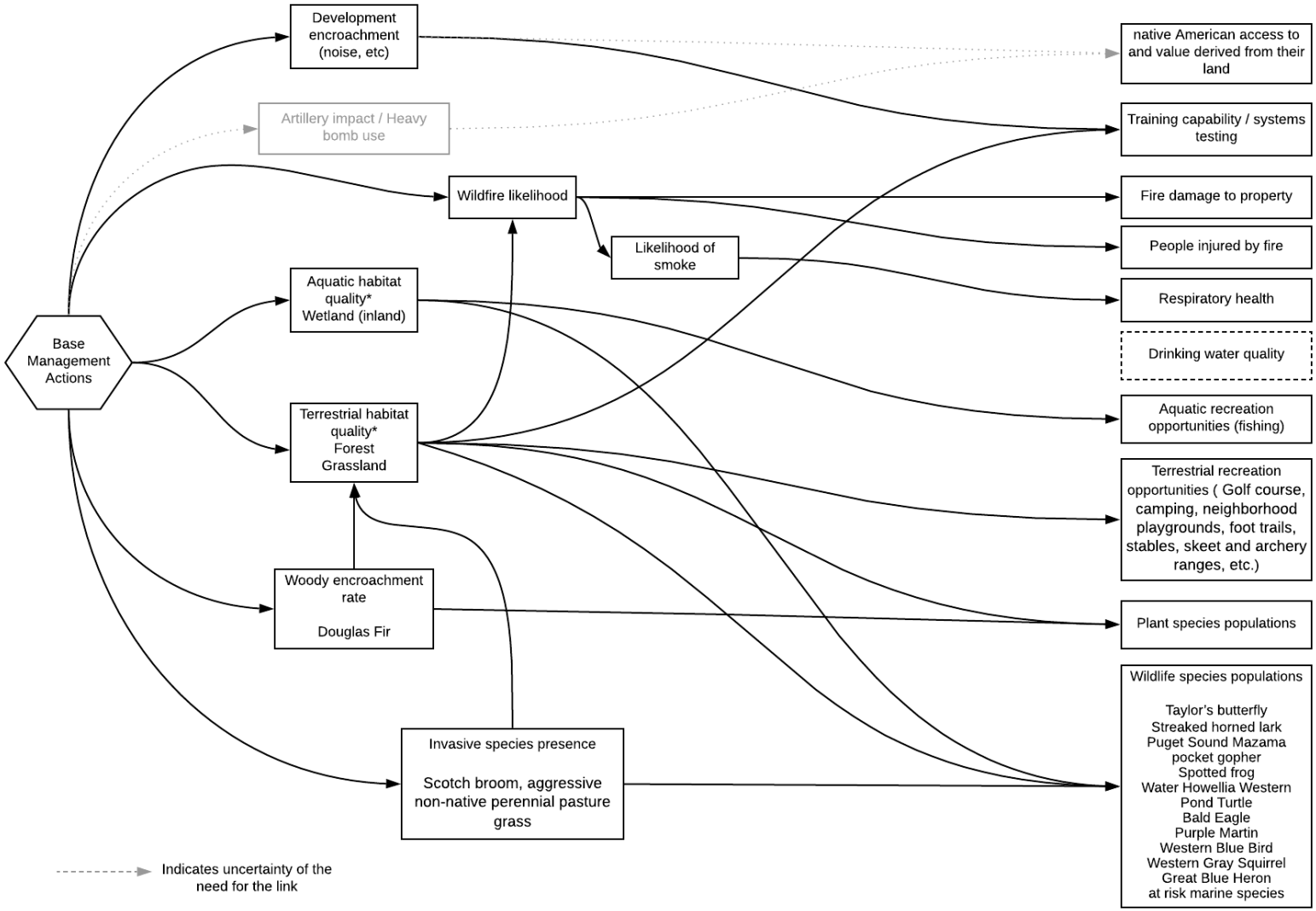
Fort Hood, Texas



Camp Lejeune, North Carolina



Joint Base Lewis-McChord, Washington



7.3 Appendix 3. Methodology for Economic Valuation of Services at Eglin AFB

Metric	Value	Unit	Methodology	Source
Parcel Value	215,263	$/parcel	Mean parcel value in Okaloosa County The parcel value is broken down by land value ($68,752), building value ($137,335) and other features value ($7307).	Florida Department of Revenue (2019). *Florida Property Tax Data Portal*. Available: http://floridarevenue.com/property/Pages/DataPortal.aspx
Respiratory Health	92.33 (range: 56.32–201.82)	$/exposed person/day	willingness to pay for a reduction in one wildfire smoke induced symptom day	Richardson, L.A., P.A. Champ and J.B. Loomis (2012). "The hidden cost of wildfires: economic valuation of health effects of wildfire smoke exposure in southern California" in *Journal of Forest Economics*, Vol. 18(1): 14-35.
Social Cost of Carbon	12 (95% CI: $1 to $43)	$/metric ton	uncertain value of incremental carbon emissions (for year 2020 and 5% discount rate)	U.S. Interagency Working Group on Social Cost of Greenhouse Gases (2016). *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866*. Available: https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf
Longleaf Pine Land Value	11,680	$/hectare (or $580/hectare/year at a 5% interest rate)	Medium to high density loblolly pine stand, maximizing the net present value of timber production.	Susaeta, A. and P. Gong (2019). "Economic viability of longleaf pine management in the southeastern United States" in *Forest Policy and Economics*, Vol. 100: 14-23.
Energy Savings	48,600	$/day	Energy savings from bioenergy production on site (avoided purchase of energy from the grid)	Galik, C.S., R.C. Abt, G. Latta, A. Méley and J.D. Henderson (2016). "Meeting renewable energy and land use objectives through public–private biomass supply partnerships" in *Applied Energy*, Vol. 172: 264-274.

Metric	Value	Unit	Methodology	Source
			(WTP for guaranteed population survival in South Carolina (1999) / RCW population in South Carolina in 2000) * all households in Florida	
			For 99% chance of survival for the species in South Carolina, WTP per household per year is 2014$ 14.09 - 22.36. $22.36 was used for this calculation.	Reaves, D.W., R.A. Kramer and T.P. Holmes (1999). "Does question format matter? Valuing an endangered species" in *Environmental and Resource Economics*, Vol. 14: 365-383.
Red-cockaded woodpecker (endangered species)	251,036	$/individual species member	669 RCW in South Carolina in 2000	Chadwick, N. (2005). "Red-cockaded woodpecker". Charleston, SC: South Carolina Department of Natural Resources, US Fish & Wildlife Service. Available: http://www.dnr.sc.gov/cwcs/pdf/Redcockadedwoodpecker.pdf
			1,871,307 households in South Carolina (not used in calculation, provided as an option because WTP come from South Carolina)	U.S. Census Bureau (2019). "Florida; South Carolina" (QuickFacts). Available: https://www.census.gov/quickfacts/fact/table/fl,sc/HSD410217
			7,510,882 households in Florida	Idem
			# hunting days x WTP for deer hunting	
Deer hunting	40,000,000	$/year	22 days per hunter per year (avg) in FL in 2011	United States Department of the Interior, U.S. Fish and Wildlife Service, U.S. Department of Commerce and U.S. Census Bureau (2011). *National Survey of Fishing, Hunting, and Wildlife-Associated Recreation*. Washington, D.C.

Metric	Value	Unit	Methodology	Source
			~8700 hunting permits sold in 2018. Used as a proxy for number of hunters. Estimated using the total permits sold in 2018 (27,000) and average proportion of all recreation permits sold between 2000 - 2010 that were hunting permits (~30%)	Total 2018 hunting permits from Eglin recreation staff; proportion that are hunting from Final Environment Assessment for Integrated Natural Resources Management Plan Activities (Eglin AFB, 2013) at https://apps.dtic.mil/dtic/tr/fulltext/u2/a616715.pdf
			WTP for deer hunting in FL: $166.75 per person per day in 2006, $207.60 in 2018	Aiken, R. 2009. "Net economic values of wildlife-related recreation in 2006: Addendum to the 2006 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation." Report 2006-5. Washington, DC: U.S. Fish and Wildlife Service
			# fishing days x WTP for fishing	
Fishing	11,000,000	$/year	19 days per hunter per year	United States Department of the Interior, U.S. Fish and Wildlife Service, U.S. Department of Commerce and U.S. Census Bureau (2011). *National Survey of Fishing, Hunting, and Wildlife-Associated Recreation*. Washington, D.C. U.S. Census Bureau (2019). "Florida; South Carolina" (QuickFacts). Available: https://www.census.gov/quickfacts/fact/table/fl,sc/HSD410217
			~6600 fishing permits sold in 2018 (see hunting permits for calculation)	Total 2018 hunting permits from Eglin recreation staff; proportion that are hunting from Final Environment Assessment for Integrated Natural Resources Management Plan Activities (Eglin AFB, 2013) at https://apps.dtic.mil/dtic/tr/fulltext/u2/a616715.pdf

Metric	Value	Unit	Methodology	Source
			WTP for bass fishing in FL: $69.29 per person per day in 2006 (lower estimate is $37.58) --> $86.26 in 2018	Aiken, R. 2009. “Net economic values of wildlife-related recreation in 2006: Addendum to the 2006 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation.” Report 2006-5. Washington, DC: U.S. Fish and Wildlife Service