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Demonstrating the Applicability of a Robust Decision Making (RDM) to Conservation Decision-Making Under Uncertain Future Climate: Pilot Study Using the Northern Pygmy Salamander *(Desmognathus organi)*

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ABSTRACT: Climate change challenges conservation planners in making decisions about habitat site selection and augmentation. This pilot study explores the use of Robust Decision Making (RDM), a decision analytic approach employed in water and coastal management, for conservation decision-making. It employs the RDM approach to design a theoretical decision experiment that compares the differences in performance between stylized static and adaptive land purchase strategies that notionally aim to protect additional habitat for *Desmognathus organi*, a salamander in the south central Appalachians, under uncertain future climate conditions. The static strategy purchases a specific parcel of land in the present, whereas the adaptive strategy leases two parcels in the present and purchases the most suitable later. Purchase decisions are based on projected future habitat suitability for *D. organi*, estimated using species response models trained with an ensemble of climate model projections. Using RDM methods that emphasize scenario-based analysis and statistical discovery of factors that favor one decision versus another in different futures, we find that the adaptive strategy tends to perform slightly better than the static strategy in terms of selecting highly suitable habitat over a wide range of futures. RDM shows promise as an approach to support conservation decision-making. Additional methodological development is needed to apply it to real-world conservation problems.

INTRODUCTION

Climate change and its associated uncertainty present conservation planners with a significant challenge, in particular, making habitat site selection and augmentation more difficult (e.g., Hodgson et al. 2009; Dawson et al. 2011; Grimm et al. 2013). Conservation planners have always grappled with uncertainties including understanding the interests of different species, measuring population sizes, identifying interactions among species, monitoring land use practices and species responses to these, securing land for conservation purposes, and other factors (e.g., Pressey et al. 1993; Costello and Polasky 2004; Strange et al. 2006). The loss of climatic stationarity adds a new, uncertain dimension to conservation decision-making (e.g., Dawson et al. 2011; Grimm et al. 2013; Wiest et al. 2014; LeDee and Ribic 2015; Mantyka-Pringle et al. 2016; Shah et al. 2016). Climate uncertainty presents not only a normative challenge – how to best compare alternative choices using uncertain scientific information – but also an organizational and behavioral one. Decision makers can find it difficult to consider a wide range of futures and instill confidence in their choices when the future is poorly understood.

This study describes a pilot application of Robust Decision Making (RDM) (Lempert et al. 2003) in a conservation decision-making context. RDM is an iterative, quantitative, analytic approach for supporting decisions under conditions of deep uncertainty, defined as the condition in which the parties to a decision do not know or do not agree on the system model relating action to consequence and/or the prior probability distributions for important inputs to those models. Conservation planning in a changing climate exhibits deep uncertainty (Mooney et al. 2009; Dawson et al. 2011; Moritz and Agudo 2013; Staudinger et al. 2013; Staudt et al. 2013). RDM has been employed in several contexts such as water and sea level rise management (e.g., Groves et al. 2008; Fischbach et al. 2012; Lempert et al. 2012; Groves et al. 2012; Groves et al. 2013; Tingstad et al. 2014), although never before for biodiversity or conservation-related decision support.

In addition, RDM has often been used to support adaptive management plan development, which may be one important way of addressing the deep uncertainty climate change imposes on conservation planning (Lawler 2009; Mawdsley et al. 2009; Araújo et al 2011). Adaptive management, which we consider here as explicitly designing plans to evolve over time in response to new information regarding future environmental, financial, and/or other conditions, is an increasingly popular concept in the conservation and biodiversity management literature (e.g., Hodges 1991; Staudinger et al. 2013; Stein et al. 2013).

In decision analytic research such as this, a problem can be simplified in order to better understand its decision characteristics and experiment with new analytic approaches. Thus, this pilot study focuses on a single salamander species, *Desmognathus organi*, chosen due to its location in the south central Appalachians, where climate change is expected to have a substantial impact (e.g., Milanovich et al. 2010), and because we had access to detailed data required for ecological modeling. We chose this species and area to coincide with another research effort focusing on salamander species in the Appalachians (Moskwik 2014). A single species alone is rarely emphasized in conservation plans and literature unless it has special significance (which *D. organi* does not appear to have), but it was a necessary simplification to enable focused exploration of the RDM-based approach in a new context.

The study also drastically simplifies conservation decision-making for the same reason – by comparing the differences in performance, using an RDM approach, between notional static and adaptive land purchase policies designed to augment the amount of Appalachian salamander habitat contained within Federal park lands. The stylized static policy purchases a specific parcel of land today based on future habitat suitability estimated using an ensemble of climate model projections, while the stylized adaptive policy leases and protects two parcels today and purchases one of them later when the future climate trajectory becomes clearer. This study compares strategy performance by evaluating each of them over a wide range of future climate projections, using multiple configurations of species response models. Using the resulting database of simulation results, we compare the two policies and suggest the future climate conditions that might incline notional decision makers towards one or the other policy approaches.

This work was undertaken as part of a broader, National Science Foundation (NSF) funded effort to understand the impacts of different types and spatial resolutions of climate change projections on decision-making in both species conservation and water planning contexts. As an initial, exploratory application, this study has numerous limitations, which we address throughout this paper. The work reported here lays the foundations for a methodology employed in subsequent efforts.

The next section describes our study area in further detail and our research approach and methods. The third section presents results comparing the performances of the stylized static and adaptive land purchase strategies. We close with discussion about whether and how RDM might be further developed to be useful for conservation planning and remarks on future applications of this work.

MATERIALS AND METHODS

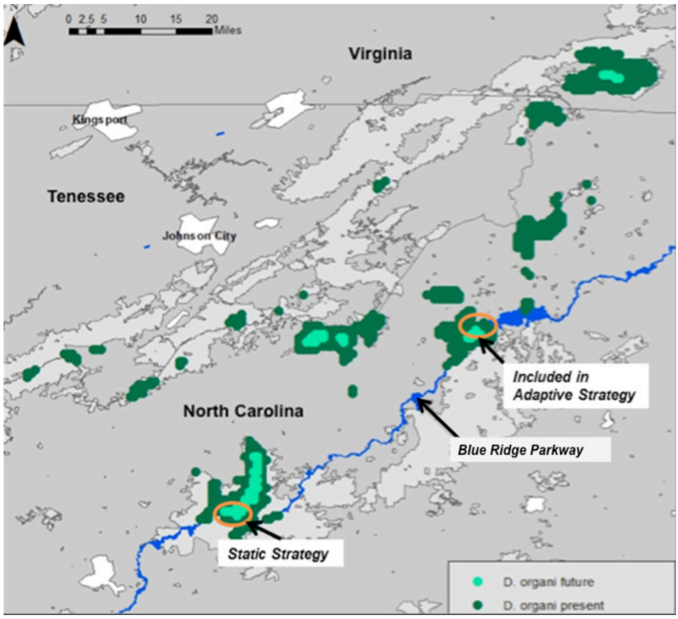
Species and Study Area

The Plethodontidae salamander *D. organi* (northern pygmy salamander) occurs at high elevations in North Carolina, Tennessee, and Virginia (Crespi et al. 2010). Presently suitable habitat for *D. organi* extends across a range of lands with different uses and levels of protection, including private, private conservation easement, National Park Service (NPS), U.S. Forest Service (USFS), Fish and Wildlife Service (FWS), and other government lands. Most populations occur at elevations greater than 1500 m in spruce-fir forests, although populations are encountered at lower elevations in mesophytic hardwoods on north slopes (Organ 1961).

Figure 1 shows the estimated contraction in suitable habitat for *D. organi* by 2041-2070 based on average estimates from the species distribution model ensemble (described later in this paper) driven by average changes in climate projected by our climate model ensemble (described later in this paper). By mid-century, our models suggest that *D. organi* suitable habitat (where environmental conditions are conducive to species presence) will be reduced to about eight percent of its present area.

For the purposes of developing our concepts for applying RDM to conservation decision-making, we considered any government-owned lands used primarily for conservation and recreation to be protected. We considered as unprotected all private land (including conservation easements) and other government-owned lands (e.g., military installations). This delineation is not entirely accurate; for example, human recreation on Federal lands may harm ecosystems, while some private landowners may have very little impact on the environment. Military installations do provide some protected habitat, and some conservation easements may be afforded higher protection status than some of the public lands we delineate as *protected*. However, this simplification allowed us to make convenient assumptions in this pilot study between land ownership and risk of decline in salamander habitat suitability in the decision model described later. Although these simplified assumptions undoubtedly impact our results, we did not attempt to quantify the effect.

Figure 1: Map of study region and projected *D. organi* present and future (2041-2070) ranges. *D. organi* presence was defined as sites having an average suitability score ≥ 500 across all climate scenarios and modeling approaches, described in detail later in the paper. The orange ellipses indicate the approximate locations of the land parcels considered in the static and adaptive strategies described later in the paper. The figure includes data from the United States Geological Survey (2012) and United States Census Bureau (2013), and was created using the ESRI ArcGIS program version 10.2.1.



Robust Decision Making (RDM) Research Approach

This study explores the use of RDM as a methodological framework to examine the impact of climate assumptions on conservation decision-making. RDM is an approach within the broader field of decision science that aims to help people manage difficult decisions under conditions of deep uncertainty (Lempert et al. 2003; Lempert et al. 2006;

Hallegatte et al. 2012; Lempert 2014). The approach rests on a simple concept. Rather than using computer models and data to describe a best-estimate future, the approach runs models on tens to thousands of different sets of assumptions to describe how plans perform in a range of plausible futures. Analysts then use visualization and statistical analysis of the resulting large database of model runs to help decision makers distinguish future conditions in which their plans will perform well from those in which they will perform poorly. This information can help decision makers identify, evaluate, and choose robust strategies that perform well over a wide range of futures.

There are several important differences between RDM and Species Distribution Modeling (SDM), but in many ways these are also complementary approaches. Whereas SDM relates observations of species in the field to environmental variables in order to statistically explain species-environment relationships (e.g., Guillera-Arroita et al. 2015; Schneiderman et al. 2015), RDM focuses analysis on decision-making and the scenario factors that lead to one decision being favored over another. As such, information derived through SDM can feed an RDM analysis – as it does in this analysis through our use of species response models – and an RDM analysis could also inform SDM by suggesting which species and environmental factors appear most influential in a specific conservation decision context.

Climate Models

This study focuses on future climate as a key uncertainty that could affect the performance of the adaptive and static land purchase strategies, employing eleven alternative climate projections from the North American Regional Climate Change Assessment Program (NARCCAP). We decided to use these particular projections because we had prior experience working with them and they were readily available.

NARCCAP pairs low-spatial resolution global General Climate Models (GCMs) with higher-resolution (50 km) Regional Climate Models (RCMs). The GCMs are each forced with the Special Report on Emission Scenarios (SRES) A2 scenario (Intergovernmental Panel on Climate Change, undated). For each GCM-RCM projection, we aggregated the NARCCAP data from three-hourly frequency to monthly climatology, generating thirty-year monthly time series for precipitation and daily minimum and maximum temperatures. Climate variable time series were then spatially interpolated from the native grid to the 800 m resolution required by the species distribution models using a kriging algorithm, with elevation as a covariate. We then computed differences (future minus current for temperature; future divided by current for precipitation), which we applied to the PRISM Climate Group's 30 arc-second 1971-2000 average monthly maximum and minimum temperature and precipitation dataset in a final downscaling step (DiLuzio et al. 2008). More detailed, local projections could have benefited our study, but were not available at the time of analysis. Importantly, we focus on the use of multiple climate projections as a means of exploring the effects of uncertainty on outcomes, and the downscaled GCM-RCM results are suitable for that purpose.

These eleven NARCCAP projections suggest consistently hotter future temperatures, spanning a range of about 1.5°C, and consistently wetter conditions, for the most part, spanning a range of about 250 mm/year in average annual precipitation. We expect *D. organi* may be particularly sensitive to warmer temperatures (Milanovich et al. 2010).

Projections from the eleven NARCCAP models described above provided important inputs for the suite of species distribution models used in our analysis. We used all of the models described below to conduct our work (we did not select a single or handful of models with the best "fit", although future work could weight models based on performance metrics). Importantly, we did not average the projections to create a single ensemble. Instead, we considered each as a distinct representation of a plausible climatic future in the analysis so as to inform how differences in expectations regarding climate can impact decision-making.

Species Distribution Models

We divided our study area into approximately 800 m by 800 m land parcels according to the 30-arc second grid used for the PRISM Climate Group's gridded climate data described in DiLuzio et al. (2008). This spatial scale may not be appropriate for all conservation land purchase decisions, but was necessary to use here because of the particular data and methods available to us for the species response modeling, which is an important limitation of our study. Following grid generation, we incorporated information about land use, including urbanized areas from the U.S. Census Bureau (US Census Bureau 2013) and type of land ownership (government or private) based on the land cover data from the United States Geological Survey (USGS) National Gap Analysis Program (GAP) Protected Areas Data Portal (United States Geological Survey 2012) using the ArcGIS program in order to assign each 800 m by 800 m land parcel land use and ownership characteristics. We did not attempt to reconcile actual property ownership lines with our imposed grid.

We calibrated the species distribution models using recent *D. organi* presence data and current climate data. For modeling algorithms we used five available in BIOMOD 1.1-7.04 (Thuiller et al. 2009), including generalized linear models (GLM), multivariate adaptive regression splines (MARS), random forest (RF), generalized boosted models (GBM), and generalized additive models (GAM).

For current climate data we used the PRISM Climate Group's 30 arc-second 1971-2000 average monthly maximum and minimum temperature and precipitation dataset (DiLuzio et al. 2008). Using this dataset we calculated twenty-one bioclimatic variables, commonly used in species distribution modeling, using DIVA-GIS 7.5 (Hijmans et al. 2001).

When employing the different species response models using the eleven different future climate projections, our full factorial design yielded 1,430 individual futures. Every future provided a habitat suitability score between 0 (lowest) and 1,000 (highest) for each 800 x 800 m grid cell considered in the analysis. Suitability is distinct from actual presence/absence, although the two factors can be related in that more suitable land is more likely to support the species. For the purposes of this study, we consider land with a suitability score of at least 500 to be "suitable" for *D. organi*. This was chosen for convenience, and could be more thoroughly evaluated in the future, including through engagement with stakeholders and additional simulation efforts. We refer the interested reader to Moskwik (2014) for a full description of our species distribution modeling methods.

Based on our threshold suitability score of 500, the mean of all species distribution models suggest that only eight percent of the current range of *D. organi* will remain suitable by mid-century (our estimate could change if the threshold suitability score for presence is varied). Specifically, the range contracts upward to higher elevations (Figure 1), consistent with expectations under a warming climate. Based on our projections, we do not expect any shift in the range outside of areas presently suitable for the species. This is also consistent with observed recent downward expansions of *D. organi* (Moskwik 2014) in concert with regional cooling during the 20th century (Rogers 2012). We do not consider the impact of stressors such as deforestation, invasive species, or other threats.

By examining variance in our results across the 1,430 futures using an Analysis of Variance (ANOVA) test, we found that alternative species distribution models, combined with different climate projections, contribute significant structural, or model-based, uncertainty. Factors affecting the suitability scores for *D. organi* include the modeling algorithm (e.g., random forest model, generalized boosted model), environmental variables (e.g., temperature, precipitation) used as predictors, future climate projection, and spatial modeling region. Of these factors, the choice of environmental variables to include as species distribution model predictors contributes the most to the uncertainty (51% of the total variance) with respect to habitat suitability, followed by the species distribution model structure (37% of the total variance). Importantly, the future climate projection only accounts for six percent of the total variance, which impacts our ability to assess the differences between static and adaptive land purchasing strategies under uncertain future climate conditions.

Strategies, metrics, and decision model

Our stylized analysis compares static and adaptive land purchase strategies. The static strategy purchases an 800 m x 800 m parcel of private land (one of the boxes in the grid previously described) in the near-term that has the highest mean future (2041-2070 average) suitability score for *D. organi* calculated assuming equal weightings over all climate projections and species distribution models. For simplicity, we focus on one 800 m by 800 m parcel of privately held land, but our general approach could be straightforwardly expanded to consider larger land purchases. We focus on land adjacent in one of the four cardinal directions (for simplicity) to current NPS holdings based on an assumption about the benefit of increasing the size of these lands, something that may be reconsidered in future work.

Using the same mean future suitability score calculation, the adaptive strategy initially places under lease the top two ranking parcels for suitability and subsequently chooses the higher ranking of the two land parcels for purchase using subsequent information regarding which climate projection is being most strongly validated by actual climate trends over time in a particular scenario, and employing equal weighting over the alternative species distribution models.

Although the adaptive strategy affords additional flexibility, it also imposes costs. In this analysis, we represent this cost of undertaking the adaptive strategy through increased risk that the habitat quality may degrade due to lack of management that would be conducted on a purchased plot of land in the static strategy.

For simplicity in the design of strategies for this pilot analysis, we do not consider employing a conservation easement, which could have more complex costs associated with it than a lease. In addition, we do not explicitly consider the price of entering into a purchase or lease contract, or the fact that different plots of land have different values.

To evaluate the success of the static and adaptive land purchase strategies, this study uses metrics that focus on the suitability of habitat for *D. organi*; that is, how well a parcel of land meets environmental conditions estimated to be best for the species. As described earlier, suitability is measured here on a 0 to 1,000 scale, with the latter endpoint representing the highest possible suitability rating.

In general, measures of effectiveness for the protection of a single species can include species abundance, habitat area, and habitat quality (e.g., Gering et al. 2003; Hodgson et al. 2009; Nelson et al. 2009). This study uses three measures that focus on habitat area and quality; in particular, asking:

- Is at least ten percent of the area of presently suitable land protected in the future (2041-2070)?
- Did the purchased land contribute to the ten percent conservation goal?
- What is the estimated suitability of the purchased land during 2041-2070?

The first measure focuses on a notional overarching conservation goal. For 1971-2000, 692 parcels exist in the study area with average suitability score ≥ 500, as determined by species distribution modeling described later in this section. This first measure is satisfied if in the future (years 2041 to 2070) the 69 parcels with the highest habitat suitability have scores of at least 500 and are all contained on protected land. In some futures there may not be a sufficient number of suitable parcels to achieve this goal no matter what land is purchased. Alternatively, in other futures, protected areas may include enough suitable habitat that the goal may be met whatever land is purchased. Finally, there are some futures in which the purchase of exactly one parcel of land will achieve the goal.

The second measure focuses on whether or not the purchased land contributes to meeting the conservation goal described above. This measure requires the purchased land to have suitability of at least 500 and to be among the 69 parcels with the highest suitability scores in mid-century, but can be met whether or not the overall conservation goal is achieved. The third measure focuses only on the future quality of the land purchased as measured by its suitability in each future scenario and is evaluated independently of the other two metrics. For the purposes of this pilot study, we make the simplifying assumption that suitability scores in the present and future may be interpreted as having the same biological meaning.

It is useful to note that defining measures of effectiveness for land management strategies represents an ongoing challenge (e.g., Fleishman et al. 2006; Boitani et al. 2008). Overall, “effectiveness” is a values judgment that should be made by decision makers, which increases the need for decision support approaches, such as that proposed here, that offer flexibility in the objectives they consider.

Our decision model, which brings together the different aspects of our analysis to help enable implementation of the RDM approach, ranks the suitability of different land parcels and calculates the three measures described above. To rank the parcels by suitability, the model conducts a simple sorting procedure where it identifies all non-urban private land parcels adjacent in one of the four cardinal directions to protected land, and then ranks them by *D. organi* suitability.

To calculate aggregate measures of success described above for the two strategies, the model adjusts the suitability score for each parcel in our study area based on its land use category. Any land presently within an urban boundary has suitability set to zero because we do not expect to find *D. organi* in urban environments. In this pilot study, conservation easement/leased land and privately owned lands had suitability scores degraded in each model run by factors of twenty and fifty over the course of the entire future time period, respectively. These values were chosen for convenience, and are intended to reflect our assumption of increased risk to habitat resulting from the lower level of formal management regulation than would be present in protected lands. The suitability of a private land parcel purchased in the static strategy remains unchanged because this land then becomes protected and thus at no risk for degradation in our simplistic approach, while the suitability of private lands leased by the adaptive strategy degrades because these now fall within our category of leased land at risk of some degradation.

The decision model produces adjusted suitability scores at mid-century for each parcel of land for each strategy under every projection from the species distribution models. The model then uses these suitability scores to calculate the metrics described earlier for each strategy.

RESULTS AND DISCUSSION

To compare the static and adaptive land purchase policies, we used the decision model to choose the specific land parcels considered as part of those policies and evaluated them over multiple futures. We then employed the resulting database of model runs to assess the value of the adaptive strategy and to identify the climate conditions that tend to favor it over the static strategy.

Table 1 provides an initial summary of the performance of the two strategies over the 1,430 futures using the three metrics previously described. The static plan results in 10% of habitat area protection in more futures (325) than the adaptive plan (308), though this difference is not significant with 95% confidence according to a Chi-Square test. Both strategies meet this goal in relatively few futures because at least one of the 69 most suitable parcels of future habitat often resides in private or existing conservation easement land that was not selected as part of a purchase strategy, or in some cases there are insufficient numbers of suitable land parcels to achieve the overarching conservation goal regardless of ownership. The static plan may result in 10% habitat area protected in more futures because land leased as part of the adaptive plan can degrade before it is purchased.

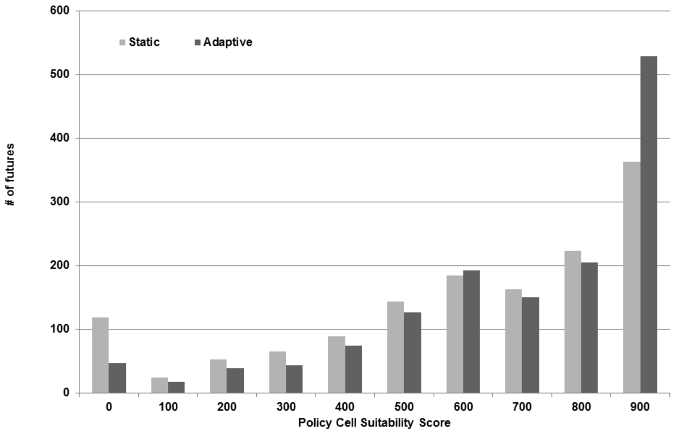
Table 1: Number of futures in which static and adaptive plans satisfy the three metrics.

Metric	STATIC	ADAPTIVE
10% of habitat area protected	325	308
Purchased land contributes to top 10% habitat protected goal	766	974
Purchased land has suitability > 500	1076	1204

For the other two metrics we defined, the adaptive plan performs better than the static. The adaptive plan contributes to the 10% habitat protected goal in more futures (974) than the static (766), which is significant within a 95% confidence interval according to a Chi-Square test (p=0.001). The adaptive plan also purchases land with suitability scores greater than 500 in more futures (1,204) than the static (1,076). On average, the suitability of land purchased increased by 82 suitability points using the adaptive plan (adaptive strategy average suitability = 744, static strategy average suitability = 662), significant with 95% confidence according to both a t-test and an ANOVA. (This is not surprising, considering that a t-test is a special case of the one-way ANOVA.)

The histogram in Figure 2 shows how, compared with the static policy, the adaptive strategy substantially increases the number of futures in which the purchased land has a high suitability score (> 900). Relative to the static policy, the adaptive strategy also decreases the number of land purchases with very low suitability scores (< 100). The static strategy increases the number of futures with land purchases with suitability scores between 700 and 900. These patterns suggest that in some futures the adaptive strategy can identify the best available land better than the static. However, there appears to be a range of futures for which it seems that the costs of the adaptive strategy (due to land degradation) exceed its benefits. Altering our assumptions about land degradation could change these results. One particularly important assumption in this pilot analysis is that protected lands do not degrade, which is realistically not the case.

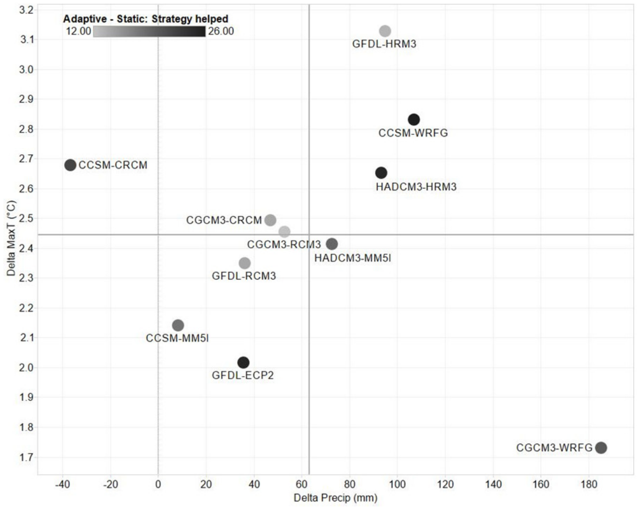
Figure 2: Histograms of land parcel suitability scores for the static and adaptive policies.



To identify the climate conditions that tend to favor the adaptive over the static strategy, Figure 3 compares the two strategies based on the difference in the number of futures in which the purchased land makes a difference in achieving the goal of protecting at least ten percent of the area of presently suitable land. These differences are displayed along axes that represent each climate projection's spatially averaged deviation from the current (PRISM) annual maximum temperature and annual mean precipitation, respectively. For climate projections close to the mean deviations from current climate conditions, the static and adaptive strategies perform similarly in terms of selecting a parcel of land that was highly suitable relative to all other parcels (regardless of ownership). For projections further from the mean delta, the adaptive strategy tends to perform better than the static. This pattern makes sense since the static strategy purchases land based on the climate ensemble mean projection.

Figures 2 and 3 suggest that the improvement gained by the adaptive strategy remains small relative to the total variance across futures. This is due to at least two factors. The adaptive strategy responds to the notional decision maker gaining additional information about the climate at a later point in time, but the large majority of the variance in the suitability scores depends on uncertainty associated with the species distribution models. In addition, the adaptive strategy leases the top two land parcels based on the climate ensemble mean, and thus may be choosing from a relatively narrow portfolio of options. Alternative adaptive strategies that lease a more diverse range of parcels might perform better. The relative lack of climate sensitivity in this species, the present design of the adaptive strategy to select from a narrow portfolio of options, and the inherent assumption that decision makers will be able to ascertain the climate trajectory with greater clarity in the future, lead us to only cautiously suggest the benefit of an adaptive strategy, such as that presented in this pilot example.

Figure 3: Relative benefit of the adaptive strategy compared with the static strategy in different climatic futures. Specifically, the difference in number of times the adaptive strategy was successful in achieving the goal in metric 1 (Is at least ten percent of the area of presently suitable land protected in the future (2041-2070)?) versus the static strategy, compared with each climate projection's spatially averaged deviation from the current (PRISM) annual maximum temperature and annual mean precipitation.



It is also worth noting that up until this point, we have made no assumptions regarding the distribution of probabilities across the 1,430 futures considered in the analysis. This is an important consideration since, as Figure 3 suggests, the value a decision maker attributes to the adaptive strategy compared to the static may depend on her expectations about the relative likelihood of the alternative climate projections. If the projections close to the ensemble mean are significantly more likely in a decision maker's mind than those further away, the benefit of the adaptive strategy will be minimized relative to the situation where the decision maker believes that the full range of climate projections are equally likely.

CONCLUSIONS

Managing climate uncertainty in conservation planning is a topic of increasing interest. Predictions for species' habitat availability in the future (e.g., Spencer et al. 2010; Stein et al. 2013) can be highly sensitive to climate projections, which are deeply uncertain. At present, many conservation plans do not quantitatively consider the uncertainty due to future climate change (e.g., Olson and Dinerstein 2002; Hoekstra et al. 2005; Spencer et al. 2010), although numerous assessments of biodiversity and future ecosystem health note the importance of climate change and its impacts (e.g., Parmesan, 2006; President's Council of Advisors on Science and Technology 2011; UK National Ecosystem Assessment 2011; Grimm et al. 2013; Nelson et al. 2013; Stein et al. 2013; Intergovernmental Panel on Climate Change 2014).

This article describes a new application for decision analytic research, demonstrating some initial steps for how RDM methods could help support the process of selecting and/or augmenting lands for species conservation. To do this, we followed the common practice in decision analytic research of simplifying the underlying research problem in order to understand its decision characteristics more deeply and experiment with a new analytic approach. We used some data available for a single salamander species in the Appalachian Mountains to demonstrate a simple, theoretical example. Although it appears that the RDM approach may have some promise for conservation planning research, there are also many limitations brought to light by our study that indicate more methods development is needed before the approach can be applied to a more complex, real world situation.

As a quantitative decision analytic approach for supporting decision-making under conditions of deep uncertainty, RDM offers several useful attributes for conservation planners that complement existing approaches and tools. The RDM method represents uncertainty with multiple runs of simulation models, which makes it very flexible in terms of the ecological models utilized, the types of climate and other uncertain information included, and the representations and algorithms employed to describe the alternative conservation strategies under consideration. In this study, we used highly detailed species distribution models to estimate land suitability, a relatively broad ensemble of climate projections, and a simple but easily generalizable representation of an adaptive land purchase strategy. RDM enabled us to examine the value of alternative, stylized ecological reserve site augmentation. Such information could provide useful information to decision makers and could help facilitate deliberation and engagement with stakeholders.

In particular, this study finds that an adaptive land purchase strategy that leases two parcels of land and then subsequently purchases the one most favorable depending on the climate trajectory tends to perform slightly better over a wide range of plausible futures than a static strategy that purchases the single best-estimate parcel today. The adaptive strategy does impose costs because in this study the suitability of land under lease can degrade faster than that purchased today for protection. The impact of these costs may be seen in the statistically insignificant difference between static and adaptive plan performance in achieving the overarching conservation goal described by metric 1.

Here, we summarize a few of the most important limitations of this pilot study. The assumption in our adaptive strategy that decision makers will be able to link observed climate trends with a particular climate trajectory in order to make a future decision is almost certainly overly optimistic. Thus, this analysis likely represents an upper bound to the benefits of the very simple "lease two, then buy one parcel strategy" considered here. In addition to more realistic assumptions about the potential for future learning regarding climate, a successful adaptive strategy would also likely require efforts to reduce uncertainty regarding the species distribution models used. A successful adaptive strategy might also employ a broader set of policy levers, such as protecting diverse parcels of land (perhaps as part of an effort to protect multiple species or preserve genetic diversity within a single species), identifying ecological corridors, or enacting some type of habitat exchange policy that shifts the location of protected areas over time (e.g., Cuperus et al.1999; Venter 2014).

In addition, ecosystems are complex; conservation measures may impact some species positively and others negatively, and interdependencies, such as within a food web, may need to be considered (e.g., Tylianakis et al. 2010). Climate change, with its effects on species' movements and ecosystem composition, makes it even more difficult to define broad conservation goals and specific metrics (e.g., Hodgson et al. 2009; Dawson et al. 2011). Further, land protection status can be associated with land management objectives without explicit consideration of biodiversity features or goals (e.g., Boitani et al. 2008), which can disconnect land protected status from conservation decisions. The measures used in this study clearly represent only a small window into the full set of those that might be appropriate.

This pilot study has several other limitations. In many ways, it lacks a rigorous approach that would be used to support real-world conservation decisions. Also, we have not formally assessed decision maker preferences and goals with respect to *D. organi*. As a pilot study, this analysis did not include any stakeholder deliberations, but the general RDM approach is designed to facilitate such interactions. In addition, we did not consider issues related to salamander population dynamics or advances in understanding of the species ecology of *D. organi*, which is a recently revised species. Further, the species distribution models used here neglect potentially important interactions among species.

The study employs a simple, and not entirely accurate, representation of land use and considers notional measures of success relevant to only a single species. We consider only one particular type of conservation investment and focus on a small subset of the possible land use considerations and associated uncertainties, in particular the rate at which habitat may degrade based on the type of land ownership.

While broader than many in the literature, the range of climate projections considered here samples only a small range of the plausible futures and is insufficiently dense to provide good statistics for the vulnerability map in Figure 3. Finally, we did not analyze the impacts of variability associated with the species response modeling, which represents a much larger source of variability than future climate.

Despite limitations, this study illuminates important differences between conservation planning and previous RDM applications and suggests some initial ideas for managing climate uncertainty in conservation planning. Important differences with previous RDM applications include focus on finer scale geography and significantly more uncertainty in the system (species response) models than in previous water management applications. This pilot study adapts tools developed in previous RDM studies to this new context. In so doing, it also provides useful information on the extent to which the future habitat of *D. organi* may contract over a wide range of plausible future climate change and suggests that compared to a land purchase strategy that focuses on the best-estimate future climate, an adaptive land purchase strategy might expand the range of climate futures over which conservation strategies benefit the species.

The RDM framework can be straightforwardly extended to address many of the limitations of this pilot study by, for instance, considering multiple species, a wider range of climate projections, strategies that employ a richer array of policy options and potential for learning, and facilitating the reframing and refocusing of goals with which the biodiversity community may need to engage in the face of the climate change challenge. Overall, as a flexible, iterative, multi-scenario approach to decision support, the RDM approach used in this study – once further developed and refined for conservation applications – may prove generally useful in helping the biodiversity community design and evaluate adaptive management strategies under a wide range of potential future climate conditions.

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