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Enhanced Adaptive Management: Integrating Decision Analysis, Scenario Analysis and Environmental Modeling for the Everglades

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Received

24 January 2013

Accepted

19 September 2013

Published

11 October 2013

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We propose to enhance existing adaptive management efforts with a decision-analytical approach that can guide the initial selection of robust restoration alternative plans and inform the need to adjust these alternatives in the course of action based on continuously acquired monitoring information and changing stakeholder values. We demonstrate an application of enhanced adaptive management for a wetland restoration case study inspired by the Florida Everglades restoration effort. We find that alternatives designed to reconstruct the pre-drainage flow may have a positive ecological impact, but may also have high operational costs and only marginally contribute to meeting other objectives such as reduction of flooding. Enhanced adaptive management allows managers to guide investment in ecosystem modeling and monitoring efforts through scenario and value of information analyses to support optimal restoration strategies in the face of uncertain and changing information.

Climate change presents the most complex challenge facing an entire generation of environmental managers and regulators^{1–16} and is especially important for large-scale restoration projects, like the Greater Everglades Ecosystem Restoration (GEER). Not only are future climate conditions uncertain, but the political and regulatory responses proposed in the face of the changing environment also need to be considered in selecting restoration alternatives and managing their operational implementation. Because of inherent uncertainty and the inability to develop courses of actions optimal for all future scenarios, the U.S. Army Corps of Engineers (USACE) and other agencies increasingly incorporate adaptive management as the way to address climate change in these situations^{2–6}. The Water Resources Development Act¹⁷ recommends adaptive management in the context of ecosystem restoration. The implementation guidelines state that every ecosystem restoration project must include monitoring and adaptive management (contingency) plans and their associated costs in its feasibility study. In addition, recent guidance documents from the U.S. National Research Council^{4–6} advocate scenario analysis to assess the robustness of competing alternatives, inform the plan selection, and more fully depict the potential performance of the selected plan over a range of uncertain future conditions. Future conditions may be related to changes in climate, budget cuts, and evolving stakeholder preferences. Nevertheless, there is no specific guidance on which scenarios to select and use in different management contexts, especially as it relates to adaptive management.

Adaptive management approaches and applications^{18–37} have been the subject of multiple National Academies of Science reports^{4–6} and there is a clear consensus that its implementation in environmental restoration does not always meet the original intent of the methods, and also does not formally integrate scenario analysis in practice^{4,5,38}. Current approaches often are “trial and error” implementations^{27,38,39}, which require new decisions to be made at each review point in the management horizon and have no formalized method for learning from current activities. Moreover, the costs of adjusting restoration alternatives and of monitoring plans are often not considered^{27,37–39}. Even in the Everglades, which has an adaptive management program, integrating the results of



modeling, scenario analysis, and multiple restoration indicators to inform decision-making on the most robust alternatives and most beneficial monitoring gives has been challenging. Decision analytic approaches can help large restoration efforts address these needs.

For example, adaptive management as it is being currently implemented in GEER is based on a passive adaptive management approach that learns from implementing one management alternative at a time based on monitoring data that may or may not be relevant to this decision (Fig. 1). In the GEER, millions of dollars have been spent developing sophisticated hydrological and ecological models, as well as on monitoring different ecological and environmental endpoints³⁸. Despite this increased knowledge, some level of uncertainty about which alternative will best achieve the restoration goals and the effects of those alternatives will always exist³⁸. Uncertainty and variability associated with monitoring data as well as decision uncertainty in selecting courses of action are not explicitly integrated in the learning process, which is the key feature of adaptive management. Without a framework that links results of modeling and monitoring to management decisions, the degree of learning from the results of monitoring and ability to use those results to refine the monitoring plan will be limited.

Another shortcoming of adaptive management, as often practiced, is the lack of a rigorous quantification of stakeholder preferences³⁸. Many approaches to group decision making have difficulty in encompassing the values and priorities of multiple stakeholders^{39–44}. However, a quantitative inclusion of these values is necessary to make robust decisions^{37,45–49} that balance competing objectives. Adaptive management may also fail due to a focus on planning by decision makers to the detriment of action. Resulting “decision procrastination” may be due to the complexity of the problem, the lack of unified stakeholder priorities or risk aversion on the part of decision makers. A unique, transparent and justifiable approach that characterizes stakeholder values related to performance measure goals, uncertainty and risk is required to overcome these problems.

An Enhanced Adaptive Management (EAM) approach is proposed that uses a decision analytic model to provide managers with a framework for selecting robust restoration alternatives and associated monitoring plans in the face of uncertainty. The proposed EAM model: (i) evaluates strategies defined as sequential decisions to select and implement restoration alternatives and monitoring plans (Fig. 1 and Fig. S1) given uncertainty defined by probability of response; (ii) calculates payoffs associated with restoration alternatives for all

possible strategies that take into consideration environmental, financial, and social objectives; and, (iii) quantitatively assesses stakeholder preferences and integrates associated weights in prioritizing management alternatives.

In our case study, the decision model evaluates different restoration alternatives designed to restore water flow and associated ecosystem functions to the Everglades. The model is based on a probabilistic decision network (or influence diagram⁶⁰) that aims to represent the objectives of environmental managers (Fig. 2) (Methods). The impact of each restoration alternative on water depth, nutrients, and salinity as well as monitoring and implementation costs is considered. For this simplified model, different rainfall and soil oxidation scenarios are considered to be external drivers affecting water depth. The relative importance of water depth, nutrients, and salinity on habitat value is represented by expert-elicited weights. The model represents stakeholder preferences as the quantitative trade-off between habitat value and cost of the strategy. In contrast with passive adaptive management approaches, the payoff is evaluated for sets of present and future decisions about alternative restoration plans as opposed to focusing on the potential value of the present plan (Fig. 1). The selection of the monitoring plan is based on the value of information⁸ that is calculated as a change in the payoff resulting from the implementation of different monitoring plans for the same alternative plans (Methods). The utilization of this framework, therefore, addresses many of the deficiencies of historical applications of adaptive management.

An EAM case study is developed based on the needs of the Comprehensive Everglades Restoration Plan (CERP), which was developed in 2000 to respond to the disruption of the natural quantity, quality, timing and distribution of water in Greater Everglades Ecosystem by control and other water management infrastructure^{4–7,50,51} (SI). CERP entails over 60 individual projects with a total projected cost of over US \$10 billion^{4,5}. The case presented here is a simplification of the management situation facing the Everglades Water Conservation Areas (WCAs), such as 3A and 3B (Fig. 3). Over decades of flood control projects, the natural flow of water across this area has been disrupted through the development of a system of levees and canals for the development of agriculture and urban areas that support a population of over 7.5 million people. For instance, parts of WCA 3A and 3B are getting drier and wetter, with profound consequences for the unique ridge and slough peatland landscape⁵⁰, and for many hydrologically sensitive species such as the American alligator and numerous species of wading birds. For the restoration of these areas, the USACE is considering levee degradation and canal backfilling in WCA 3A, 3B, and Everglades National Park. For this exercise, modeling data was considered for the whole length of the Hydropattern Restoration Feature (HRF) and of the Miami canal (Fig. 3). The spatial extent and implementation scale of these restoration alternatives (e.g., major vs. minor levee degradation and canal backfilling) have different potential to affect water levels and hydroperiod, thus resulting in varying degrees of restoration efficiency and effectiveness. Thus, managers face five different restoration alternatives (four combinations of minor and major degree of degradation and backfilling of levees and canals, as well as a “no action” alternative) that they can alter adaptively over time considering the information from environmental models and from three potential monitoring plans.

The payoff is the calculated output of the model used to evaluate restoration alternatives. The payoff is dependent on the combination of “node states,” where the “node state” is one of the possible values and associated probability for each variable (see Supporting Information). The decision nodes are characterized by discrete alternatives (choices) associated with cost values. The chance nodes are characterized by state values and associated occurrence probabilities. For chance nodes with predecessor nodes, we define probability distributions for each state conditional on each possible combination of

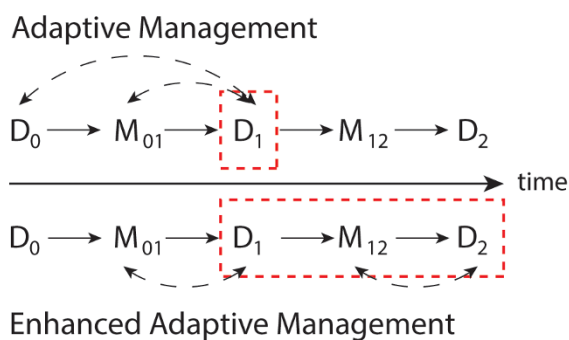


Figure 1 | Adaptive Management and Enhanced Adaptive Management decision process. Classic adaptive management is focused on sequential decisions of restoration alternatives (within red dotted square) as a function of monitoring before the decision and previous decisions (e.g. M01 and D_0). These components constitute the “learning” of adaptive management (dotted arches). The focus of EAM is on the best alternative within a strategy that includes a sequence of decisions (at the current time and in the future) and a monitoring plan (within red dotted square). The learning is considered only from the monitoring to consider the uncertainty of negative learning, erroneous decision of decision makers.

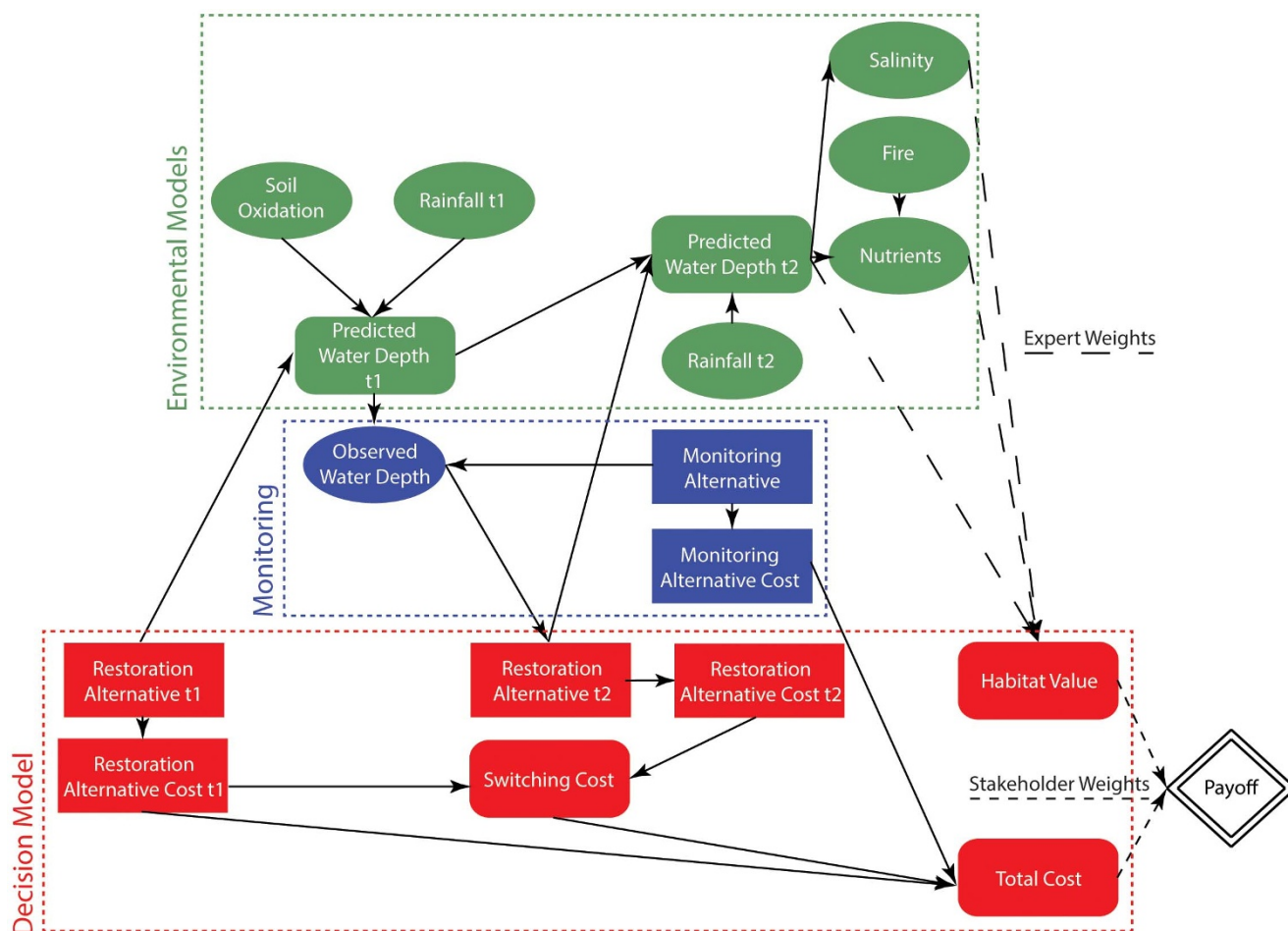


Figure 2 | Probabilistic decision network representing the proposed Enhanced Adaptive Management (EAM). The EAM model includes a decision model which groups together environmental models (red shapes), stakeholder and expert weights, and monitoring variability (Blue shapes). The expert weights (w_D , w_N , and w_S) for water depth, nutrient concentration, and salinity are shown as dashed lines. Stakeholder preferences (w_{HV} , and w_C) are defined for habitat value and cost and indicated in the diagram as a dotted line. Rectangles are decision nodes. Rounded rectangles are calculation nodes. Ovals are random (probabilistic) nodes. More details are provided in SI.

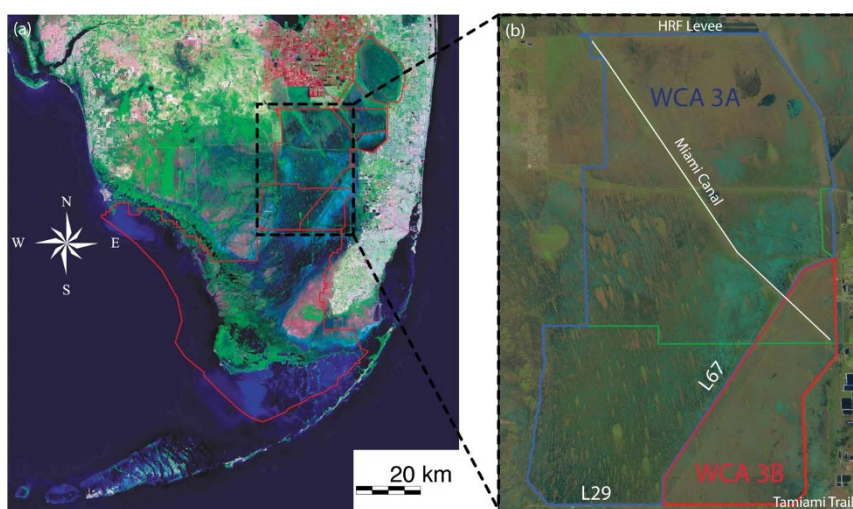


Figure 3 | Greater Everglades Ecosystem Restoration (GEER) (delineated in red in (a)) and Water Conservation Areas (WCAs) 3A and 3B (b). Satellite image courtesy of the U.S. Geological Survey (<http://earthexplorer.usgs.gov/>). The Miami canal, and the levee system (Habitat Restoration Feature (HRF) in the north), and the Tamiami trail (b) are under consideration by the US Army Corps of Engineers for their possible modifications (backfilling, degradation, and suppression respectively) in order to restore the Everglades ecosystem. In our case study we consider five alternatives of major and minor levee degradation and canal backfilling for WCA 3A in a sequential decision process. Within the same decision process we consider variability of monitoring of water depth. We do not consider the alternative of suppression of the Tamiami trail. More details are provided in SI.



“node states” of the immediate predecessor nodes along the decision network. Calculated nodes have values determined by the specified relationships linked to the “node states” of the immediate predecessor nodes, both chance and decision nodes. Calculated nodes have as many possible states as the product of the number of possible states of their immediate predecessors. It is possible to define “ecosystem state” as a random variable calculated as ensemble of payoff values determined by the decision of adopting one of the possible combinations of restoration alternatives given the uncertainties of all the other variables. Thus, the ecosystem state is characterized by one or more payoff values.

The payoff represents a trade-off between habitat value and total cost. The EAM model simulates a two period decision process (period one and period two), in which five restoration alternatives can be chosen. The restoration alternatives are characterized by major/minor interventions on levees and canals (degradation and backfilling, respectively). Any of the five alternatives can be selected in period one and in period two. The operational cost associated with the choice of restoration alternatives in period two (i.e., the “switching cost”) depends on the choice of restoration alternatives in period one. We used the combination of decisions in period one and period two to determine the cumulative probabilities of the payoff.

The combination of five restoration alternatives, three rainfall scenarios, and two soil oxidation scenarios yields thirty possible water depth states in period one. The performance of management strategies depends on climate change effects, including rainfall and fires variations. Here, we consider only rainfall as a climate-related variable because of the greater importance of this variable to water depth (Fig. S6), and because of the ambiguous relationship between fire and climate. These factors are modeled as stochastic variables characterized by a state and a probability of occurrence as specified in the Methods and Supporting Information (SI). We consider three rainfall scenarios as a function of climate change: current rainfall (average annual rainfall), wet (double the current average annual rainfall) and dry (half of the current average annual rainfall). Operational implementation of any alternative requires regular re-evaluation of the performance of that alternative based on the emergent monitoring information. We consider two decision points in our case study: in the beginning of the project (time t_1) to implement one alternative plan, and a later period of time when new monitoring results are available (time t_2) to consider implementing another alternative plan.

To inform restoration decisions, multiple variables may need to be monitored in order to characterize the relevant biogeophysical dynamics of the system. In this initial study, however, we consider only water depth since it is the most extensively and precisely measured in the Everglades (i.e. Everglades Depth Estimation Network or EDEN)⁵². The monitoring plan is considered to be changeable over time, similar to restoration alternatives, and provides varying levels of certainty of decision variables. The incoming monitoring data allows quantification of the efficacy of restoration alternatives in the context of each rainfall scenario. Three monitoring plans (low, medium and high) are considered to reflect differences in the extent and quality of monitoring, and its associated costs. For example, high-tier monitoring could include an extension of the current water-depth monitoring network, or the adoption of advanced sensor systems.

In addition to the uncertainty of monitoring that is ultimately linked to the available budget, uncertainty characterizes future climate scenarios, predictions of restoration alternatives to achieve the multiple objectives, and the decision-making process of managers independently of monitoring plans. The implemented decision model utilizes functional relationships among decision and environmental variables and rainfall scenarios to calculate the payoff associated with each restoration alternative. Details of these relationships are described in the Methods and the Supporting Information.

The payoff as a result of implementing any restoration alternative for different strategies is characterized by the predicted ability of that alternative to meet two objectives: minimizing operational (construction and implementation) cost, and maximizing ecosystem health. The total cost includes costs of: (i) implementing restoration alternatives selected in the beginning of the project; (ii) changing from one alternative to another; and (iii) monitoring effort. The health of the ecosystem is proportional to the habitat value that is calculated as the sum of water depth, nutrient concentration, and salinity concentration, weighted by the experts’ valuation of the contribution of each metric to the overall function of the system (Methods). The utility function associated with water function reflects the value of water flow for ecosystem health as well as the risk of flood damage with higher water flow. We are aware that flooding in some areas may have less impact than flooding in other areas, and that it is not just depth of water that matters but also its timing and distribution. However, our goal is to use a simplified model to show the usefulness of the decision model in dealing with such multi-objective environmental challenges.

The value of information (VoI) associated with each monitoring plan for each restoration alternative is calculated as the difference in payoff for different information on water depth as a result of the extent or increased accuracy of monitoring efforts (Methods). The payoff is a unitless output intended to represent the relative utility of each restoration alternative for the study area, that is in this case WCA 3A.

Results

The payoffs associated with the four restoration alternatives as well as the no-action alternative given different climate change scenarios are presented in Fig. 4a. The alternative involving minor levee degradation and minor canal backfilling brings an increase in payoff in both wet and dry scenarios as compared to the no action alternative. Aggressive restoration alternatives (major levee degradation and major canal backfilling) result in lower or equal payoff for all climate change scenarios (Fig. S2 and Table S8). In Fig. 4a we consider the scenarios for the same alternative in period one and period two and low level of monitoring. Fig. 4b evaluates the payoff considering climate change as in Fig. 4a and the ability to switch alternatives in period two. The adaptive ability to change restoration alternatives in the future brings an additional payoff for all alternatives. The highest payoff (the tallest bar on Fig. 4b) is associated with the major canal backfilling and major levee degradation in period one, and continuing with the minor canal backfilling and major levee degradation in period two. The best overall strategy for period one, considering all possible rainfall scenarios and the ability to switch strategies after monitoring results are collected, is major levee degradation and minor canal backfilling (cumulative payoff of 0.13 in Fig. 4b) (Fig. S3). This strategy results in high habitat values with respect to cost. The choice of major canal backfilling in period one may be associated with additional costs if the alternative chosen in period two requires those canals are re-dug. Thus, the alternative with major levee degradation and minor canal backfilling guarantees the highest cumulative payoff regardless of the alternative chosen in period two.

The payoff considering an adaptive strategy composed of the choice of the highest paying sequential restoration alternatives in periods one and two, climate-related rainfall, and the choice of monitoring effort is represented in Figure 4c. These results demonstrate the increased value associated with enhanced monitoring effort (Fig. S4). The overall payoff increases substantially with monitoring effort increasing from low to medium. For all alternatives in which the levee degradation is minor the high-level monitoring plan (black bars) is not optimal because the operational cost becomes too high for the benefit derived from the additional information. On the contrary, the implementation of low-level monitoring (red bars) results in significantly lower performance given the inability to collect the

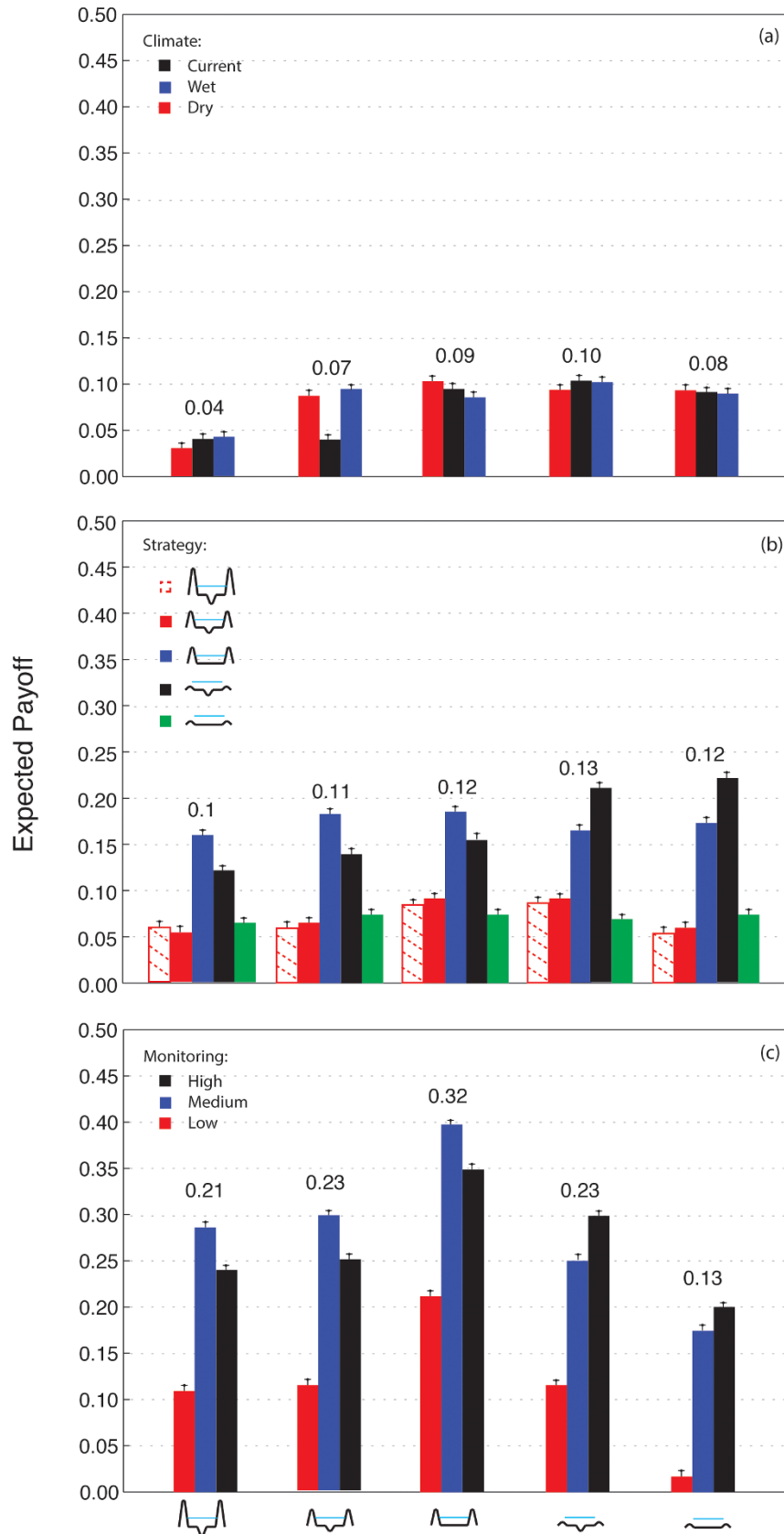


Figure 4 | Expected value of the average payoff for each restoration alternative as a function of: (a) climate change (Fig. S2); (b) adaptive decision strategy and climate change (i.e., change from one alternative to another) (Fig. S3); (c) and, monitoring plans, adaptive decision strategy, and climate change (Fig. S4). A scenario corresponds to each bar of the histograms. The VoI is defined as the difference in payoff between two scenarios with different monitoring plans. Variation in climate change scenarios (a) is conducted under fixed monitoring cost and no decision adaptation. Monitoring cost is fixed at low level when adaptive decision strategies are evaluated (b). The error bars represent the standard deviation of the payoff due the uncertainty assigned evaluated by GSUA (Methods and SI).



information necessary to adjust the course of action based on model predictions. With low-level monitoring, the choice of alternative in period two may not reflect an accurate understanding of the consequences on habitat value and cost of the restoration. The highest payoff is associated with the medium-level monitoring plan (blue bar). Overall, the alternative with the highest payoff (0.32) is minor levee degradation and major canal backfilling. This alternative provides a good balance of habitat quality and operational cost in all climate scenarios and strategies. For example, rebuilding levees and reopening canals may be required in the wetter scenario and this sequence of alternatives is very costly. Starting with a minor levee degradation and major canal backfilling provides more adaptive flexibility to switch to more aggressive or less aggressive restoration strategies and thus results in a higher payoff (Fig. 4b and Fig. 4c). For each alternative, the increase in expected value going from low to medium to high monitoring is equal to the VoI provided by that monitoring reduced by the cost of that monitoring. Note that for all alternatives the VoI of medium monitoring exceeds the cost. However, the additional VoI of high-level monitoring exceeds its additional cost for the alternatives with major levee degradation.

By deconstructing the potential payoffs associated with each restoration alternative, Table 1 presents the contribution to the payoff associated with the utility of the water depth as well as the objectives of habitat value and operational cost. This payoff is calculated considering all rainfall scenarios, all the feasible strategies, and monitoring variability. The alternative with the highest payoff (0.32; minor levee degradation and major canal backfilling) is the best overall, but it does not result in the highest habitat value and greatest flood risk reduction (Fig. S5 and Supporting Material Results and Discussion). Nevertheless, its low operational cost makes the overall payoff associated with this alternative the highest. Attempts to recreate pre-drainage patterns (major levee degradation and major canal backfilling) result in the highest habitat quality, but have significant operational costs and lower utility given the probability of high water depth with associated flood risk.

Global sensitivity and uncertainty analysis (GSUA) of the EAM model is used to understand the important variables for the payoff and the variability of the payoff given uncertainty in all variables (Methods and SI). The sensitivity analysis shows that the management decisions of a restoration alternative and a monitoring plan are the most important variables affecting the payoff (Figure S6). However, monitoring and the choice of a restoration alternative are interacting variables, because the payoff of each alternative is based on an understanding of the response of each objective to that action. Therefore, monitoring is a fundamental variable to consider in adaptive management because its value is responsible for the largest effect on the payoff. Uncertainty analysis illuminated the effects of variability in stakeholder preferences and expert weights. To explore the effect of large variation in expert weights, we vary first one parameter and then two parameters at a time (Fig. S7). For the single parameter uncertainty analyses, the value of the experts' weights for water depth, nutrients and salinity contribution to habitat value ($w_D = 0.2$, $w_N = 0.3$, and $w_S = 0.5$) were allowed to vary by

50%. The new ranges result in change in payoff from the original value of 25%, 15%, and 13% for depth, nutrients and salinity, respectively (Fig. S7a). Supporting Information provides more discussion about GSUA results. These analyses reinforce the benefits of explicit incorporation of stakeholders' values into decisions when multiple objectives (habitat restoration and controlling costs) need to be met.

Discussion

It is increasingly commonplace to speak of the need for adaptive decision making in complex environmental domains. In this study, a formal decision model is employed to prioritize restoration alternatives in sequential time periods using information derived from environmental models, hypothetical monitoring plans and stakeholder preferences. The model allows for learning by incorporating the results of field experiments and complex models. Furthermore, the utility of collecting additional information (e.g., through monitoring or modeling) can be assessed based on the expected value it adds in the context of site management. The quantitative consideration of preferences of stakeholders in our decision model shifts the outcome from selection of an ecologically optimal restoration (e.g., maximizing some or all environmental metrics) to consideration of an effective restoration alternative preferable to stakeholders.

In the past, optimal strategies have been defined as those for which the best outcome is predicted given current conditions. Passive adaptive management considers that future conditions may change and future decisions may be made^{35,53}. Enhanced adaptive management furthers this approach⁵⁴. Because of the availability of future scenarios, the EAM model can explore strategies and identify *a priori* the risk averse alternative with the highest payoff given the range of future decisions, budget limitations, and preference changes. With this framework, the optimal alternative can always be identified in the presence of new information from monitoring or when considering novel restoration designs.

This EAM approach facilitates the engagement of stakeholders. In our case study, hypothetical stakeholder interests were incorporated. The EAM approach requires three kinds of inputs from either stakeholders or decision makers. First, the objectives that the adaptive management is designed to accomplish must be specified, as well as those metrics that best inform those objectives. Specific cases have documented how utilization of decision analytic tools enhanced stakeholder participation, including the case of Bergen Harbor⁵⁵. Second, the relative importance of different objectives, expressed as weights, must be identified. An extensive social science literature describes different mechanisms for developing and interpreting interviews with stakeholders⁵⁶. Third, stakeholders should have some input into the range of management alternatives, even if they do not contribute the alternatives themselves. The set of alternatives to be considered by the EAM needs to be inclusive, so that the range of expected utility spans all the realistic outcomes.

Our simple but realistic case study, based on an existing Everglades restoration challenge, presents a rational and transparent framework for selecting beneficial restoration alternatives. We show that restoration alternatives that aim to recreate pre-drainage patterns may result

Table 1 | Contribution to the payoff (U) considering all rainfall scenarios, the possibility to switch to an other restoration alternative in period two, and different monitoring plans (Fig. 4c and Fig. S5)

Symbol	Levee Degradation	Canal Backfilling	$U_{\text{water depth}}$	$U_{\text{habitat value}}$	$U_{\text{total cost}}$	U
	-	-	0.32	0.05	0.16	0.21
	Minor	Minor	0.30	0.08	0.15	0.23
	Minor	Major	0.25	0.19	0.12	0.32
	Major	Minor	0.15	0.20	0.12	0.23
	Major	Major	0.10	0.23	0.20	0.13



in the highest habitat quality, but have significant operational costs and potential increases in flood damage risks (Fig. S5). While previous adaptive management efforts largely lack decision analytic models, this enhanced approach identifies a preferred, and logically consistent, strategy for immediate action, monitoring and downstream action in the face of uncertain scenarios for cost, efficacy and climate.

The uncertain effects of climatic change and of other environmental variables give rise to other environmental planning situations for which a similar decision analytic approach to adaptive management is suitable. The overall model structure in Fig. 2 would serve as a starting template for the adaptive management of any ecosystem. Situation-specific variables in the environmental model would be replaced, e.g., different soil oxidation and rainfall as a driver of water depth might be replaced by storm frequency and intensity as drivers of predicted and observed beach erosion in coastal ecosystems. Similarly, the payoff might involve value drivers associated with different habitats of species and other measurable ecosystem variables. After the components of a model with similar structure are identified, a similar set of probability assessments would be required for the newly defined uncertain variables. Likewise, weight assessments would be needed for the new components of the payoff function.

Whether or not it is possible to retain most of the model structure, this approach can be applied generally to environmental management cases. A generalized approach will require an interactive modeling process including the following steps:

- First, a comprehensive stakeholder group should identify the management objectives to be met with any action, and how best to measure those objectives with large-scale socio-environmental metrics. A set of potential management actions and their influence on the socio-environmental metrics should be identified in order to assist the development of EAM decision model;
- Second, local-scale variables influencing each metric should be incorporated into the quantitative decision model. These variables should include measureable aspects of the system that inform the changes in function anticipated following adaption of any alternative. The causal relationship between each pair of node-variables in the influence diagram needs to be hypothesized or derived from existing empirical and/or computational studies in order to link the nodes of the model;
- Third, the monitoring plan to be undertaken following any action should be defined in terms of the uncertainties and relationships specified in the model;
- Fourth, the comprehensive stakeholder group should be reconvened to go over the model, make any changes and suggest remedial actions to be considered, and provide their various inputs for the relative importance of the specified objectives;
- Finally, the decision makers and modelers can develop an assessment of each strategy according the anticipated payoff, as well as a global sensitivity and uncertainty analysis considering the range of preference of the larger stakeholder group. These analyses can either inform the decision maker, provide justification of any action to be taken, or form the basis for further discussions with stakeholders at the policy level.

Developing new adaptive management models for the range of problems thus requires additional effort and coordination on the part of stakeholders, decision makers, and the engineers and scientists who propose and evaluate management alternatives. While this is a hurdle to broadly adopting this methodology, the cost of this investment in a coherent approach to EAM planning at the onset of a project is small in comparison with the expected benefits from streamlining and focusing adaptive management efforts throughout its progression. Therefore we emphasize the need of adopting the enhanced adaptive management model for any ecosystem restoration effort in which uncertainty exists in achieving multiple objectives represented by numerous variables.

Methods

The probabilistic decision model depicted in Fig. 2 was developed to calculate payoffs for each alternative within a strategy. A strategy is defined by the combination of restoration alternatives in period one and two (sequential decisions), and by a monitoring plan. This model introduces four submodels that are integrated in order to value the different restoration alternatives and monitoring plans, considering variability in rainfall and restoration decisions. More detailed explanations and rationales for the submodels are given in Supporting Information (SI).

Environmental sub-model. The predicted water depth D_t for each period t is calculated as a function of the pre-existing soil conditions, the restoration alternatives chosen at the beginning of period t and the rainfall at period t . Here we consider $t = 1$ year. Predictions of water depth are based on hydrological models. Specifically we make use of the Regional Simulation Model (RSM)⁵⁷ outputs for different restoration alternatives. Rainfall and soil conditions are treated as uncertain, as is depth for period 1 (implicitly because initial depth is “unknown” and depends on the monitoring plan). The final state of the ecosystem is characterized in terms of depth D as well as salinity S and nutrient levels N that are calculated as uncertain functions (i.e., using conditional probabilities between connected nodes in the decision network) of D and other factors. All the variables are normalized to a 0–1 scale.

Habitat value calculation. The habitat value of the Water Conservation Area for supporting various aquatic habitat functions is given as

$$HV = D w_D + S w_S + N w_N, \quad (1)$$

i.e., a weighted sum of the water depth D , salinity S and nutrient levels N from the environmental sub-model. The weights w_D , w_S and w_N sum to one for normalization and reflect the contribution of each factor to the habitat value assessed by experts. The utility of water depth is lower for both low water levels, when ecosystem health is negatively impacted, and high water levels, when the risk of flood damage is elevated. Alternatives that include canal backfilling and levee degradation have a lower payoff related to water depth than alternatives that include flood control structures (deep canal and high levees) (Fig. S5). On the contrary, with regard to water depth, alternatives with canal backfilling and levee degradation have higher payoff related to salinity and nutrients than alternatives that preserve flood control structures. As for the habitat value, alternatives that include major canal backfilling and major levee degradation result in the highest payoff (Fig. S5). Specifically, major changes are more costly than minor changes in either canals or levees. Furthermore, canal backfilling is more costly than levee removal (Supporting Methods in SI, and Table S8).

Monitoring. The observed water depth is a noisy measurement of actual water depth. The accuracy in the measurement of the water depth depends on the quality of the monitoring plan, MA . While it is natural to make judgments about (i) what average depth might be measured when the actual depth is at a given level, from a decision making perspective, it is necessary to think about (ii) what the true depth might be given the measurement that was obtained. The model uses Bayes’ theorem to convert a table of conditional probabilities for (i) into conditional probabilities for (ii) for purpose of capturing the uncertainty about water depth going into period 2 (Tables S6 and S7 in SI).

Decision model. Decisions about restoration alternatives and costs of these alternatives are embedded into the decision model. Costs are estimated for restoration alternatives RA_t in period t , along with costs for the monitoring level selected. The overall payoff is the resulting habitat value less costs (C) incurred, with weights to normalize the tradeoff, i.e.

$$U = HV w_{HV} - (C(a_1) + C(a_2|a_1) + C(m)) w_C, \quad (2)$$

where w_{HV} and w_C are the stakeholder preferences for the habitat value relative to the cost. Combining all four models, the payoff is calculated for each set of alternatives and strategies considering uncertainties. More information is provided in the Supporting Information.

The timing of period one and two is not specified. The first restoration period is selected simultaneously with the monitoring plan and without knowledge of the outcome of any uncertain events in the model, while the second restoration period is taken with knowledge of the information from monitoring and potentially of the first decision about restoration alternatives. A strategy (an adaptive management plan) differs from a pre-set sequence of alternatives, because it combines the choice of a first period restoration alternative and monitoring plan with a decision rule for selecting the second period restoration action depending on what is observed in between.

Random variables have associated discrete marginal and conditional probabilities (Tables S1–S7 in SI). Monte Carlo simulation is used to calculate the average expected payoff for each combination of restoration alternatives and monitoring plan. The Monte Carlo simulation is used to calculate a distribution of payoff values for each strategy. For each level of monitoring, the highest value alternative including this level is noted. If the monitoring cost parameter is set to zero, the difference between the average habitat value obtainable with any pair of monitoring plans is the incremental VoI^8 associated with the higher quality of the two monitoring plans. If the monitoring cost parameter is set to reflect actual monitoring costs, the difference represents the net incremental value of information and the best alternative is the one with the highest average value.



Value of information. In classical approaches, VoI is defined as the increase in average value (or utility) attained by obtaining information prior a decision. Here we consider the payoff as the utility of a decision maker that balances the habitat value of the ecosystems and the cost of the alternative within a strategy (restoration designs in period one and two, and monitoring plan). Thus the VoI is calculated as:

$$VoI = U(MA_1) - U(MA_2), \quad (3)$$

where, MA_1 and MA_2 are different monitoring alternatives for the same restoration alternative within the same strategy. If a monitoring alternative is characterized by no uncertainty the corresponding payoff is called as value of perfect information.

Sensitivity and uncertainty analysis. A local and global sensitivity analysis⁵⁸ is performed by varying one and two variables at a time, and by using the Morris method⁵⁹ (Supporting Information). The local sensitivity analysis is performed to check the sensitivity of the payoff to variations of stakeholder preferences (Figure S6). The Morris method calculates the importance of each variable for the payoff by varying all variables at the same time and the interaction of each variable with all the others (Figure S7). The uncertainty analysis is performed by assigning a standard deviation to each variable equal to 50% (plus and minus) of the standard deviation of the variable average value. The payoff is then calculated for the new set of values of each variable. The probability of occurrence of each variable state is maintained the same.

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Acknowledgements

The authors are grateful to Laure Canis for developing an initial version of the model. This study was funded by the Jacksonville District of the US Army Corps of Engineers and from the USACE Environmental Benefit Analysis (EBA) program. Permission was granted by the USACE Chief of Engineers to publish this material. The views and opinions expressed in this paper are those of the individual authors and not those of the U.S. Army, or other sponsor organizations.

Author contributions

I.L., J.M.K. and M.C., designed the study. L.S. provided policy perspectives on adaptive management and applications. The modeling effort was performed by M.C., I.L., C.F., J.M.K. and G.A.K. A.L. provided Everglades data. All authors contributed to the preparation of the manuscript.

Additional information

Supplementary information accompanies this paper at <http://www.nature.com/scientificreports>

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Convertino, M. *et al.* Enhanced Adaptive Management: Integrating Decision Analysis, Scenario Analysis and Environmental Modeling for the Everglades. *Sci. Rep.* **3**, 2922; DOI:10.1038/srep02922 (2013).



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DOI: 10.1038/srep03795

SUBJECT AREAS:

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ERRATUM: Enhanced Adaptive Management: Integrating Decision Analysis, Scenario Analysis and Environmental Modeling for the Everglades

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SCIENTIFIC REPORTS:

3 : 2922

DOI: 10.1038/srep02922
(2013)

Published:
11 October 2013

Updated:
15 January 2014