Using NASA resources to inform climate and land use adaptation: Ecological forecasting, vulnerability assessment, and evaluation of management options across two US DOI Landscape Conservation Cooperatives

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TABLE OF CONTENTS

1. Rationale and Objectives

Over the coming century, change in climate may exceed the resilience of ecosystems and lead to major disruptions of habitats and species (IPCC 2007a). Such potential changes present a profound challenge for natural resource managers globally, including in the US (Baron et al. 2009). Future climate change is anticipated to drive shifts of hundreds of kilometers in the range of ecosystems and species, and play out over decades to centuries (Iverson et al. 2008, McKenney et al. 2007). At the same time, land use intensification is likely to constrain both the movements of organisms and the adaptation strategies of managers (Heller and Zavaleta 2009). Thus, successful management in the future will require consideration of large spatial and temporal scales, the ability to anticipate biological response under various future scenarios, and cooperation among resource managers across large regions (Glick and Stein 2010).

Accordingly, the US Department of Interior (DOI) has initiated various programs to meet these management challenges. The National Park Service Inventory and Monitoring Program (NPS I&M) was created in 2000 to provide a framework for scientifically sound information on the status and trends of national park condition (Fancy et al. 2009). With the 270 park units organized into 32 networks, the NPS I&M has become a leading program for monitoring ecological response to climate and land use change at regional scales. Under the soon to be released NPS Climate Change Adaptation Strategy, co-I's Olliff and Monahan along with our other NPS colleagues are developing an implementation plan to integrate monitoring, science, and management for adaptation planning. Based partially on the success of the NPS I&M, in 2009 the DOI launched the creation of Landscape Conservation Cooperatives (LCCs) across networks of the federal lands (US DOI Secretarial Order 3289 2009). Once fully operational, the goal of the LCCs will be to craft practical, landscape-level strategies for managing climate-change impacts, with emphasis on: 1) ecological systems and function, 2) strengthened observational systems, 3) model-based projections, 4) species-habitat linkages, 5) risk assessment, and 6) adaptive management. The NPS implementation plan will be used as a basis for achieving this goal.

A promising framework for climate change adaptation was recently developed by an interagency working group (Glick and Stein 2010). The four steps of the framework are to: 1) identify conservation targets; 2) assess vulnerability; 3) identify management targets; and 4) implement management options (Fig 1). Vulnerability refers to the extent to which a species, habitat, or ecosystem is susceptible to harm from climate change impacts (Schneider et al. 2007). Components of vulnerability include sensitivity to change, exposure to change, and capacity to adapt to change (IPCC 2007b). Determining which resources are most vulnerable enables managers to better set priorities for conservation action. Understanding why they are vulnerable provides a basis for developing appropriate conservation responses.

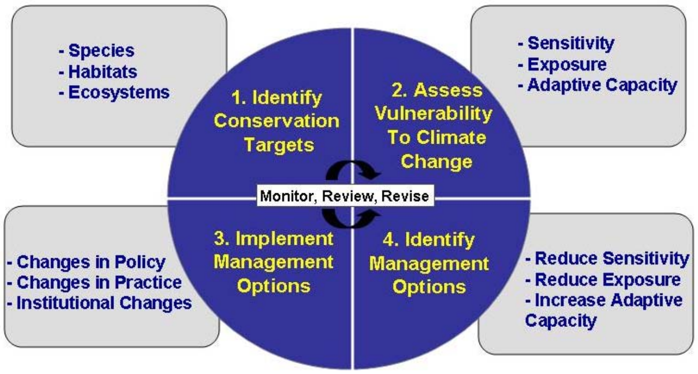

Fig. 1. A framework for climate change adaptation planning. From Glick and Stein 2010.

An important component of assessing vulnerability involves forecasting biological responses under alternative future scenarios. The Terrestrial Observation and Prediction System (TOPS) is increasingly used for ecological forecasting (Nemani et al. 2008). Sponsored by NASA, the TOPS framework integrates operational satellite data, microclimate mapping, and ecosystem simulation models to characterize ecosystem status and trends. Through past NASA support our team has used the TOPS as a basis for understanding land use trends and impacts in national parks and for enhancing the decision support systems of the NPS I&M Program.

Using the framework of Glick and Stein (2010), the proposed project will develop and apply decision support tools that use NASA and other data and models to assess vulnerability of ecosystems and species to climate and land use change and evaluate management options. Our collaborative team of NPS, NASA, and academic scientists and managers will focus on national parks within the Great Northern (GNLCC) and Appalachian (ALCC) LCCs. Thus, the project will contribute to decision support for the agency currently most engaged in climate change adaptation, but also provide data and methods highly relevant to LCCs as they become fully operational. Specific objectives are to:

1. Quantify trends in ecological resources from past to present and under projected future climate and land use scenarios using NASA and other data and models across two LCCs.
2. Assess the vulnerability of ecosystems and illustrative species to climate and land use change by quantifying exposure, sensitivity, adaptive capacity, and uncertainty in and around focal national parks within LCCs.
3. Evaluate management options for the more vulnerable ecosystems and species within these focal parks.
4. Design multi-scale management approaches for vulnerable ecosystems and species to illustrate adaptation strategies under climate and land use change.
5. Facilitate technology transfer of data, methods, and models to federal agencies to allow the decision support tools to be applied more broadly.

2. Current & Past Work

2.1 Decision Support for the NPS I&M Program

The proposed work builds on our current NASA Applied Science project, "*Ecological Condition of US National Parks: Enhancing Decision Support Through Monitoring, Analysis, and Forecasting*". Known as PALMS (Park Analysis of Landscapes and Monitoring Support), the goal of that project was to integrate the routine acquisition and analysis of NASA products and other data into the NPS I&M Program. This was done within four case-study sets of national parks across the US. We first identified a set of high-priority indicators of park condition that could be generated from TOPS and related products. These involved climate, hydrology, land cover and use, disturbance, primary production, and biodiversity. We then mapped the areas around the parks within which land use may strongly influence park condition. Called Protected-area Centered Ecosystems (PACEs), these are the locations outside of the parks that should be included in the area monitored and analyzed (Hansen et al. *in review*). Ecological hindcasts and forecasts from TOPS and other models were then used to analyze trends in the indicators from 1900 to present and to 2050 under alternative scenarios. The results were synthesized to identify the trends of highest importance to park management. The resulting data, analyses, models, and methods are being delivered to the NPS via an internet-based interface Ecocast (e.g., http://ecocast.arc.nasa.gov/dgw/dboard/SIEN), methods manuals in the format of NPS I&M Standard Operating procedures (SOPs), and workshops and trainings sessions. For details, see http://science.nature.nps.gov/im/monitor/lulc/palms. We are in the final year of the project and formal assessment has revealed a high level of satisfaction among collaborators (Hansen et al. 2009).

2.2 Vulnerability of US National Parks to Climate and Land Use Change

Under LCLUC funding, we are also analyzing change in climate and land use over the past century for 60 national park units and surrounding PACEs as context for assessing vulnerability. Analyzing the PRISM climate data (Daly et al. 2008) for 1895-2007, we found a high degree of variation among parks in monthly and annual 100-year temperature trends. 76% of the parks had significant trends in temperature, with most warming in line with the global average of 1^{0}C over the past century (Haas et al. *in prep*). Some parks, especially in the Appalachian and Rocky Mountain regions, warmed substantially more: Delaware Water Gap (2.0 °C); Rocky Mountain (1.9°C). Rates of land use change in the PACEs also varied regionally (Davis et al. *in prep*). Fifteen measures of population density, housing density, and other land use factors were summarized using principle components and cluster analysis. PACEs in the eastern US were largely within an "exurban" cluster defined by a predominance of private lands, rapid population growth, and dense exurban housing (Fig 2). Many western parks were in a "wildland" cluster defined by expansive public lands, low population density, and low housing density. Parks such as those in the mid-Atlantic region have undergone high rates of both climate and land use change, suggesting that they are relatively vulnerable to near-term future change. The proposed work will expand on this approach using both hindcasting and forecasting as a basis for assessing park vulnerability

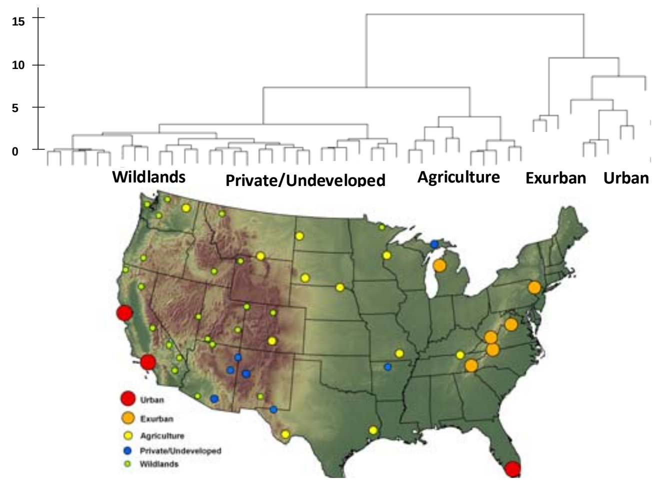

Fig. 2. Dendrogram of hierarchical clustering (top) and geographic locations of clusters of national parks based land use change (bottom).

2.3 Statistical Modeling of Biodiversity

A variety of methods have been used to quantify statistical relationships between species and biophysical factors thought to define their physiological tolerances or niche axes (Elith and Leathwick 2009). Termed bioclimatic, niche, habitat suitability or resource selection models, these approaches are often used to predict biodiversity under projected future change (Pearson and Daswon 2003, Thuiller 2007). Under three NASA-funded projects, we have evaluated the utility of NASA products for improving these models. We found that MODIS-derived estimates of primary productivity, vegetation lifeform, and land cover, and LIDAR-derived estimates of canopy structure were significant predictors of bird species richness and species abundances (Phillips et al. 2008, *in press*, Hansen et al. *in review*, Goetz et al. 2010a). We used the resulting functions to predict the spatial distribution of bird diversity across North America under current biophysical conditions and land use (Hansen et al. *in review*, Goetz et al. *in prep*.). One of our co-I team used ecophysiological models for reconstructing past and ensemble forecasting future responses of species to climate change (Monahan and Hijmans 2008, Tingley et al. 2009) (Fig 3).

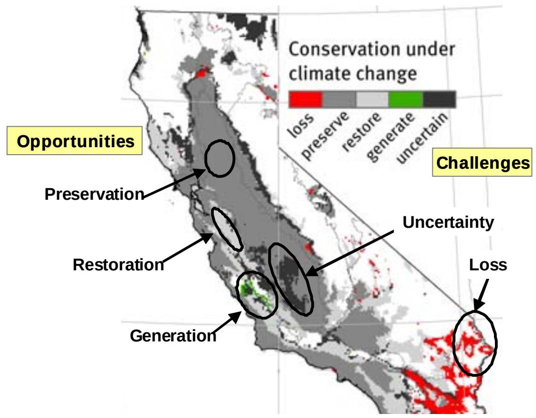

Fig 3. One approach for linking model-based climate and land use change forecasts to resource management, here illustrated for the Snowy Egret in California out to the year 2100. From Monahan et al 2008.

He also addressed issues of uncertainty (Parra and Monahan 2008), including challenges associated with predicting into no analog climates (Monahan 2009). This work emphasized relevance to resource managers. We learned managers were more likely to embrace forecasting results if: complex model ensembles are consolidated into easily-interpreted maps; spatially-explicit estimates of uncertainty are depicted; emphasis is placed on scenarios designed to bracket a range of expected outcomes; model results are presented as one of many decision-support tools

2.4 Quantification of Connectivity

Connectivity is a complex ecological property that is expressed at a hierarchy of spatial scales. Our team has evaluated connectivity of "natural landscapes" across the US (Theobald 2010), forests in the eastern US (Goetz et al. 2009a, Jantz and Goetz 2008), and individual animal species within regional landscapes (e.g., wolverine, elk, lynx). We have also used and tested the leading methods of quantifying connectivity to determine the pros and cons of emerging methods, including least-cost, graph theory, landscape flow, and Circuitscape (Theobald 2006, *in prep*).

2.5 Ecological Forecasting Using TOPS

TOPS (Nemani et al., 2008) is a modeling framework that automatically integrates and preprocesses Earth Observation Satellite data fields so that land surface models can be run in both near real-time and used to generate short and long-term forecasts. TOPS includes multiple component models, and for operational modeling and monitoring a modified version of the BIOME-BGC model (Thornton et al., 1997, 2005) is used to estimate various water (evaporation, transpiration, stream flows, and soil water), carbon (net photosynthesis, plant growth) and nutrient flux (uptake and mineralization) processes. In addition, TOPS has recently been extended to incorporate multiple biogeochemical cycle models, including the Lund–Potsdam–Jena Dynamic Global Vegetation Model (LPJ, Sitch et al., 2003). Using inputs from satellites, weather networks, and general circulation models (GCMs), TOPS drives these models to forecast variables at a variety of spatial scales, from global primary productivity anomalies at 0.5 x 0.5-degree resolution to local estimates of ecosystem variables at resolutions as fine as 250m. At each spatial resolution, TOPS uses different sources of satellite data (Ikonos to MODIS) and meteorological data (weather station to global atmospheric model outputs). TOPS has provided data that has resulted in more than 50 published scientific studies since 2003 (ecocast.arc.nasa.gov/pubs/pbs.php), and has supported eight NASA Applied Science funded projects to date. As part of the PALMS effort, for example, we conducted a series of TOPS runs for Yosemite National Park utilizing the downscaled World Climate Research Program (WCRP) Coupled Model Intercomparison Project (CMIP3) climate scenarios (Maurer et al., 2007) to drive the Biome-BGC component model within TOPS for the period from 1950-2100 to evaluate ecosystem conditions including measures of hydrologic response and impacts to vegetation productivity within Yosemite (Nemani et al., 2008) (Fig 4).

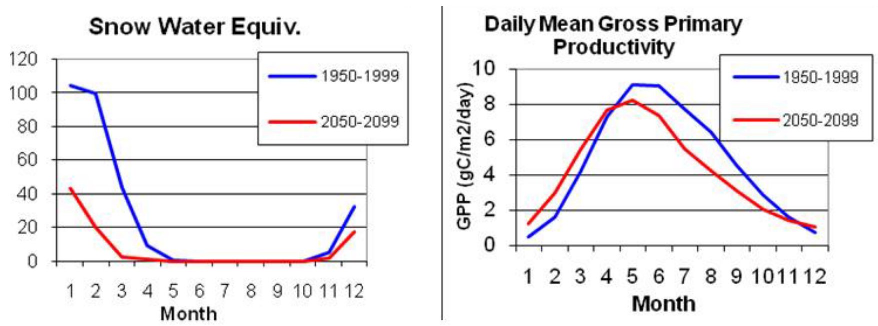

Fig 4. TOPS predictions for two ecosystem processes in Yosemite National Park (Nemani et al., 2008).

2.6 Integration of Land Use Change and TOPS

The Spatially-Explicit Regional Growth Model (SERGoM) characterizes land use change based on housing density (Theobald 2005). SERGoM forecasts housing development by establishing a statistical relationship between neighboring housing density, population growth rates, and transportation infrastructure. The model is dynamic in that as new urban core areas emerge, the model re-calculates travel time from these areas. Five main input spatial datasets are used: a) 2000 Census Bureau data on the number of housing units and population by census block; b) undevelopable lands data on land ownership based on an updated of the Conservation Biology Institute's PAD v4 database (CBI 2008); c) road, land cover (NLCD 2001), and groundwater well density data (to allocate the location of housing units within a block); d) county population projections drive the growth forecasts; e) commercial/industrial land use data mapped from NLCD 2001. SERGoM has been used, e.g., in an integrated assessment under a series of IPCC scenarios based on socioeconomic storylines (Leinwand et al. in press).

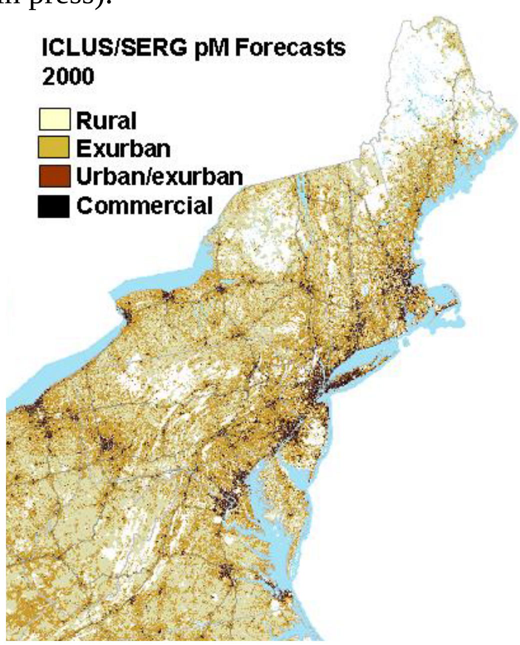

Fig 5. Housing density classes in 2050 for the A1 SRES scenarios for a portion of the northeastern US, from SERGoM.

SERGoM and TOPS were integrated in recent work supported by the NASA LCLUC program to model mitigation of climate and land use change impacts on hydrology and carbon cycles in the eastern U.S. (Goetz et al., 2009b). Nine climate scenarios from the WCRP CMIP3 data set and three land use scenarios from SERGoM were used to drive TOPS from 2000 to 2100 to evaluate both independent and synergistic impacts of climate and land use change (Fig 5). Results from related work using TOPS show that both Biome-BGC and LPJ match the MODIS GPP/NPP estimates and observed fluxes from Fluxnet sites (Wang et al., 2010). As part of this project, we will expand the science results from the study for the eastern U.S., and extend the geographic domain to include the western U.S.

3. Proposed Work

The proposed project is designed to enable progress on the start-up activities of the LCCs (e.g., years 1-4), by developing and testing a process on NPS lands that will inform NPS adaptation planning and serve as a model for the LCCs. The approach is a telescoping one where more primary steps are done across the LCCs and higher order steps are done for the focal NPS PACEs. We will first develop basic biophysical data sets. Best current knowledge will then be used to hindcast and forecast drivers and ecological responses. These ecological responses will include ecological processes and "coarse filter" aspects of biodiversity. Uncertainty in these predictions will be included in the vulnerability assessments for the NPS PACEs. Both vulnerability and management feasibility will be used to guide the assessment of management options. An illustrative adaptation strategy will be developed for each NPS PACE for a response variable deemed of high priority. The data, methods, models, and results will be transferred to the collaborators to enhance the decision-support capacities of the NPS and LCCs.

3.1 Study Areas

The project will focus on the Rocky Mountains ecoregion of the GNLCC and the mountainous portion of the ALCC (Fig 6). These areas were selected for several reasons. (1) Both have high conservation value. The GNLCC includes some of the most intact and functional ecosystems in the US (GNLCC Implementation Plan 2010). It includes vast public lands, low rates of development, and ecological processes such as animal migrations that are expressed over large spatial scales. The ALCC harbors many endemic species and is one of the most biologically diverse areas in the US (ALCC Brief 2010). It is dominated by private lands with high human population densities and more intense land uses (see section **2.2**). (2) Warming in the past century has been relatively rapid in both LCCs and these LCCs center on north/south tending mountain ranges, which present unique challenges and opportunities for climate change adaptation. (3) These LCCs encompass a wide range of land management partners (e.g., NPS, FWS, BLM, USFS), who will benefit from the project. (4) The project team has made previous investments in these regions. Most of the local NPS I&M networks participated in PALMS study, allowing the proposed study to build on a solid foundation of collaboration. Co I. Olliff is co-lead for the GNLCC and a Steering Committee Member for the ALCC, allowing results of this project to be directly integrated into development of these LCCs. Finally, the co I.s have experience in ecological research in these regions. In addition to the LCCs, the project will focus on two additional and highly relevant spatial scales: (1) potential dispersal zones, which are larger than LCCs and designed to capture the geographic range of expected biological movements under future climates, and (2) NPS PACEs within the LCCs, which will provide effective case studies for vulnerability assessment and management applications. These parks include Glacier, Yellowstone, and Rock Mountain National Parks in the GNLCC and Delaware Water Gap NRA and Shenandoah and Great Smoky Mountains National Parks in the ALCC.

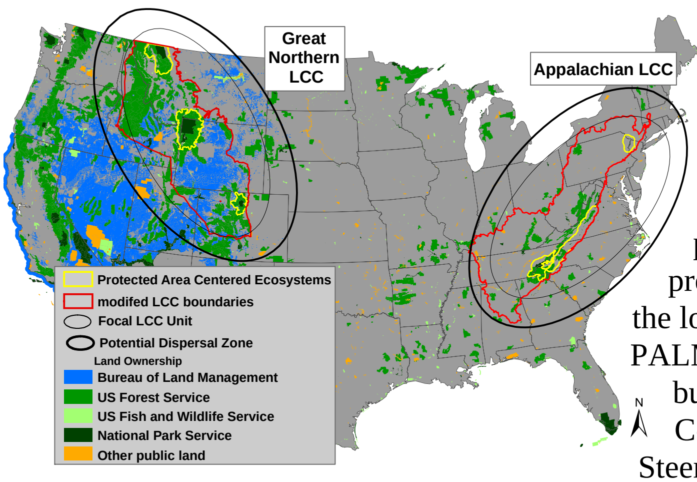

Fig 6. Proposed study area.

3.2 Ecological Hindcasting and Forecasting

3.2.1 Indicators and Modeling Approach

The NPS I&M has identified a suite of physical, chemical, and biological indicators that characterize "vital signs" to evaluate status and trends in park condition (Fancy et al. 2009). We have identified a list of indicators for this project that both can be generated using NASA resources and are priorities to the NPS I&M Networks and LCCs (Appendix 1).

We will follow and expand upon the modeling methodology utilized in the eastern U.S. (section **2.6**). The TOPS runs will use both the Biome-BGC and LPJ component ecosystem models. Biome-BGC will be used primarily to assess impacts on vegetation productivity, phenology, runoff, and snow dynamics, while LPJ will be used to model potential shifts in plant lifeforms and changes in fire frequency and intensity. These ecosystem models will be driven by the WCRP CMIP3 downscaled IPCC Fourth Assessment Report (AR4) climate scenarios (Maurer et al., 2007) and SERGoM land use changes scenarios. The data provided by these modeling experiments will provide quantitative measures of current and future ecosystem states that will be used to assess the potential vulnerability of ecosystems and species habitats within the LCCs to climate and land use change impacts (Fig 7).

The subset of WCRP CMIP3 and land use scenarios of highest interest to the NPS and LCCs will be determined in a workshop with collaborators. Our target is 2 climate scenarios from 3 GCMs (e.g., GFDL, GISS, and CCSM), 3 land use scenarios, and the 2 ecosystem models for a total of 36 model scenarios. TOPS incorporates the WRCP CMIP3 multi-model dataset (Maurer et al., 2007) downscaled to a resolution of 1/8 degree for the US using the methodology of Wood et al. (2004). This Bias-Corrected Spatial Disaggregation method downscales the climate-model outputs in both spatial and temporal dimensions, and preserves statistical characteristics (e.g., the covariance structure of temperature and precipitation fields) critical for simulating ecosystem processes. We will regrid the 1/8 degree scenarios onto a 1-km^2 grid as

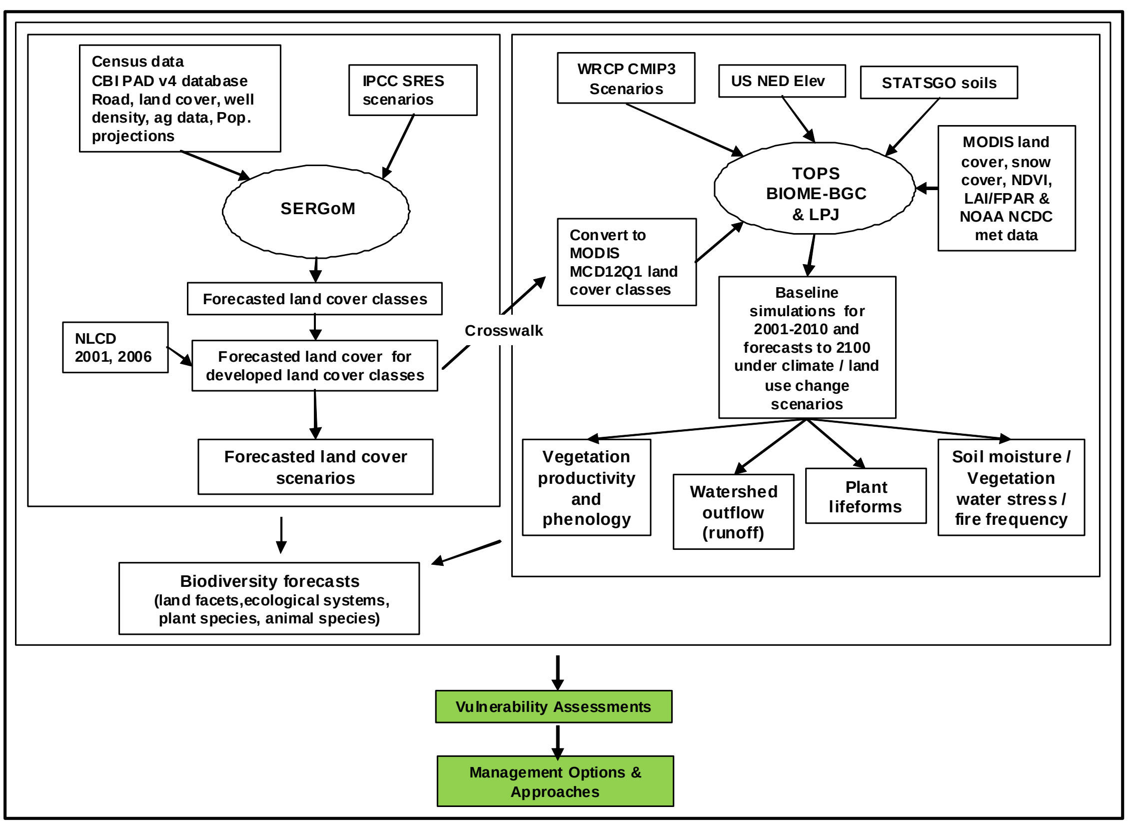

Fig 7. Overview of the components and data flow for the proposed modeling effort and project.

required for this project.

We will divide the runs into two time periods: a baseline period spanning 2001-2010, and a forecast period spanning 2010-2100. Runs for the baseline period, will be driven by TOPS in both prognostic and diagnostic modes. In diagnostic mode, TOPS utilizes interpolated meteorological surfaces from the Surface Observation Gridding System (Jolly et al., 2005) and MODIS data including observations of snow cover, leaf area index, NDVI, land cover, and land surface temperature to drive the component models. In prognostic mode, the various photosynthetic and nutrient cycling processes are simulated by the model without integration of satellite inputs, and the downscaled climate change scenarios are used to drive the model. A comparison of estimates of gross primary productivity and streamflow from the prognostic and diagnostic simulations for the baseline period will be made against observations from the USGS streamflow gauges and U.S. Fluxnet sites to characterize (1) uncertainty inherent in the model simulations in diagnostic mode, and (2) the additional uncertainty introduced when the models are run in prognostic mode and driven by the climate scenarios. Land cover data will be updated on a decadal timestep using the approach described below. Outputs from SERGoM will be crosswalked to the MODIS MOD12Q1 Type 3 land cover (LAI/fPAR biome type) and LPJ lifeforms.

This modeling will require significant compute resources which will be provided by the NASA Earth Exchange (NEX). Through the NEX project (http://nex.arc.nasa.gov), TOPS has also been implemented in a supercomputing environment at the NASA Advanced Supercomputing facility. NEX combines state-of-the-art supercomputing, Earth system modeling, workflow management, NASA remote sensing data feeds, and a collaborative networking platform. Through NEX, the proposed project will have access to the full range of necessary datasets and compute resources to achieve the project objectives.

3.2.2 Land Use Change

Decadal hindcasts and forecasts of land use change will be done with an enhanced version of the SERGoM v1.2 model (US EPA 2009). Updates of various input data sets will be used, especially 2010 US Census block-level housing data, developable lands from the Protected Areas Database-US v1.1 (CBI edition), groundwater well locations, and potentially developed areas from more recent land cover data sets (e.g., NLCD 2006; GAP). The enhanced model will add agriculture (cropland, rangeland) to the land use classes previously used (commercial/industrial, urban, suburban, exurban). Forecasts for 2010 to 2100 will be developed using historical transition probabilities (for two time periods 1990-2000 and 2000-2010) calculated at both macro (county to state) and micro (neighborhood to pixels) analysis levels (Verburg et al. 2004) using a hierarchical transition probability framework (Johnson et al. 1999). Macro-level probabilities between classes will be calculated from USDA NRCS Natural Resource Inventory land use classes (available from 1987-1997, and 2007 at the state level) and urban categories weighted to meet population increases (from 1990, 2000, and 2010 census). We will also examine the USGS Land Cover Trends data sets that provide ecosystem-level estimates of cover changes (e.g., agriculture to urban developed). Micro-level probabilities will be calculated using detailed land use layers (90 m) computed for 1990, 2000, and 2010 using existing SERGoM methods. To complement our forecasts (2010-2100), we will develop land use hindcasts for 1940 to 1980 by downscaling US Census of Agriculture estimates of cropland and rangeland and by developing a set of spatially-explicit rules that start from current (1990, 2000) land use patterns and incorporate water infrastructure (irrigation canals) and soils data (STATSGO). We will conduct an accuracy assessment for the 1990 and 2000 land use layers using data from the Land Use Change Inventory Database we are developing under separate funding. The resulting matrix will be used to examine the sensitivity of the resulting forecasts (after Pontius and Li 2010).

3.2.3 Biodiversity

While the LCCs will be assessing the full hierarchy of biodiversity, we will focus on the coarser biodiversity levels (Hunter et al. 1988) in order to make initial progress. These will include land facets, vegetation lifeforms, and ecological system types. Such "coarse-filter" approaches to conservation planning are known to capture up to 80-90% of species within a planning area (Noss 1987). Moreover, these coarser levels are often key predictors of species distributions. We will illustrate the utility of these coarser levels for modeling two animal species known to be sensitive to climate and land use change: brook trout (ALCC) and wolverine (GNLCC).

3.2.3.1 Land Facets. Hunter et al. (1988) emphasized that a diverse representation of physical environments in a network of reserves increases resilience under climate change. Land facets, "recurring landscape units with uniform topographic and soil attributes", are determinants of biodiversity and connectivity within networks of reserves (Beier and Brost 2010). We will develop an indicator that estimates biodiversity responses to climate and land use change as a function of the distribution and connectivity of land facets. Typically these units are generated by intersecting a series of classed data layers such as elevation zones, bedrock geology, and topographic feature (e.g., ridgetop, steep slope, etc.). We will explore generating these units using a multi-variate clustering method (e.g., k-means or CART modeling techniques; Hargrove and Hoffman 2005) based on measures of elevation, topographic wetness adjusted for solar insolation, and major soil types (SSURGO) using high resolution data (10-30 m DEMs).

3.2.3.2 Lifeforms. The LPJ model was used to assess the potential changes in vegetation lifeforms globally at a spatial resolution of 0.5^0 under climate change (Lucht et al. 2006). Using the TOPS framework, we will drive LPJ with the finer scale WCRP CMIP3 data to produce outputs at a spatial resolution of 1 km to assess potential shifts in distribution for the seven non-tropical vegetation lifeforms parameterized in LPJ (Sitch et al., 2003). These include for example temperate needle-leaved evergreen, broad-leaved summergreen, and herbaceous classes. These lifeforms are coarser than the ecological system types more commonly used by resource managers. We will use the LPJ lifeform outputs primarily to validate our statistical projections of ecological system types.

3.2.3.3 Ecological Systems and Dominant Plant Species. Ecological system types are widely used in conservation planning because they contain valuable resources and because they represent key elements of habitat for many species (Glick and Stein 2010). We will use the classification of Comer et al. (2003), which defines terrestrial ecological systems as groups of plant community types that tend to co-occur within landscapes with similar ecological processes, substrates, and/or environmental gradients. Classes with high aerial extent, for example, are Northern Rocky Mountain dry-mesic montane mixed conifer forest in the GNLCC (50%) and Appalachian (Hemlock)-Northern Hardwood Forest in the ALCC (10%).

Within each NPS PACE, we will select for analysis the subset of ecological systems (ca 5) that are identified as the highest priorities in workshops with the collaborators. We will model the potential future locations of these ecological systems using statistical models parameterized through analyses of the biophysical envelope of current locations of these ecosystems. Current locations will be derived from (http://www.natureserve.org/explorer/servlet/NatureServe). Candidate biophysical predictors will include the climate, ecosystem process, and land facet indicators from Appendix 1. We anticipate that TOPS products such as phenology, snow cover, runoff, soil moisture and primary productivity, which have not been previously widely available at a resolution of 1 km, will improve the strength of the statistical models (see section **2.3**). The modeling techniques will include regression-based model selection with control of spatial autocorrelation using mixed models and Random Forests, with which we have considerable experience (e.g. Phillips et al. 2008, Goetz et al. 2010a).

As a means of validation, we will also model the habitat suitability of plant species that are dominant in each ecological system. Following the methods of Iverson et al. (2008) and McKenny et al. (2007), we will used field data from the USFS Inventory and Monitoring Program to develop statistical models for dominant plant species. Correspondence in the predictions from the vegetation lifeform, ecological systems, and dominant plant species modeling will be used to quantify uncertainty.

3.2.3.4 Brook Trout. Brook trout are a species of special concern in eastern parks because they are largely confined to upper headwater streams by intolerance of warmer waters and constraints to dispersal into mainstem reaches. Hence, connectivity and gene flow among subpopulations is highly constrained, reducing population viability. This condition is expected to become more limiting under future climate and land use change (e.g. Clark et al. 2001). We will partner with additional parties to model brook trout impacts. The Nature Conservancy's Eastern U.S. Freshwater Program is assembling data on obstructions and watershed condition and developing appropriate evaluation criteria to identify priority river and stream networks. Our effort would also benefit from (1) use of data compiled the Eastern Brook Trout Joint Venture, which includes information on species status at the HUC 11 catchment scale, and (2) data being collected by the USGS on brook trout habitat in small headwater reaches. Together these efforts provide the *in situ* data needed to develop and assess conditions first under current and then future hydrologic conditions (as predicted by TOPS). The proposed work will build upon capabilities developed to predict the richness and sensitivity of indicator stream biota (Goetz and Fiske 2008, Goetz et al. *in press*).

3.2.3.5 Wolverine.

The wolverine, nearly extirpated from the U.S. by 1920, has recovered to some extent in the northern Rockies, but is under consideration for listing as an endangered species. The species occupies subalpine forests with persistent snow cover and is dependent on long-distance dispersal among mountain ranges (Copeland et al. 2010). Individuals are known to have dispersed >800 km to unoccupied habitats in Colorado and California (e.g, Inman et al. 2004). Because of sensitivity to climate change, the GNLCC includes the wolverine among its species of concern. We propose to model wolverine habitat connectivity among patches of suitable habitat and to quantify landscape permeability for within-home-range and dispersal movements throughout the GLCC. We will seek opportunities to validate the habitat connectivity model by comparison with a published genetic distance model from the Northern Rockies (Schwartz et al. 2009) and detailed movement models from an ongoing GPS and telemetry studies (Inman et al. 2007), and will continue collaboration with key partners, including the Wildlife Conservation

Society. Using the climate, land use, and ecosystem process indicators developed for this project, we will examine how landscape permeability is likely to change due to the expansion and intensification of mountain valley development, increasing forest fire and insect disturbance, and declining snowpack levels. These models will be used to identify likely climate refugia, to prioritize suitable sites for habitat protection or population enhancement, and to evaluate wolverine management options across multiple jurisdictions. In particular, forecasting the coupled effects of climate and land use change will be useful for restoration efforts the Southern Rockies, and to inform the USFWS' listing and critical habitat decisions.

3.3 Vulnerability Assessment

This assessment will provide objective information on components of vulnerability and uncertainty for the indicators that will be used to rank priority for research/management. Three components of vulnerability will be considered to varying degrees (Fig 8). Exposure will be the degree of change in climate and land use (Table 1), which are considered drivers of ecological processes and biodiversity. Sensitivity of ecosystem processes will be evaluated as change in ecosystem processes as a function of change in exposure. Potential impact on ecosystem processes will be quantified as the actual predicted change, which integrates exposure and sensitivity. Similarly, sensitivity of biodiversity indicators will be evaluated as change in biodiversity as a function of degree of change in exposure in climate, land use, and ecosystem process. Potential impact on biodiversity will be quantified as the actual predicted change, given the predicted changes in the three drivers. Adaptive capacity is more difficult to capture with these indicators. We will consider connectivity as one component of adaptive capacity, the degree of difficulty of ecological system types (based on expert opinion) and species (based on connectivity analyses) reaching newly suitable locations. For each level of the assessment, uncertainty will be represented as degree of agreement among scenarios. Expert opinion will be used to integrate these results and assess vulnerability. Both vulnerability and uncertainty will be used by collaborating experts to assess priority for research and management. The assessment will be done for the NPS PACEs for the two time periods.

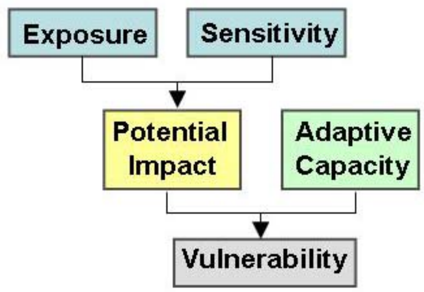

Fig 8. Key components of vulnerability, illustrating the relationship among exposure, sensitivity, and adaptive capacity. From Glick and Stein 2010.

The primary means of analysis of exposure, sensitivity, and potential impact will be simple univariate summaries of rate and degree of change for the indicators. For the future period, where alternative scenarios are forecast, these plots will be expressed as means, medians, ranges, variability across the scenarios and degree of agreement among scenarios. These univariate plots will allow the science and management experts to weigh change in

Table 1. Structure of the vulnerability analyses.

Category / Indicator	Quantitative Analysis[1]		Expert opinion[2]
	Time Period		
	past-2010	2010-2100	
Climate and Weather	Exposure		Vulnerability Priority Ranking
Land Cover and Use			
Ecosystem Process	Sensitivity Potential Impact		
Land facets	Sensitivity Potential Impact Adaptive capacity		
Ecological systems			
Dominant plant species			
Animal species			

[1]Uncertainty will be quantified for each indicator and period.
[2]Priority ranking and vulnerability will be assessed for each indicator and period

each indicator in their ranking of vulnerability. Because climate, land use, and ecosystem processes are each represented by several variables, we will additionally use ordination and classification techniques to quantify multivariate axes of change and group the land management units along these axes (see section **2.2**). At our annual workshops, the collaborators will prioritize importance for research/management of each indicator based on vulnerability and uncertainty. The use of expert opinion in addition to quantitative analyses is consistent with previous successfully vulnerability assessments (e.g., Ervin 2003a,b).

3.4 Evaluation of Management Options

The biological indicators within the NPS PACEs will be categorized based on priority ranking (section **3.3**) and management feasibility. The collaborators will place each indicator into one of three categories: 'Low Risk', 'Manageable', or 'Lost Cause' (Fig 9). This framework is sensible for management because it recognizes the limits of our ability to control natural systems in the face of large scale environmental change. For example, certain high-elevation species like the pika maybe lost under climate change irrespective of any reasonable management action (Ruhl 2008), while other urban adaptable species like Nuttall's woodpecker may persist irrespective of environmental change (Tingley et al. 2009). We will rely on our collaborators to ensure that proposed management options are relevant and linked to NPS policy and planning.

	Low Risk	**Manageable**	**Lost Cause**
Management	None needed	Helpful	Not helpful
Change	Little	Moderate	High
Vulnerability	High	Moderate	High
Resiliency	High	Moderate	low
Adaptability	High	Moderate	low

Fig 9. Classes and criteria for categorizing biological indicators for management.

For indicators deemed 'manageable', four basic types of management options are envisioned: (1) reduce existing stressors, (2) manage for ecosystem function, (3) protect refugia and improve habitat connectivity, and (4) implement proactive management and restoration. Choice of appropriate management option will depend on the nature of the vulnerability. For example, indicators that have suffered historic declines due to anthropogenic influences may require proactive management and restoration, while others that remain stable and viable may benefit from the protection of refugia and improvements to connectivity. This categorization of biological indicators and development of management options will be done at the third workshop with collaborators.

3.5 Illustration of a Multi-scale Management Approach

We will illustrate multi-scale management plans for the NPS PACEs and a handful of biological indicators that are targeted by each LCC. These plans will be guided by the DOI Adaptation Strategy (US DOI 2009) (Fig 9). The approach here is to create a spatial vision for achieving the management options. Central to this vision is the creation of maps that clearly identify opportunities for preservation (areas where the indicator has persisted over time and is expected to continue to persist in the future), restoration (areas where the indictor occurred historically prior to anthropogenic influences and could recolonize with proactive management), and generation (areas where the indicator has never occurred in recent times but could in the future given climate and land use forecasts) (see section **2.3**). Additionally, the maps will deliver two other types of information that are equally relevant to enacting management: loss (areas where the indicator is not expected to persist in the face of environmental change) and uncertainty (areas where we have low concordance or confidence in our predictions).

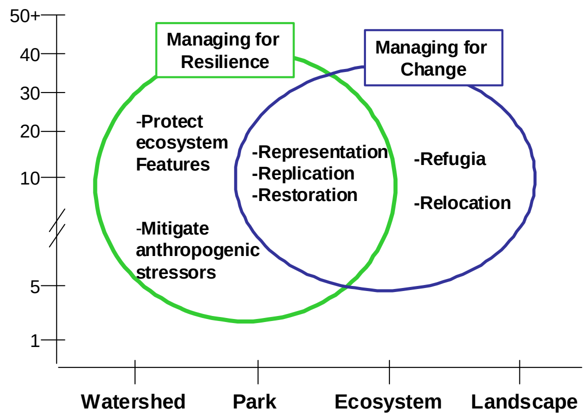

Figure 10. Adaptation strategies linked in space and time. Modified from US DOI in prep.

3.6 Decision Support

We will transfer the forecasting tools, data, and analytic methods described above to the NPS and interested LCC parties. This transfer will be done by the three primary means successfully used in the PALMS project. TOPS outputs will be served via the internet-based interface Ecocast (and component data services) and databases maintained on NPS I&M servers. Our methods will be documented in the format of NPS I&M (SOPs). Workshops and training sessions will teach collaborators to develop, analyze, and/or interpret the products.

3.6.1 Delivery of Outputs

To facilitate streamlined access to information produced by TOPS for the PALMS project, we have built the TOPS-NPS Ecocast Data Gateway. Through this interactive web application, users can easily visualize current or historic park conditions and query the map for specific parameter values. Data are organized around monitoring objectives, and users can select specific dates of interest. This ability to examine a parameter's behavior in both space and time can assist NPS personnel in developing an understanding of emerging patterns in park conditions. In addition, users can obtain access to automatically calculated data layers and maps for long-term trends and persistent anomalies to assist management personnel in quickly identifying emerging patterns in ecosystem conditions. Ecocast has been implemented for the Delaware Watergap and Upper Delaware Scenic River, Yellowstone/Grand Teton, and Rocky Mountain National Parks. To facilitate direct data access, we have also implemented an OPeNDAP data server and we are in the process of implementing an ArcGIS Server to facilitate direct data retrieval from commonly used geographic information system tools within U.S. land management agencies. In the proposed project, we will expand implementation of Ecocast to remaining focal parks and use existing Ecocast data services to distribute data to LCC partner agencies. In addition to the TOPS data delivered through Ecocast, we will serve all data and analyses through the NPS I&M website. These will be compiled and described within an ArcGIS geodatabase. While this database will not be as user friendly as Ecocast, collaborating spatial analysts will be able to access and use these products across the I&M program.

3.6.2 SOPs

NPS I&M networks develop peer-reviewed monitoring protocols that conform to standards in Oakley et al. (2003). These protocols consist of a narrative that describes the indicator and why it’s important, and a set of Standard Operating Procedures (SOPs) that document what is required to measure the indicator, analyze the data, and report the results. In the proposed project, we will expand the SOPs we developed under the PALMS project to include the additional methods proposed herein. These can found at the I&M PALMS web site (see above). Some methods for hindcasting and forecasting require substantial expertise, specific software, or processes that may require external contracts (e.g., use of sophisticated ecological models) as noted on Appendix 1. By producing SOPs for each project, we are explicitly recognizing and conforming to the existing culture and processes within NPS. These will also be useful to other LCC partners in the future.

3.6.3 Workshops and Training Sessions

We have learned that sustained interaction with collaborators is essential to successful decision-support. Thus, we will convene one major workshop/training session each of year with the project. Participants will be the NPS collaborators and interested parties from other agencies within each LCC. Topics will be: Year 1 – introduction, project scoping (e.g., selection of dispersal area boundaries, ecosystem types, dominant plant species) and review of past decision support approaches; Year 2 – review/interpret initial trends in indicators, evaluation/training on initial SOPs; Year 3 – conduct vulnerability assessment, evaluation/training on near final SOPs; and Year 4 – develop/evaluate management options and applications, final training, synthesis.

3.7 Expected Results and Broader Implications

Overall, we expect that the project will provide a direct means for the NPS to incorporate NASA data and products into their adaptation strategy planning during the initial and formative years of the LCCs. More specifically, the project will: help to develop an operational framework for adaptation strategy planning; compile key data sets such as downscaled climate scenarios, land use, and time series of historic biodiversity data; use ecological forecasting tools to project past and potential future trends in key indictors; assess vulnerability of ecosystem processes, ecological systems, and illustrative species to climate and land use change; and demonstrate the development and implementation of management options for NPS PACEs. The timing of this project is critical as the NPS is soon to release the NPS Climate Change Response Strategy and is beginning to develop an implementation plan to provide guidance to field managers on incorporating the four legs of the strategy—Science, Adaptation, Communication, and Mitigation—into operational management. The collaboration from this project has already informed the implementation planning and can serve as a case study for NPS Climate Change Adaptation. The transfer of the technology underlying the project should enhance the decision support capabilities of the NPS during the project and subsequently. The project may also serve as a model for adaptation by additional LCCs as they develop.

The project is also expected to make contributions to conservation science. The merging of the TOPS models of ecosystem processes with the SERGoM model of land use change is expected to have widespread application in global change science. Our hierarchical approach to representing biodiversity will advance the coarse to fine filter approach to analyzing biodiversity. Thirdly, the project will evaluate the extent to which habitat suitability models may be improved by inclusion of TOPS outputs such as phenology.

The project has high potential to contribute to public education on global change science and management. The interpretive staffs of the NPS collaborators provide educational programs to millions of park visitors annually and reach millions more through web sites and other types of outreach (e.g., http://www.nps.gov/climatefriendlyparks/. The concrete examples of climate and land use change, biological response, and adaptation strategies emerging from the project should be highly useful in these educational programs.

4. Management Plan

4.1 Team Roles and Management Structure

Dr. Hansen will direct the project; focus on the ecological system and plant species modeling and the vulnerability assessment, and participate in each of the project elements. Dr. Goetz will focus on land use and hydrologic change in the east and on brook trout modeling, and be the liaison with the eastern NPS I&M networks and ALCC. Mr. Melton (and Dr. Wang) will focus on the TOPS modeling and on decision support and data distribution via the TOPS Ecocast data services. Mr. Melton will also work with the other P.I.s on selecting IPCC scenarios for the project and application of the model results to support vulnerability assessments and management planning for the LCCs. Dr. Monahan will focus on the development of management options applications in the NPS PACEs. He will also serve as the overall liaison with the NPS I&M program. Dr. Nemani will have an advisory and supervisory role in the TOPS modeling and participate in project analysis and synthesis. Mr. Olliff will co-lead with Dr. Monahan the development of management options applications and be the primary liaison the western NPS I&M networks and GNLCC. Dr. Theobald will focus on forecasting of land use change, work with Dr. Goetz on connectivity of biological elements, focus on the hydrological modeling along with Goetz and Melton, and lead the wolverine modeling. Each of the NPS collaborators will be the primary representatives of their networks and parks and participate fully in project planning, implementation, training, and outreach.

4.2 Deliverables and Timelines

SCHEDULE	Year 1		Year 2		Year 3		Year 4	
Task	Q1-Q2	Q3-Q4	Q1-Q2	Q3-Q4	Q1-Q2	Q3-Q4	Q1-Q2	Q3-Q4
Study Design								
Refine dispersal zone, ecological systems types, dominant plant species	■							
Forecasting								
Compile core data for forecasting	■							
Select IPCC scenarios	■							
Validate Models		■	■					
Climate/land use ensemble forecasts		■	■	■				
Compile biodiversity data	■	■						
Analysis, validation, forecasts		■	■	■				
Illustrative species modeling		■	■	■				
Vulnerability Assessment								
Analyze trends in indicators				■	■			
Vulnerability assessment					■			
Management options								
Develop options						■	■	
Evaluate options							■	
Management approach								
Design approach							■	■
Decision Support								
SOPs			■	■	■	■	■	
Workshops and training	■		■		■		■	
Serve data/products				■	■	■	■	■
Outreach								
Reporting, publishing, outreach	■	■	■	■	■	■	■	■

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