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TESTING THE ROBUSTNESS OF MANAGEMENT DECISIONS TO UNCERTAINTY: EVERGLADES RESTORATION SCENARIOS

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Abstract. To effectively manage large natural reserves, resource managers must prepare for future contingencies while balancing the often conflicting priorities of different stakeholders. To deal with these issues, managers routinely employ models to project the response of ecosystems to different scenarios that represent alternative management plans or environmental forecasts. Scenario analysis is often used to rank such alternatives to aid the decision making process. However, model projections are subject to uncertainty in assumptions about model structure, parameter values, environmental inputs, and subcomponent interactions. We introduce an approach for testing the robustness of model-based management decisions to the uncertainty inherent in complex ecological models and their inputs. We use relative assessment to quantify the relative impacts of uncertainty on scenario ranking. To illustrate our approach we consider uncertainty in parameter values and uncertainty in input data, with specific examples drawn from the Florida Everglades restoration project. Our examples focus on two alternative 30-year hydrologic management plans that were ranked according to their overall impacts on wildlife habitat potential. We tested the assumption that varying the parameter settings and inputs of habitat index models does not change the rank order of the hydrologic plans. We compared the average projected index of habitat potential for four endemic species and two wading-bird guilds to rank the plans, accounting for variations in parameter settings and water level inputs associated with hypothetical future climates. Indices of habitat potential were based on projections from spatially explicit models that are closely tied to hydrology. For the American alligator, the rank order of the hydrologic plans was unaffected by substantial variation in model parameters. By contrast, simulated major shifts in water levels led to reversals in the ranks of the hydrologic plans in 24.1–30.6% of the projections for the wading bird guilds and several individual species. By exposing the differential effects of uncertainty, relative assessment can help resource managers assess the robustness of scenario choice in model-based policy decisions.

Key words: Everglades restoration; habitat index models; relative assessment; resource management; scenario analysis; spatially explicit models.

INTRODUCTION

Contemporary social, economic, and political issues complicate the management of natural reserves. Policy makers must consider a diversity of stakeholders whose agendas encompass different, often conflicting priorities. Within the managed systems themselves, the contrasting needs of different species and habitats must also be accommodated in a dynamic balance. To cope with the political and practical realities of reserve management, resource managers use scenario analysis to compare the relative merits of different management plans. Alternative plans are then ranked according to a chosen criterion (e.g., Klenner et al. 2000). Scenario analysis and similar modeling approaches have become valuable tools in the planning process. But while modeling approaches can reduce uncertainty associated with differences in alternative plans or futures, decisions based on model output typically rely upon multiple uncertain assumptions whose validity often goes untested. We introduce an approach that uses relative assessment to test the robustness of management decisions to the kinds of uncertainties that are typical of models used in natural resource management. To illustrate our approach, we use two management alternatives that represent different plans for structural modifications in water delivery systems designed to regulate the hydrologic regime of the south Florida wetlands.

Resource managers commonly use computer models to simulate complex ecological systems (Dunning et al. 1995, Beissinger and Westphal 1998, DeAngelis et al. 1998, Groom and Pasqual 1998, Menges 2000, Jager and

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King 2004). Modeling allows researchers to address complex planning issues by projecting the effects of different policy decisions using specific performance criteria. Models designed to simulate large, heterogeneous systems can themselves be quite complex. Several modeling approaches (e.g., discrete or continuous dynamical systems, Markov chains, individual based methods, Bayesian models, and so on) may be combined in a hierarchical modeling framework that involves hundreds of parameters and a diversity of data types (e.g., DeAngelis et al. 1998, Gaff et al. 2000, Clark et al. 2004). Scenario analysis involves the direct comparison of projections based on different data sets or model formulations, each of which represents a different scenario. Scenario analysis has also been used to cope with uncertainty in the responses of ecological systems to changing management practices by simulating system responses under a range of plausible future conditions (Van der Heijden 1996, Bennett et al. 2003, Peterson et al. 2003). For example, Sala et al. (2000) used scenario analysis to evaluate the sensitivity of biodiversity projections to biome-scale changes in environmental conditions.

Uncertainty in model assumptions can arise for many reasons, such as incomplete knowledge of system processes and species dynamics, stochasticity in model inputs (e.g., weather patterns, mortality, and so on), complex model structure, and inaccuracy in the measurement of parameters (Conroy et al. 1995, Taylor 1995, Beissinger and Westphal 1998, Higgins et al. 2002). Additionally, errors associated with assumptions or subcomponent interactions can propagate during model runs, a problem that may be exacerbated as model complexity increases. Thus the assumptions that form an integral part of the modeling enterprise represent an important additional source of uncertainty. For example, the direct comparison of model projections assumes that modeling uncertainties do not interact differentially with alternative scenarios, and that the propagation of error is similar for each alternative. If untrue, the reliability of comparative approaches may change unpredictably with variation in parameter settings or input data (Mills et al. 1999, Saltelli et al. 2000). Therefore, the practice of assuming that scenarios respond similarly to uncertainty may leave policy decisions vulnerable to unforeseen ecosystem responses, even when a range of future conditions are considered.

Here we describe a relative assessment approach for investigating the effects of uncertainty on model projections. We define relative assessment as any technique that compares the relative differences in the output of models with respect to a specific assessment criterion. The assessment criterion provides a measure of the appropriateness of different model formulations or the suitability of alternative management scenarios, as determined by the needs of the researcher, the objectives of a stakeholder, or aims of the model. Several workers have used relative assessment to assess alternative population viability models (Ellner and Fieberg 2003, McCarthy et al. 2004) while Drechsler et al. (2003) employed a similar approach to compare metapopulation models. Saltelli et al. 2000 discussed statistical methods for uncertainty analysis and sensitivity analysis in the field of environmental risk assessment. Ours is the first example we are aware of that applies relative assessment to a complex problem in resource management.

Methods

As resource management comes to rely more on models to guide the planning process, managers must become adept at dealing with the uncertainty inherent in modeling approaches. Our objective in this paper is to introduce an approach that may be generally beneficial in comparisons of alternative management scenarios for natural systems. We demonstrate our approach using alternative hydrologic management plans drawn from the Comprehensive Everglades Restoration Plan (CERP; U.S. Army Corps of Engineers and South Florida Water Management District 1999). Specifically, our experimental goal was to determine whether the ranking of two alternative hydrologic plans changes in response to changes in model parameter values and input data.

General modeling approach

Our technique extends the typical approaches of scenario analysis by providing a scheme to determine the robustness of scenario rank order, relative to alternative model input data and assumptions. Let $i = 1, 2, \ldots, k$ indicate a collection alternative scenarios, each of which is defined by a particular collection of anthropogenic and environmental factors that affect the modeled ecosystem or a particular model configuration. Let P represent a particular configuration of the model, including the values of model parameters, specific assumptions and functional forms used. The anthropogenic and environmental factors are represented by E_j, $j = 1, 2, \ldots, n$, and can encompass a wide range of phenomena. For example the E_j's could represent a spatiotemporal sequence of rainfall or a temporal sequence of geographical information system map layers corresponding to fire events, and so on. The E_j's can also represent human actions that directly influence the ecosystem, such as hunting and hunting regulations or the stocking of a species being modeled. When the primary difference between scenarios are differences in the anthropogenic factors we refer to the scenarios as management plans.

Let $M_i(P, E_1, \ldots, E_n)$ for $i = 1, 2, \ldots, k$ be the output of a model which projects the response of natural system components under scenario i with model parameters P and environmental inputs E_j. These model outputs may be quite general such as spatiotemporal series associated with numerous ecosystem components. Suppose that a ranking of the scenarios is carried out based upon some

TABLE 1. Taxonomic groups, across-trophic-level system simulation (ATLSS) reporting units, and taxonomic subregions.

Taxonomic subregion	Species affected	ATLSS reporting unit
R1	American alligator, Snail Kite	water conservation areas 3A and 3B
R2	Snail Kite	water conservation areas 1, 2A, 2B
R3	American alligator	Shark River, NE Shark River, and Taylor Sloughs
R4	wading birds	central rookeries
R5	wading birds	southern rookeries
R6	Cape Sable Seaside Sparrow	core area
R7	Cape Sable Seaside Sparrow	western area
R8	Cape Sable Seaside Sparrow	eastern area
R9	white-tailed deer	Everglades National Park
R10	white-tailed deer	Big Cypress

Notes: The ATLSS reporting units were grouped into blocks according to habitat type (Fig. A1). Taxonomic subregions contain one or more blocks (defined in Fig. A1).

evaluation criteria and utilizing the results of the models, $\mathbf{R}(M_1(P, E_1, \ldots, E_n), \ldots, M_k(P, E_1, \ldots, E_n))$. Here $\mathbf{R}$ is a vector containing a permutation of the scenario indices, i, such that the first element of the vector is the index corresponding to the highest ranked scenario and the last element of the vector is the index corresponding to the lowest ranked scenario. The vector $\mathbf{R}$ provides a relative assessment of the various scenarios based upon given environmental inputs and model parameter assumptions.

We say that a relative assessment is robust to a particular variation in model parameters and/or environmental inputs if the variation does not change the ranking $\mathbf{R}$. That is, when the model results M_i are recomputed based upon a particular variation in the E_j and P, the rank order of the models in $\mathbf{R}$ does not change. Thus, robustness is a feature of the model assumptions, the level of variation applied to inputs and parameters, and the evaluation criteria incorporated in the vector $\mathbf{R}$ that determines the rank order of alternative scenarios.

Study system: Everglades Restudy area

To illustrate the relative assessment formalism we have developed, we consider the example of the restoration of the Florida Everglades. In this example, alternative management plans are principally distinguished by the identity of the hydrologic plan. We evaluated the impact of different hydrologic plans separately for each of four wildlife species and two wading bird functional guilds composed of the long-legged wading birds and the short-legged wading birds (Table 1). Hereafter we use the terms taxa and taxon as generic terms for the species and functional guilds listed in Table 1. We evaluated the six taxa independently within the entire Restudy area and within taxon-specific geographic subregions, which are defined in Table 1 and shown in Fig. A1 of the Appendix.

Management background

The Central and South Florida Project Comprehensive Review Study (U.S. Army Corps of Engineers and South Florida Water Management District 1999), "the Restudy," guides restoration efforts in south Florida, including Everglades National Park, Big Cypress National Reserve, and several management areas covering the historical Everglades (Fig. A1). The Restudy was initiated to determine the feasibility of altering the existing policy of South Florida water management to include greater emphasis on aquifer protection and ecosystem conservation (more information *available online*).[5]

Within the South Florida wetlands, geographic variation in water level is managed according to the design of the hydrologic management plan. The hydrologic management plan determines the location, timing, and rate of managed water releases in South Florida. To aid the process of deciding which hydrologic plan to implement, the South Florida Water Management District (SFWMD) developed spatially explicit models of surface hydrology that are parameterized with empirical data on the topography and hydrological dynamics across south Florida (Fennema et al. 1994, Walters and Gunderson 1994; see Plate 1). These hydrology models describe how water levels in different parts of the study area are affected by changing water release schedules. Here, stage height is used as a standard of measurement for surface water level. The hydrology models produce a map of stage heights in the management area that correspond to a specific hydrologic plan. Different hydrologic plans may produce different stage height maps given the same fixed sequence of rainfall inputs. The models also incorporate the effects of changes in precipitation but typically use historical rainfall data from the past 30 years (1965–1995) and do not vary this input. More details on the environmental setting and management background of the system are provided in the Appendix.

As part of the CERP planning effort, the U.S. Geological Service (USGS) established the across-trophic-level system simulation (ATLSS; DeAngelis et al. 1998) program to evaluate the ecological impacts of the alternative hydrologic plans that CERP considered. ATLSS developed a multi-model framework that

[5] ⟨http://www.evergladesplan.org/about/rest_plan_pt_03.aspx⟩

PLATE 1. Collecting hydrology and weather station data, Everglades National Park, Florida, USA. Photo credit: Everglades National Park Photo.

incorporates the output of multiple submodels, including spatially explicit species index (SESI) models. Each SESI model has parameters which govern the response of model components to input data, including parameters that account for interactions between inputs, and parameters that weight different subcomponents to provide an overall index of habitat potential. For details on the SESI models, see Curnutt et al. (2000). Separate SESI models were developed for specific taxa that were chosen to represent a range of biotic conditions and life histories (DeAngelis et al. 1998).

The SESI models take as input the stage height projections of the hydrology models. In addition to stage height, the inputs to the SESI models include vegetation maps of the study area compiled from satellite images provided by the Florida gap analysis project (Pearlstine et al. 2002). The output of each SESI model is a projection of the relative potential of wildlife habitat for breeding, foraging, or both, based on empirically validated demographic parameters. Because the hydrology model projections depend upon the particular hydrologic management plan being evaluated, the output of the SESI models provides a measure of the impact of alternative management plans on wildlife habitat potential.

In our uncertainty analysis, we considered two alternative 30-year hydrologic base plans, F2050 and D13R. The plan F2050 corresponds to maintaining the infrastructure as envisioned prior to CERP. The plan D13R was arrived upon through the Restudy. The stage height maps representing each alternative hydrologic plan were fed to the SESI models to generate a map of habitat potential for each taxon. The particular example we use here to illustrate a robustness analysis is rather complex, involving as it does regional analyses of biotic system changes over south Florida with a planning horizon of several decades and utilizing multiple species models. Our choice is motivated both by the desire to illustrate that a robustness analysis is feasible for even complex management situations such as Everglades restoration planning, and by the importance of carrying out such an analysis for a project estimated to cost at least $8 billion (U.S. Army Corps of Engineers and South Florida Water Management District 1999). While our focus here is on scenario analysis, the issues of model reliability and robustness that we address apply generally to the kinds of planning problems encountered in resource management.

Organization of spatiotemporal environmental data

The vegetation communities in South Florida occur as a patchy mosaic across the landscape. This mosaic is mirrored by the distribution of each taxon, creating a complex geographic pattern of species occurrence. To manage this complexity, we divided the landscape into 10 subregions that roughly correspond to the major habitat types found in the study area (Table 1, Fig. A1). These subregions are aggregations of 24 reporting units previously developed for the ATLSS project. The selection of the ATLSS reporting units was designed to accommodate the needs of local resource managers (DeAngelis et al. 1998). As a consequence, the ATLSS reporting units, and the 10 subregions used here, reflect to some extent the U.S. National Park Service boundaries, water management areas, and drainage basins. In our analysis, we generated a separate SESI value for each of the 10 subregions, as well as a separate value for the Restudy area as a whole, which includes the individual subregions as well as additional areas. Thus the subregions and the Restudy area represent the geographic units of our analysis.

We employed a spatial grid composed of 500×500 m cells to partition the study area into approximately 17 000 cells. For each taxon we calculated a separate SESI value for each grid cell. In our analysis, we used a spatiotemporally averaged SESI value to quantify the effect of each hydrologic plan on wildlife habitat potential. Each of the 10 different taxon-specific subregions described above contain a particular subset of the grid cells. For each subregion, we calculated the average SESI value over all of its associated grid cells.

The SESI values used in our analysis also incorporate temporal variation. For each year over the 30-year period of historical data, we calculated a separate spatially averaged SESI. Finally, we calculated the average of these 30 annual SESI values for each taxon and subregion. It was this spatiotemporally averaged SESI value that we used to rank the two alternative hydrologic management plans.

Experiments performed

We performed our uncertainty analysis using the spatiotemporally averaged SESI values computed as above, and three groups of experimental scenarios. For each experimental scenario we determined the effect of the change in parameters, or input data, on the rank order of the two alternative plans, compared to the ranks determined using standard parameters and inputs. The experiments therefore address two kinds of uncertainty: parameter uncertainty and input uncertainty. Below, we describe how we determined the effect of these two kinds of uncertainty on the ranking of the hydrologic management plans.

Scenario group 1: uncertainty in the model parameters for American alligator reproduction

Models designed to project the behavior of ecological phenomena frequently involve multiple parameters that describe aspects of the system considered important to its dynamics. For example, most models of population growth contain a growth rate parameter. The particular value used for a parameter may be determined from measurements taken in the field or may be gleaned from existing literature. In either case, there is rarely, if ever, a single value that can be categorically identified as the best estimate. For example, the growth rates of wildlife populations fluctuate according to temporal and spatial variation in birth rates, mortality, and migration. Such variation leads to uncertainty in the suitability of management decisions when based upon model output. As the number of model parameters that must be assigned a specific value grows, so does the uncertainty over a model's projections. Relative assessment provides a means of testing the effects of uncertainty in parameter values on the robustness of management decisions by comparing the rankings of alternative management plans given different sets of parameter values. We refer to a particular set of parameter values as a parameter scenario. Our application of the relative assessment to parameter uncertainty is described below.

We tested the robustness of the projections of the hydrologic models to variation in parameter values using the SESI model for the American alligator (*Alligator mississippiensis*). The alligator model includes three subcomponents that describe aspects of alligator biology considered to be important to its reproduction: habitat type, flooding probability, and suitability for nest building. While we could have chosen any of the SESI models in our analysis, we chose the alligator model because uncertainty in the environmentally driven subcomponents of this model is high relative to the models for other taxa. For example, it is difficult to obtain precise estimates for the probability that a female will build a nest in a particular location.

Each subcomponent of the alligator SESI model is weighted by a coefficient that determines its relative contribution to the overall index. We generated 100 parameter sets in which the weights on each subcomponent were randomly changed in the range of $\pm 20\%$ relative to their standard settings and ran the SESI model using these parameters. For each random parameter set, P, we used the spatiotemporally averaged SESI to calculate the difference D between the two alternative hydrologic plans in two separate subregions of the Restudy area (R1 and R3, defined in Table 1). In each subregion $D = \bar{I}_{\mathrm{D13R}} - \bar{I}_{\mathrm{F2050}}$ and $\bar{I}$ is the subregional average of the alligator SESI for a particular hydrologic plan, as indicated by the subscripts. We then repeated the above procedure using 100 parameter sets in which the weights were randomly changed in the range of $\pm 30\%$ relative to the standard settings. Here, one complete scenario = hydrologic plan + 30-year baseline stage height sequence + randomized model parameter weights. In each model run, we used the historical 30-year time series of stage height when calculating the SESI value for each of the two hydrologic plans. See the Appendix for additional details of our procedure.

Scenario groups 2 and 3: uncertainty in predominant climate conditions and rainfall levels

While the consequences of parameter uncertainty may be addressed by quantifying the effects of changing parameter values, uncertainty often remains concerning the data used as input to ecological models. Input data may represent environmental conditions that influence species growth or behavioral patterns, the availability of essential resources, or a particular management activity, such as controlled burning. In dynamic modeling, inputs often represent a data sequence that includes variation in conditions over time, space, or both. Again, there is often uncertainty regarding the precision of field-based or previously-published estimates of input levels. Relative assessment allows researchers to reduce input uncertainty by determining the effect of changing input levels on the ranking of alternative management plans.

We used two climate change themes to test the effect of variation in input data on the rank order of the two hydrologic plans. Our intention was to generate strong differences in the pattern of water level variation to illustrate the general approach. Here, we relied upon hydrologic data produced by SFWMD. Because SFWMD produced only two different hydrologic data sets representing climatic scenarios, our options for investigating the water-related responses of the different models were limited. We therefore generated artificial test data for our first group of climate scenarios, scenario group 2, by permuting the baseline historical

TABLE 2. Summary of scenario groups.

Scenario group	Taxon	No. iterations	Data prepared for each iteration
1	alligator	100	Random variation in weighting of SESI subcomponents; up to ±20% and ±30% of baseline.
2	all taxa	28	Resampling and permutation of historical stage height to create three climate themes: wet, dry, and average.
3	all taxa	1	Baseline stage height ±25% shift in rainfall.

Notes: See Appendix for details on randomization, resampling, and permutation procedures. "All" includes six taxa: American alligator, Snail Kite, Cape Sable Seaside Sparrow, long-legged wading birds, short-legged wading birds, and white-tailed deer.

30-year sequence of stage heights that were generated by the SFWMD hydrology model.

For scenario group 2, we used a procedure of selective sampling and random permutation to generate artificial variation in the year by year stage height pattern. We used this approach to assemble test data representing three different climate themes of wet, dry, and average conditions. The wet and dry themes represent hypothetical 30-year sequences during which stage heights were much higher, or much lower, respectively, than the historical sequence. The "average" theme represents a 30-year sequence of average stage height. In scenario group 2, one complete scenario = hydrologic plan + climate theme stage-height sequence + standard parameter settings. The procedure we used to generate the stage-height sequences for the three climate themes used in scenario group 2 are described in the digital appendix and summarized in Table 2.

For scenario group 3 we used two sets of hydrology model output that represent a hypothetical shift in rainfall of ±25% relative to historical levels. To generate these two sets of output, SFWMD created artificial rainfall data for use as input to the hydrology model. Specifically, for each day in a given year, SFWMD changed the observed amount of rainfall by 25%, with the change being either a 25% increase or a 25% decrease, depending on the scenario. Again, the data used as input to the SESI models corresponded to a 30-year sequence of annual stage height maps that was generated by the SFWMD hydrology model. One complete scenario of scenario group 3 = hydrologic plan + artificial rainfall data + standard parameter settings.

To determine the robustness of the rank order of the alternatives to variation in input data (scenario groups 2 and 3), we compared the difference in the baseline SESI, $D_{\mathrm{Base}} = I^{\mathrm{Base}}_{\mathrm{D13R}} - I^{\mathrm{Base}}_{\mathrm{F2050}}$, calculated using the historical stage height data, to the difference in the SESI, $D = \bar{I}_{\mathrm{D13R}} - \bar{I}_{\mathrm{F2050}}$, calculated using each artificial climate regime. We performed this procedure for each taxon and subregion. We interpret our results in terms of the simulated effects of climate change on the spatiotemporally averaged potential of the habitat to support the six different taxa. Note that the artificial climate data we used for scenario groups 2 and 3 are vastly different from the historical data used by CERP to rank the alternatives.

Describing our example in terms of our general approach, recall that our approach considers the effect of environmental factors, E, and parameter settings, P,

TABLE 3. Number of spatial and temporal means computed for each scenario group.

Scenario group and description	No. annual SESI spatial means computed	No. total spatiotemporal differences in mean projection computed
Group 1: alligator only		
Baseline	30	1
±20% variation	3000	100
±30% variation	3000	100
Group 2: all six taxa		
Baseline	30	6
Wettest	840	168
Driest	840	168
Average	840	168
Group 3: all six taxa		
Baseline	30	6
Baseline +25%	30	6
Baseline −25%	30	6

Notes: The values in the right-most column represent the number of 30-year simulations for each of two alternative hydrologic plans, summing to a total of 1458 simulations. Baseline represents the data series used by the South Florida Water Management District to generate the original management scenarios. SESI is the spatially explicit species index, reflecting habitat potential. Scenarios are described in detail in *Methods: Scenario group 1: Uncertainty in the model parameters for American alligator reproduction* and *Methods: Scenario groups 2 and 3: Uncertainty in predominant climate conditions and rainfall levels*.

TABLE 4. Influence of parameters and input data on model projections.

Taxon	Scenario group	Simulations ranking F2050 > D13R (%)†	Simulations in which the ranks of alternatives changed (%)
Alligator	≤20% parameter variation	none	none
Alligator	≤30% parameter variation	none	none
All taxa	group 2, permuted data	54.17	24.07
All taxa	group 3, baseline ±25%	53.71	30.56

† F2050 and D13R refer to two alternative 30-year hydrologic base plans. Although differences among the taxa yielded individualistic projections, when the SESI results for all taxa were pooled, the two plans were nearly equally ranked.

on the output of models, M, and their relative ranking, **R**, according to some criterion. Here, the set M consisted of SESI models applied to the output of hydrology models that take as inputs two hydrologic plans, which we evaluated with respect to the alligator reproduction parameters (P), and variation in stage height (E). In total we analyzed the two subregions for each of two parameter variation levels for the alligator (four average values), and 16 spatiotemporal average values representing the six taxa and two subregions per taxa for the climate change themes (12 average values), which we calculated from 1458 individual scenarios (Table 3). Of these 1458 scenarios, 402 involve random variation of model parameters and 1056 represent carefully chosen sets of artificial input data.

RESULTS

Scenario group 1: uncertainty in reproduction parameters of the American alligator

The substantial random variation we added to the values of the reproduction parameters for the alligator model did not result in a change in the ranking of the two alternative plans, indicating that the relative ranking is robust to major parameter variation (Table 4, Fig. 1). For both the 20% and 30% levels of random

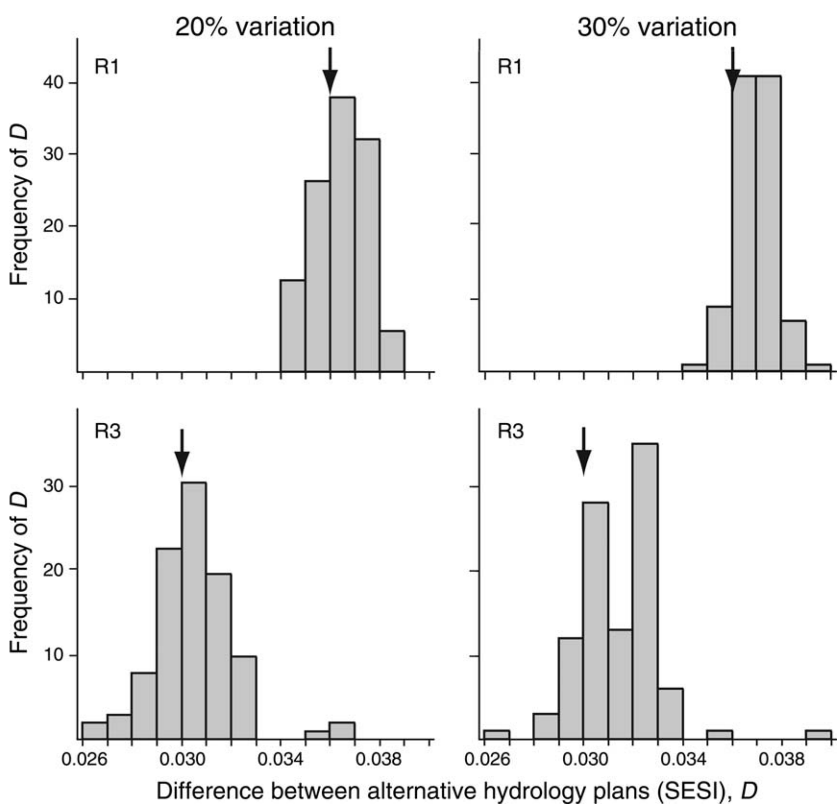

FIG. 1. The statistic D represents the difference between the two hydrologic plans in their effect on habitat potential for alligator reproduction. Frequency distributions of D, calculated using 100 randomized parameter sets, reveal that changes in the parameters of the spatially explicit species index (SESI) model do not alter the ranking of the two hydrologic plans. Different results are shown for subregions R1 and R3 (Table 1, Fig. A1) and for random variation of ±20% and ±30%. Arrows indicate the value of D for the base parameter settings.

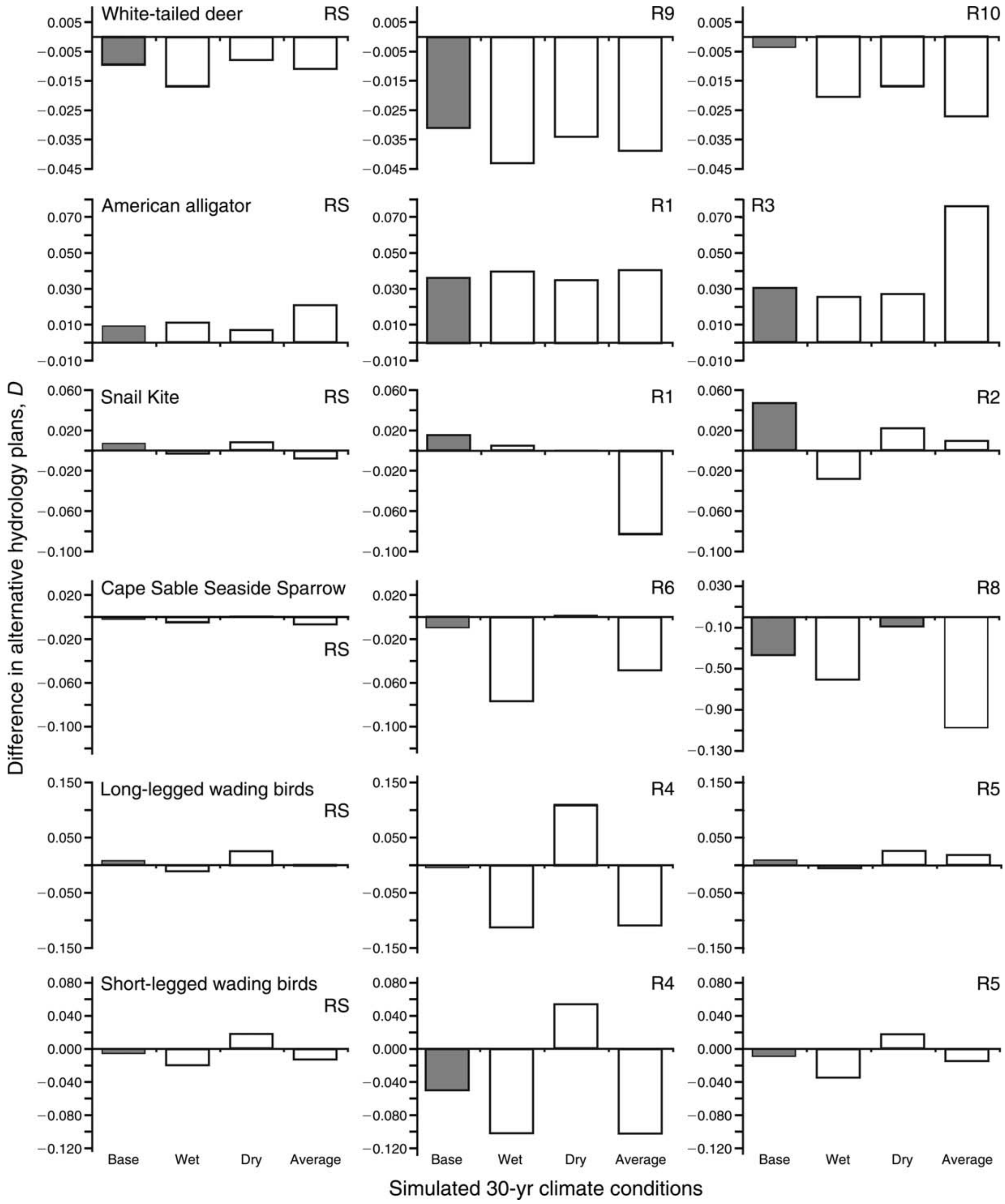

FIG. 2. Simulated drastic changes in climate conditions, which altered the 30-year pattern of stage height (see *Results: Scenario group 2* . . . and *Results: Scenario group 3* . . .), resulted in reversals in the ranking of the two hydrologic plans for some species. Bars indicate the sign and magnitude of D, the difference between the hydrologic plans in their effect on habitat potential. Positive values are where D13R was ranked above F2050. Negative values are where D13R was ranked below F2050. Each row of panels represents a different taxon, as indicated by the left-most panels. Each panel represents a different subregion (R_). RS = restudy area (left-most panels). For other subregion designations, see Table 1 and Fig. A1. Shaded bars show baseline data (D_{Base}); white bars show simulated climate conditions. A change in the sign of D relative to D_{Base} indicates a reversal in the ranking of the hydrologic plans. Note different scale numbers in the panel for Cape Sable Seaside Sparrow, subregion R8.

variation in parameters, and in both subregions, the projected spatiotemporal mean habitat value of the D13R alternative was greater than that of the F2050 alternative. Although variation in the parameters did not result in substantial changes in the difference between the two alternative plans, the mean of the frequency distributions that depict the 30% variation was slightly higher than that for the 20% variation. With respect to the different geographic subregions we examined, our analysis revealed that the difference between the two plans was greater in subregion R1 (water conservation areas 3A and 3B) compared to subregion R3 (Shark River, northeast Shark River, and Taylor sloughs). The SESI differences for the alligator in R1 were significantly higher than those of R3 (Fig. 1).

Scenario group 2: uncertainty in predominant climate conditions

The scenario group 2 climate simulations produced reversals in the ranking of the two alternative hydrologic plans for some taxa, relative to the differences documented using the baseline scenario that represents historical climate conditions (Table 4, Fig. 2). Approximately 24% of the plan rankings were changed under the artificial wet, dry, and average climate themes. That is, the fraction of white bars in Fig. 2 that are either in the opposing direction from gray bars (representing the baseline scenario), or that changed from a nonzero value to zero for each subregion/model, was 24.07%. The magnitude of the difference, D, between the average SESI of the baseline scenario and each artificial scenario is a measure of the robustness of the ranking process to simulated changes in climate conditions.

The index of habitat potential (SESI) for all taxa responded to the simulated changes in climate conditions, but the magnitude and direction of response differed among the taxa and subregions. For example, for the American alligator in subregion R3 the scenario representing average climate conditions was associated with a 152% increase in the difference between the hydrologic plans relative to the baseline scenario, but only a 12% increase in subregion R1. Reversals in the rank order of the alternatives were observed for the Snail Kite and both wading bird groups, but not for the other taxa. Geographic scale influenced the strength of the response to simulated climate change, particularly for species with limited habitat in the study area. Changes in the magnitude and sign of D relative to the baseline scenario were generally weaker in the Restudy area (left-most panels in the figure), which encompasses a larger, more heterogeneous spatial area relative to the individual subregions.

Scenario group 3: uncertainty in rainfall levels

Shifting the rainfall levels by ±25% resulted in changes in the magnitude and sign of the difference between the spatiotemporally averaged SESI values, relative to the baseline scenario (Fig. 3). Again, the preferred hydrologic plan differed among taxa, and we found disparity in the magnitude of the difference between the two alternative plans, as well as reversals in their rank order. Approximately 31% of the rankings in Fig. 3 were changed from the baseline scenario. The simulated shifts in rainfall were associated with changes in the ranking of the alternatives in five of the six taxa, but the cause of reversal (either increased or decreased rainfall) differed among the taxa and subregions (Fig. 3). Again, the strength of the change in D was frequently greater in the individual subregions relative to the larger and more heterogeneous Restudy Area.

Note that Figs. 2 and 3 (the climate scenarios) do not show the variance associated with each mean value because variance levels were too small to illustrate in most cases. The standard deviation in the difference between the plans, D, ranges from 2.0% to 6.0% of the mean. Note also that Figs. 2 and 3 present results for all of the species and subregions listed in Table 1, with the exception of the western subregion of the Cape Sable Seaside Sparrow (*Ammodramus maritimus mirabilis*). Whereas two subregions were analyzed for the other taxa, three were analyzed for the sparrow, whose habitat is comparatively more circumscribed in the study area. Rather than provide a separate figure for the sparrow we chose to include all of the taxa in a single figure, at a cost of accommodating only two of the sparrow's subregions, which we chose arbitrarily. Results for the sparrow in the western region were similar to those of the core and eastern subregions shown in the figure.

Overall impact of uncertainty on rank order of management plans

Overall, changes in input data (the climate scenarios) had the largest impact on the rank order of the hydrologic plans. For the alligator, all but one of the climate change scenarios favored plan D13R. However, the other taxa were frequently more sensitive to changes in inputs and were individualistic in their responses to the simulated climate change. The latter result reflects the differing habitat requirements of each species and how those habitats within the various subregions respond to changes in water levels. For the species considered here, nearly a third of the scenario group 3 projections reversed the ranking of the two management plans, relative to the baseline scenario (Table 4). The individualistic variation among species and subregions in the SESI projections contributed to a reduction in the absolute difference between the hydrologic plans in terms of their overall effect on the quality of wildlife habitat. As a consequence, the fraction of the projections that favored one hydrologic plan or the other was nearly equal: 54.17% favored F2050 under scenario group 2, and 53.71% favored F2050 under scenario group 3.

Discussion

The use of models to project the future behavior of complex ecological systems is a growing trend in natural

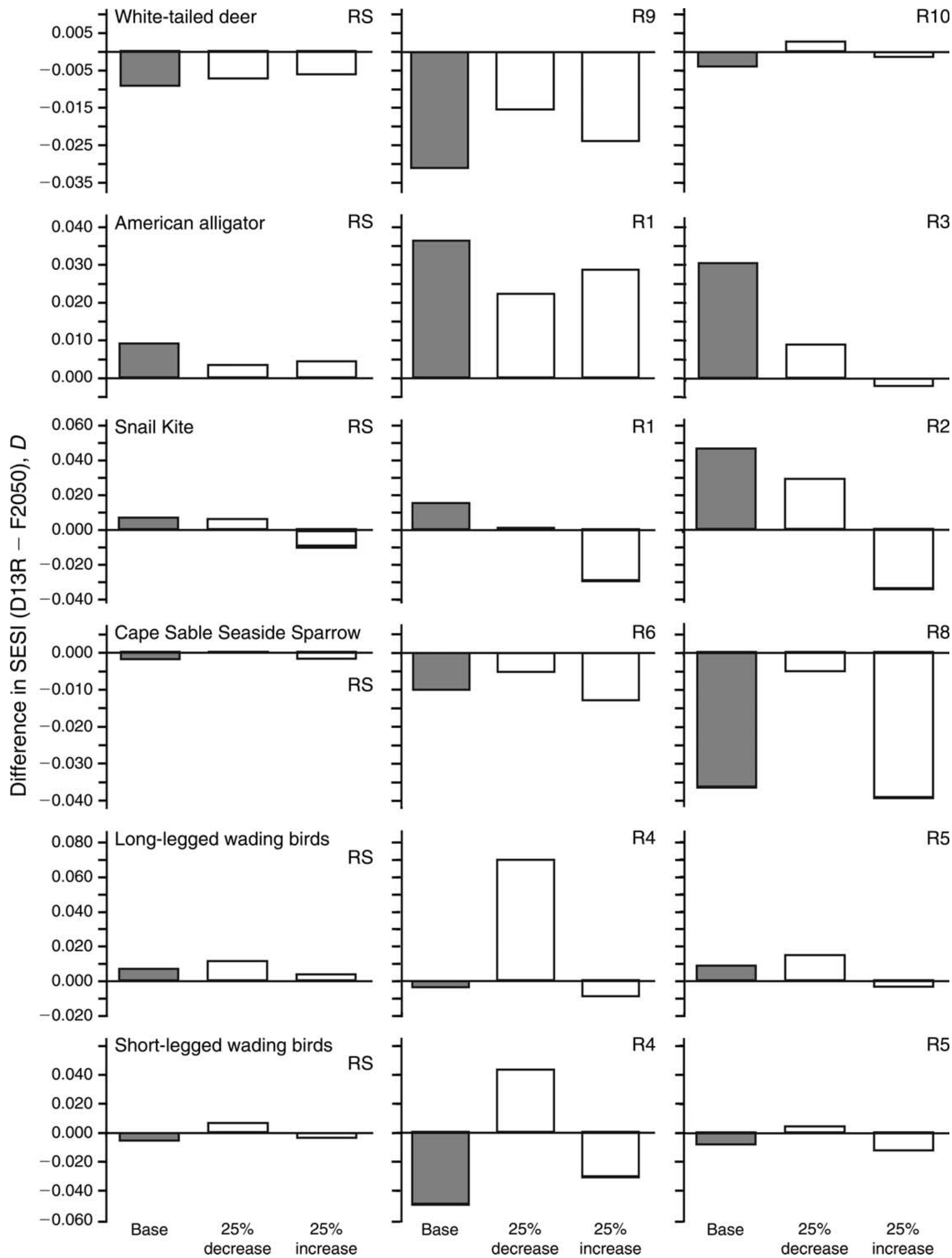

FIG. 3. A simulated shift in rainfall levels of ±25% caused changes in stage height that resulted in reversals in the ranking of the two hydrologic plans for some species and subregions (see *Results: Scenario group 3* . . .). *D* quantifies the difference between the two hydrologic plans D13R and F2050 in their effect on wildlife habitat potential. See Fig. 2 for an explanation of bars and panel codes.

resource management. Comparative approaches, such as scenario analysis, are appealing as they permit the quantitative comparison of alternative management plans while facilitating the disparate criteria of multiple stakeholders. Yet the increased uncertainty inherent in complex models and systems can diminish the reliability of model projections. As natural resource managers come to rely more heavily on models when formulating policy, they must find ways to better incorporate uncertainty analysis in the decision process. As our example illustrates, relative assessment is a useful framework for quantifying the potential impacts of uncertainty. The methodology that we developed can employ a variety of statistical methods. For example, it provides a natural mechanism for a careful analysis of ranked statistics, such as AIC. Given the tremendous growth in resampling methods we encourage additional theoretical work on ranking variation and its use in environmental decision making. Indeed we would hope that future decision support tools would incorporate procedures similar to those presented here to provide ranking statistics that are dependent upon uncertainties in model parameters and inputs.

Management implications for the Everglades

With respect to Everglades planning, the implication of our results is that the rank order of the alternative plans is dependent upon climate uncertainty and/or water management interactions with climate. This conclusion suggests the need for a future focus on both modeling and monitoring schemes to account for variation in hydrologic factors as potentially major drivers of the relative benefits of alternative management actions. A more detailed analysis of the sensitivity of models to input factors and parameter settings might also reveal other drivers of variation. For example, in discussing statistical methods for uncertainty/sensitivity analysis, Saltelli et al. (2000) used variance partitioning to determine the relative contribution (percentage of total variance) of different parameters and model subcomponents on the output of models. Their approach to quantifying the effects of parameter variation is similar to ours but is based upon the absolute difference between model outputs, whereas our approach focuses on relative differences and the effect of uncertainty on the rank order of alternatives. Ellner and Fieberg (2003) discuss a variety of computational methods for quantifying the effects of parameter uncertainty once a particular alternative has been chosen.

As Everglades restoration proceeds, priorities will be assigned to different projects based upon multiple criteria. Such increased complexity in the criteria that drive policy decisions reflects a general trend in the management of natural resources around the globe. An important consequence of this trend that deserves more attention, for the Everglades and beyond, is the increasing reliance of ecologists on technological solutions. The use of emerging technologies fuels a greater dependence on elaborate models and therefore the expertise of colleagues in mathematics, computer science and engineering (Fuller et al. 2007). The implications for multidisciplinary research are obvious, even as the integration of resource management with such disparate technologies as remote sensing and grid-based infrastructures remains a challenge.

Caveats and limitations of our analysis

Despite the many simulations we performed, the scope of our investigation was limited. The paucity of available hydrologic scenarios that account for different future climate conditions led us to focus on major changes in precipitation and water management. This restriction does not reflect upon the ability of relative assessment to assess shifts in hydrology milder from those we employed. However, the use of less drastic changes in climate-induced hydrology would probably not produce the variety of changes in the rank order of the plans that we obtained. In general, we expect the incidence and magnitude of rank shifts that arise from comparisons between different plans to be related in some manner to the differences in the plans. Nevertheless, nonlinear terms, subcomponent interactions, and multiplicative effects of differences across time and space can lead to surprises in model behavior. The advantage of relative assessment is its capacity to determine whether such surprises arise, and if so whether they lead to different policy decisions.

Note that we did not test the effect of parameter variation on every species involved in the ATLSS project. Therefore, although the results of the parameter variation experiment (scenario group 1) suggest that the ranking of the Everglades alternative hydrologic plans is robust to parameter uncertainty, we can not say with certainty that this is generally true of the alternative plans. Again, our chief purpose here was to introduce and illustrate our approach. In practice, where model output informs policy, we recommend a thorough analysis of the effects of parameter variation for each model and subcomponent that contributes to the planning process.

With respect to specific policy decisions, our results should be viewed as an example of our approach and not as an analysis of management policy in south Florida. Multiple criteria were applied throughout the CERP process with different stakeholders applying different criteria. The consequences for biological resources of choosing a particular hydrologic plan were but one element under consideration. In using two of CERP's alternative plans to illustrate our approach, we do not mean to cast judgment on CERP. Our objective here has been to elaborate a methodology for evaluating multiple criteria as they can impact policy decisions. Moreover, we have not provided a complete analysis of the relative advantages of F2050 to D13R from a biological perspective. More extensive work was done on this as part of CERP planning, accounting for many aspects of biology not considered here (DeAngelis et al. 1998, U.S. Army Corps of Engineers and South Florida Water Management District 1999).

Our focus on large climate changes does serve to augment existing knowledge compiled by CERP regarding the impacts of climate established through scenario analysis. Although a large number of alternative hydrologic plans were produced by CERP, most of them involved relatively minor changes to particular control structures in the system. Moreover, the model evaluation performed by CERP was based upon a single historical record of rainfall. One objective in simulating large shifts in climate was to assess its impact on the consistency of the rank order of the alternative plans, compared to the less severe climate data used by CERP during the process of choosing a specific plan.

Comparison to optimization approaches

As far as we know ours is the first paper that evaluates the sensitivity of scenario ranking to changes in model assumptions, parameters, and inputs. Other approaches for comparing management alternatives include optimization methods designed to choose the "best" alternative from a range of choices not limited to a specific set of scenarios (e.g., Regan et al. 2006, Sanchirico et al. 2006). What we have carried out is an intermediate step between optimization methods (choosing the best) and scenario analysis (ranking alternatives). We evaluated whether or not the conclusions of scenario analysis are robust to model assumptions and different levels of uncertainty. Our methodology is not limited to scenario analyses and can be applied to situations that are not amenable to optimization approaches, such as demographic modeling in which there is often uncertainty in vital rates (Beissinger and Westphal 1998) and the analysis of population viability or dynamics for management purposes (McCarthy 1996, Groom and Pasqual 1998). Indeed, the need to identify the subcomponents of complex models with least impact on the one hand, and to determine the effect of uncertainty on policy decisions on the other, are problems that broadly affect modeling applications in conservation and management. This suggests that relative assessment could become a widely used tool.

Advantages of relative assessment

Relative assessment has several features that we think will appeal to resource managers. First, it is not tied to a single modeling approach; analytical, numerical, and hybrid models can be evaluated using relative assessment. Second, by focusing on the ranking of alternatives, relative assessment has no inherent criteria for assessing the merits of a given scenario. Multiple criteria can be used to rank alternative management plans. This not only allows multiple stakeholders to evaluate each plan according to their own criteria, but also allows a diversity of perspectives with which to measure the robustness of the model. Third, relative assessment does not require the construction of additional models, only a change in the focus of the analysis. We believe that by allowing managers to vary any uncertain subcomponent relative assessment can improve the effectiveness of many policy decisions. For example budgets can change as can land use patterns and political priorities. By identifying the robustness of policy decisions to such uncertainty, relative assessment can help guide managers to decisions that more effectively cope with future circumstances that cannot be reliably predicted.

Conclusion

Our results underscore the importance of establishing the relative contribution of the different subcomponents of complex models, as well as the potential influence of differential species responses, spatial heterogeneity, and assumptions about future conditions. In addition to revealing the robustness of policy to uncertainty, the methodical testing of each subcomponent of multitiered approaches yields a more complete picture of system level responses to changing input levels. As the integration of complex models into the decision-making process becomes commonplace, the application of uncertainty analyses, though often tedious and time consuming, will be crucial to the suitability of policy decisions and the fate of managed ecosystems.

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APPENDIX

Management background and description of model parameters (*Ecological Archives* A018-023-A1).