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Qualitative value of information provides a transparent and repeatable method for identifying critical uncertainty

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Abstract: Conservation decisions are often made in the face of uncertainty because the urgency to act can preclude delaying management while uncertainty is resolved. In this context, adaptive management is attractive, allowing simultaneous management and learning. An adaptive program design requires the identification of critical uncertainties that impede the choice of management action. Quantitative evaluation of critical uncertainty, using the expected value of information, may require more resources than are available in the early stages of conservation planning. Here, we demonstrate the use of a qualitative index to the value of information (QVoI) to prioritize which sources of uncertainty to reduce regarding the use of prescribed fire to benefit Eastern Black Rails (*Laterallus jamaicensis jamaicensis*), Yellow Rails (*Coterminous noveboracensis*), and Mottled Ducks (*Anas fulvigula*; hereafter, focal species) in high marshes of the U.S. Gulf of Mexico. Prescribed fire has been used as a management tool in Gulf of Mexico high marshes throughout the last 30+ years; however, effects of periodic burning on the focal species and the optimal conditions for burning marshes to improve habitat remain unknown. We followed a structured decision-making framework to develop conceptual models, which we then used to identify sources of uncertainty and articulate alternative hypotheses about prescribed fire in high marshes. We used QVoI to evaluate the sources of uncertainty based on their magnitude, relevance for decision making, and reducibility. We found that hypotheses related to the optimal fire return interval and season were the highest priorities for study, whereas hypotheses related to predation rates and interactions among management techniques were lowest. These results suggest that learning about the optimal fire frequency and season to benefit the focal species might produce the greatest management benefit. In this case study, we demonstrate that QVoI can help managers decide where to apply limited resources to learn which specific actions will result in a higher likelihood of achieving the desired management objectives. Further, we

summarize the strengths and limitations of QVoI and outline recommendations for its future use for prioritizing research to reduce uncertainty about system dynamics and the effects of management actions.

Keywords: adaptive management, decision analysis, Eastern Black Rail, endangered species, hunted species, marsh birds, mottled duck, structured decision making, value of information, yellow rail

Introduction

Choosing management actions that will best advance conservation for threatened or endangered species can be difficult because managers need to make decisions in the face of uncertainty, often with limited time and resources. In many cases, management decisions are recurrent and impeded by uncertainty (Runge, Converse, and Lyons 2011; Smith 2020). In these situations, adaptive management can balance achieving conservation objectives and reducing uncertainty by pairing monitoring (i.e., learning) with management actions (Walters 2001; Williams, Szaro, and Shapiro 2007; Smith 2020). More broadly, decision analytic frameworks can identify which uncertainties are most valuable to reduce to improve the outcomes of management actions when they include Value of Information (VoI) analyses (Runge, Converse, and Lyons 2011; Moore and Runge 2012; Canessa et al. 2015; Smith et al. 2020).

A decision analytic framework guides decision-makers by breaking the problem into its key components: framing the <u>pr</u>oblem, articulating <u>o</u>bjectives, identifying possible <u>a</u>lternative actions, determining the <u>c</u>onsequences of each action, and evaluating <u>t</u>radeoffs among alternatives (Gregory et al. 2012; Hammond et al. 1999), sometimes known as the PrOACT decision model. Value of Information (VoI) is a decision analytic tool that can be used within this framework to evaluate how much the expected outcome of management could be improved if uncertainty could be reduced prior to choosing a preferring action (Raiffa and Schlaifer 1968; Bolam et al. 2019). One of the foundational premises of adaptive management is that some uncertainty impedes the choice of management action (Walters 1986), therefore, VoI analyses are integral to the design of an adaptive management program because they focus the monitoring and learning on relevant uncertainty; in doing so, VoI analyses help to identify and avoid investment in research and monitoring activities that are unlikely to affect the choice of a management alterative.

Several VoI metrics exist for comparing the expected benefit of gathering new information to resolve uncertainty among various hypotheses. The expected value of perfect information (EVPI) is the difference between the expected value under certainty (i.e., perfect information) and uncertainty (Raiffa and Schlaifer 1968) and provides a useful measure of the maximum possible benefit of fully resolving all uncertainty (Runge, Converse, and Lyons 2011; Canessa et al. 2015). The expected value of perfect partial information (EVPXI) can be useful for measuring the value of reducing particular components of uncertainty (Runge et al. 2011). The expected value of sample information (EVSI) quantifies the expected improvement in performance that results from collecting less-than-perfect information (Canessa et al. 2015; Williams and Brown 2020). These traditional, quantitative VoI methods each require data that may not be readily available at an early stage of decision prototyping. However, the qualitative index to the value of information (QVoI) provides an efficient method for identifying critical uncertainty that is consistent with quantitative VoI methods but asks less of the decision maker and analysts

(Rushing et al. 2020, M. Runge et al. unpublished data*,* Lawson et al. 2022). Therefore, QVoI offers an alternative approach at the early stages of decision making, especially for newly listed threatened or endangered species where management decisions may be made quickly under uncertainty.

QVoI analysis is a stepwise process that includes articulating and scoring alternative hypotheses, calculating QVoI, and comparing QVoI against the expected reducibility of uncertainty for each hypothesis (Rushing et al. 2020, Lawson et al. 2022). In this approach, participants create conceptual models of the managed system and identify key uncertainties within the system that may impede the choice of management actions. Based on those key uncertainties, participants articulate testable hypotheses and qualitatively describe how they think the system would respond to management alternatives under each hypothesis. Participants then score each source of uncertainty based on the magnitude of uncertainty, relevance to decision-making, and the feasibility of reducing the uncertainty through research and monitoring. Finally, a decision analyst calculates QVoI, compares QVoI against the expected reducibility for each hypothesis, then conducts Pareto analysis (Williams and Kendall 2017) to categorize and prioritize hypotheses.

Here, we present a case study developed through a decision prototyping workshop convened to structure the decision, articulate alternative hypotheses about prescribed fire in northern Gulf Coast high marshes of the United States, and use QVoI to identify and prioritize testing key uncertainties to benefit Yellow Rails (*Coturnicops noveboracensis*), Mottled Ducks (*Anas fulvigula*), and federally threatened Eastern Black Rails (*Laterallus jamaicensis jamaicensis*; hereafter, focal species). Finally, we discuss limitations and potential improvements to the QVoI analysis and elicitation process for future applications.

Methods

Study species and area

Fire regimes are important in shaping the composition and structure of fire-adapted landscapes, such as saltmarshes, as many species require periodic fire for their survival (Gill and Allan 2008; Whitlock et al. 2010; Krebs et al. 2010). Prescribed fire is used in coastal wetlands and high marsh to maintain these fire regimes to improve wildlife habitat, manage undesirable or invasive vegetation, and reduce hazardous fuel buildup (Lynch 1941; Nyman and Chabreck 1995; Allain and Grace 2001). However, the biological requirements as they relate to prescribed fire in high marsh are unknown for the focal species in the Gulf of Mexico, and the individual requirements for a species must be understood before fire can be prescribed to benefit that species. High marshes are a subset of irregularly flooded coastal wetlands that provide important habitat for the Eastern Black Rail, Yellow Rail, and Mottled Duck across the Gulf of Mexico. The Eastern Black Rail is a small, highly secretive (i.e., difficult to detect and monitor; Conway 2011) marshbird that is present in high marsh and wet meadows along the Gulf of Mexico year-round (Watts 2016) and was recently listed as threatened under the U.S. Endangered Species Act (McGowan et al. 2020; USFWS 2020). Yellow Rails can be found in coastal wetlands of the Gulf of Mexico during the non-breeding season (October – March [Anderson 1978; Soehren et al. 2018]) when many prescribed burns are conducted. Mottled ducks are a species of management concern that inhabit coastal wetlands along the Gulf of Mexico year-round but depend on high marsh for nesting and brood rearing (January – July [Bonczek and Ringelman 2021]).

All focal species are responsive to local, dynamic wetland conditions and require marshes with standing water ~10-15 cm deep with abundant emergent vegetation adjacent to relatively drier, higher elevation areas (Butler et al. 2010; Haukos, Martinez, and Heltzel 2010; Roach and Barrett 2015). Loss of wetlands due to development, degradation, and sea level rise continue to be serious conservation challenges for all focal species, especially Eastern Black Rails (Johnson et al. 1991; Stern, Morawski, and Rosenberg 1993; Niemuth and Solberg 2003; Quesnelle, Fahrig, and Lindsay 2013; McGowan et al. 2020). Given that fire is necessary to manage habitat (Nyman and Chabreck 1995) and few studies have evaluated whether marsh burning fulfills its objectives to benefit focal species, there is a growing need to reduce uncertainty about how focal species are responding to prescribed fire.

Problem framing

We organized a virtual 2.5-day workshop from September 15-19, 2020 for 21 participants with varied professional expertise (e.g., prescribed fire, focal species management, high marsh habitat management, endangered species regulation, and conservation) from state and federal agencies, universities, and non-governmental organizations and followed the PrOACT model (Fig. 1) to solicit feedback regarding the uncertainties around the potential impacts of prescribed fire on the focal species (Appendix S1). A decision analytic approach begins with identifying who will be making the decision; what the objectives are and what types of management actions are available to the decision maker; how often the decision be will made; what the spatial boundaries of the decision are, and importantly, why the decision needs to be made (Smith 2020). The who, what, where, when, and why of the decision form the basis for a problem statement (Conroy and Peterson 2013). Prior to the workshop, we asked participants to individually consider each of the decision elements for using prescribed fire as a management tool in marshes along the Gulf coast using a web-based questionnaire (Appendix S2). Given that group performance plateaus at 8-10 participants (Hogarth 1978, Troyer 2003), on the first workshop day, we randomly assigned 4-6 participants to each of three breakout groups, in which they remained throughout the duration of the workshop. Each group discussed their individual responses to the web-based (pre-workshop) questionnaire and used their responses as a guide to develop, refine, and agree upon a problem statement. The problem statements from each breakout group were next presented to, and discussed with, all participants in a plenary session. All participants then used these group problem statements as the foundation to develop, refine, and agree upon one cohesive problem statement that was used throughout the remainder of the workshop.

Objectives setting

Structured decision making uses value-focused thinking to identify fundamental management objectives (Keeney 1992). Objectives are statements about specific, quantifiable outcomes that reflect the values of the decision makers and stakeholders and relate directly to the management decision being made (Conroy and Peterson 2013). An important step in developing a complete set of objectives is to separate fundamental objectives (i.e., what are we hoping to accomplish) from means objectives (i.e., how are we going to accomplish it; Lyons et al. 2008). The participants returned to their assigned breakout groups to develop a list of objectives and create objectives hierarchies to organize fundamental and means objectives (Conroy and Peterson 2013). Each group brought their objectives to the larger group for discussion and refinement. We then developed a cohesive objectives network based on the work from the breakout groups to demonstrate the relationships between the fundamental objectives, means objectives, and management actions to benefit the focal species.

Conceptual modeling and hypothesis development

We combined the alternatives and consequences steps of the PrOACT decision model by developing conceptual models to visually represent the relationships between possible management actions and outcomes, and to identify scientific uncertainties (Burgman et al. 2006; Addison et al. 2013). Participants in breakout groups were asked to create influence diagrams (i.e., graphical representations of decision problems [Howard and Matheson 2005; Carriger and Newman 2012]) as conceptual models of system dynamics within the high marsh. Each group then focused on the prescribed fire management alternative and used the influence diagram to articulate key uncertainties and develop initial qualitative predictions on how prescribed fire might affect the system. Each group developed 3-4 testable alternative hypotheses (H_A) which followed a common format that specified a threat to the focal species, described the demographic mechanism by which they were affected, and made predictions about relevant management actions to test the hypothesis. Groups were not limited to 3-4 hypotheses; however, they were limited by the amount of workshop time allowed for generating hypotheses. Each group presented their alternative hypotheses (H_A) to the rest of the participants to gather feedback for additional refinement within the small groups. The null hypothesis (H_0) corresponding to each alternative hypothesis was implied and not explicitly stated. Following the workshop, we expressed each source of uncertainty as a pair of null (H_0) and alternative (H_A) hypotheses, coupled with the preferred management alternative associated with each.

Qualitative value of information analysis

The QVoI analysis requires a standardized rubric to evaluate each source of uncertainty (as represented in the paired hypotheses) based on three attributes: the magnitude of uncertainty (Magnitude), the relevance to decision making (Relevance), and the degree to which uncertainty could be reduced through research and monitoring (Reducibility; Rushing et al. 2020). We evaluated Magnitude on a scale from 0-4 where a score of 0 (low uncertainty) represents a firm foundation to support either the alternative hypothesis (H_A) or the null hypothesis (H_0) and a score of 4 represents no theoretical or empirical basis to support either alternative hypothesis (high uncertainty). We evaluated Relevance on a scale of 0-3 where 0 represents a case where the same alternative is preferred under both the alternative (H_A) and null (H_0) hypotheses (thus the uncertainty is not an impediment to choice of action) and a score of 3 indicates that the preferred action is very different under the null and alternative hypotheses . We evaluated Reducibility on a scale of 0-3 where 0 suggests that it will be difficult to resolve the uncertainty in favor of one hypothesis or the other and 3 indicates that it will be relatively easy to reduce uncertainty.

While it is important to maintain the minimum value of the constructed scales for Magnitude and Relevance at zero, the maximum values are arbitrary (M. Runge et al. unpublished data), and therefore could be tailored to the decision context, if necessary. Nevertheless, because the scale for Relevance was carefully crafted by Rushing et al. (2020) relative to natural variability and other uncertainties, we suggest that this 0–3 scale is maintained. Following Lawson et al. (2022), we tailored the Magnitude scale to our decision context by changing the definitions for the levels (but maintained four levels, 0–3). Specifically, we changed the numerical thresholds defining a “small”, “moderate” and “large” number of studies because the literature for our decision context is smaller than the literature reviewed in Rushing et al. 2020. Any modifications to constructed scales for Magnitude (or Reducibility) should follow best practices for constructed scales (Keeney and Gregory 2005). Narrative definitions for the scales of each attribute are found in Appendix S3.

Because EVPXI can be separated mathematically into two multiplicative components – the relevance of the uncertainty to the decision maker and the degree of uncertainty to the decision maker (M. Runge et al. unpublished data) – the product of the Magnitude and Relevance scores (i.e., QVoI) is proportional to EVPXI. QVoI can then be evaluated against Reducibility – the practicality of reducing the uncertainty (M. Runge et al. unpublished data) – to prioritize hypotheses based on their Pareto optimality. A hypothesis is considered to be Pareto optimal if choosing a different hypothesis would lead do a reduction in both QVoI and Reducibility (Williams and Kendall 2017).

We used a combination of training, group discussion, and independent scoring (Hanea et al. 2017) to elicit QVoI attributes (Magnitude, Relevance, and Reducibility). The training involved discussion about the various potential biases that may influence scoring (Wendt and Vlek 1975) and a detailed presentation of each attribute with opportunities for follow-up questions and discussion. Alternative hypotheses (H_A) from each breakout group's conceptual models were presented one-by-one in plenary, providing an opportunity for discussion of the management action and clarification of the uncertainty. Following the discussion, participants independently scored each alternative hypothesis based on the standard QVoI rubric (Appendix S3) using an online scoring system that allowed participants to score hypotheses in real-time. Because participation in the initial workshop was limited, we held a second round of elicitation after the workshop and had a second group of experts score the hypotheses using the same procedures (i.e., virtual training, group discussion, and independent scoring). Of the 21 participants at the initial workshop, 9 participated in both elicitation rounds; for these individuals, we only used their scores from the second round of elicitation in the QVoI analysis.

Following the workshops, we computed QVoI for each participant using their Magnitude and Relevance scores (QVoI = Magnitude x Relevance), then calculated the mean QVoI and Reducibility scores across all participants. We plotted the mean QVoI and Reducibility scores across all participants in two-dimensional space to assign each hypothesis to one of the four prioritization categories: highest priority, high priority, medium priority, or low priority (Rushing et al. 2020). Given that there is flexibility between the "high" and "medium" quadrants (Lawson et al. 2022), we opted to prioritize QVoI (i.e., hypotheses scoring higher in QVoI and lower in Reducibility) due to the inherent difficulty in resolving uncertainties related to prescribed fire (i.e., all uncertainties will be difficult to reduce; therefore, we prioritized those with higher Magnitude and Relevance scores).

Rather than place hypotheses into the four categories based on natural breaks in the final QVoI and Reducibility scores (e.g., Rushing et al. 2020), we used the average of the minimum and maximum final QVoI and Reducibility scores to create the four quadrants (Lawson et al. 2022). We then prioritized hypotheses based on their Pareto optimality whereby hypotheses along the frontier maximized QVoI and Reducibility. Following the workshops, we reengaged with participants to review the hypothesis classifications and their Pareto optimality then selected a hypothesis to test experimentally within an adaptive management framework over the next 5–10 years. By choosing a hypothesis along the Pareto optimal frontier, a decision-maker would only be required to compromise in one attribute or the other (QVoI or Reducibility) but not both (Williams and Kendall 2017).

Results

Problem framing and objectives setting

As a result of the problem framing exercises, the 21 workshop participants developed a problem statement that focused on using prescribed fire in high marshes to increase occupancy and abundance of focal species, identifying constraints on management, and understanding any tradeoffs among focal species. The consensus problem statement was:

In order to increase rail occupancy (Black and Yellow Rails) and Mottled Duck abundance at sites along the northern Gulf Coast of the United States, land managers (state, federal, private, and non-governmental organizations) want to use prescribed fire in high marsh habitat to optimize the vegetation structure that focal species require during the breeding and non-breeding seasons. Further, land managers would like to use prescribed fire as a means of habitat improvement for focal species while understanding other priorities may limit the desired frequency of prescribed burns at a particular locale. Land managers also aim to minimize focal species conflicts that might arise as a consequence of prescribed burns.

Our objectives were defined through an iterative process in which the workshop participants worked in separate breakout groups to create objectives hierarchies to identify fundamental and means objectives, which were later combined to a 'cohesive' version. The cohesive hierarchy identified 4 fundamental objectives in our case study: maximize occupancy probability of both Black and Yellow Rails, increase Mottled Duck abundance, and minimize management costs. As an entire group, the participants then developed, refined, and agreed upon an objectives network based on their breakout group objectives hierarchies to help visualize the relationships among each of the objectives (Fig. 2).

Conceptual modeling and hypothesis development

Each of the 3 breakout groups created an influence diagram that depicted hypothesized relationships between the proposed management alternatives and ecological factors relevant to the focal species, chance events, and the fundamental objectives of increasing occupancy and abundance (e.g., Fig. 3). Three breakout groups generated 9 alternative hypotheses (H_A; paired with implied null hypotheses [H_0]), which generally fell into three aspects of system dynamics: patchiness of burning (#1, Microtopography; #2, Interspersion; #9, Mosaic Burn; Table 1), seasonality of burning (#3, Mixed Seasonality; #5, Fall vs. Winter; #6, Matched Seasonality; Table 1), and frequency of burning (#4, Predation; #8, Fire Return Interval; Table 1). The Mixed Management hypothesis (#7) was the only alternative hypothesis to fall outside of these groupings.

Each of the patchy burn hypotheses were based on the theory that manipulating the intensity, severity, and extent of fires to induce heterogeneity in the landscape (fire diversity or pyrodiversity) is important for maintaining wildlife communities (Jin et al. 2012; Ponisio et al. 2016; Bowman et al. 2016). In other words, it is hypothesized that unburned patches act as important refugia for focal species during a prescribed fire event, and unburned patches also provide transitional habitat for focal species to utilize prior to repopulating the burned areas as the habitat recovers (Meddens et al. 2018). However, each of these patchy burn hypotheses have proposed to achieve high pyrodiversity via a different management alternative (Table 1). The Microtopography hypothesis (#1) suggested that high levels of pyrodiversity can be achieved to benefit focal species by identifying sites with high microtopographic indices to apply prescribed fire. In this case, the microtopography of the landscape creates the desired pyrodiversity. The Interspersion hypothesis (#2) suggested deliberately creating a matrix of multiple-aged vegetative refugia and new growth by applying fire in a grid-like manner across the landscape.

The Mosaic Burn hypothesis (#9) proposed the use of weather conditions (e.g., periods of high relative humidity) to promote high pyrodiversity. For example, it is likely that fires induced by lightning strikes historically occurred during the later afternoon or early evening, burning into the night when relative humidity usually increases, resulting in a burn with high pyrodiversity (Nyman and Chabreck 1995).

Three of the nine hypotheses were based on literature that suggests the season of fire can strongly affect the post-fire recovery of plant populations required for focal species persistence (Knapp, Estes, and Skinner 2009; Miller et al. 2019); however, each of the seasonality hypotheses proposed a different management alternative to produce the appropriate plant community for focal species habitat. The Mixed Seasonality hypothesis (#3) posited that prescribed burns during the growing season reduce woody vegetation (which negatively impacts focal species) whereas prescribed burns during the dormant season increase nutrient cycling and thus productivity of fire-dependent herbaceous vegetation. Therefore, sites require a combination of growing season and dormant season burns to maintain the appropriate vegetation structure required for focal species. The Fall vs. Winter hypothesis (#5) suggested that the appropriate time to burn may be dependent on the life history of the focal species. For example, prescribed fire during the fall (September – November) will reduce the amount of woody vegetation, which is beneficial for nesting Mottled Ducks, but may lower the probability of survival of resident Eastern Black Rails because fall burns could coincide with their flightless molt period (Eddleman, Flores, and Legare 2020; Hand et al. 2021). Winter burning (December – February) would not coincide with the flightless molt period. The final seasonality hypothesis, Matched Seasonality (#6), stated that when prescribed fire is used at the appropriate frequency, matching the historical fire season will produce the optimal vegetation structure for focal species persistence.

Two of the 9 hypotheses focused on the frequency of burning because fire leads to changes in the composition of the vegetation community (Nieuwenhuis 1987; Glitzenstein, Streng, and Wade 2003); therefore, understanding the appropriate frequency at which to burn is important for management. Similar versions of the Fire Return Interval hypothesis (#8) were created by each of the 3 workshop groups during the hypothesis development stage; thus, we combined the hypotheses by each group into a single hypothesis proposing that due to differences in annual precipitation and soil characteristics, the appropriate fire return interval to benefit focal species would vary regionally across the Gulf of Mexico. The Predation hypothesis (#4) stated that as fire frequency increased, the vegetation characteristics on the landscape would be less suitable to predators (i.e., vegetation would be shorter and less dense); therefore, frequent prescribed fires would lead to a decrease in predator abundance and increase survival rates for focal species.

The final hypothesis was the Mixed Management hypothesis (#7). This hypothesis proposed the management alternative that adding light grazing by cattle to the landscape can lead to soil compaction in targeted areas, creating microtopographic features that might be desirable for focal species. The addition of prescribed fire to these sites would help to control woody vegetation. The combination of management practices would therefore create the appropriate habitat heterogeneity and vegetation structure required for focal species.

Value of information analysis

We combined the two rounds of elicited scores (n=33) for Magnitude, Relevance, and Reducibility (Table 2). Based on the combined scores, the hypothesis with the highest Magnitude of uncertainty was the Predation hypothesis (#4; 3.07) whereas the hypothesis with the lowest amount of uncertainty was the Mixed Seasonality hypothesis (#3; 2.14). The hypothesis determined to be the most relevant to decision-making was the Fire Return Interval hypothesis (#8; 2.29) whereas the hypothesis least relevant to decision-making was the Predation hypothesis (#4; 1.10). Hypotheses with high Reducibility were the Fire Return Interval (#8; 2.11) and Mixed Seasonality (#3; 2.03) hypotheses, and the hypothesis with the lowest Reducibility was the Predation hypothesis (#4; 1.39).

Most of the hypotheses fell into the Highest or High priority categories (Fig. 4). Four hypotheses were classified as highest priority (#1, Microtopography; #3, Mixed Seasonality; #7, Mixed Management; #8, Fire Return Interval) and three hypotheses were classified as high priority (#2, Interspersion; #6, Matched Seasonality; #9, Mosaic Burn). Only one hypothesis landed in each of the Medium (#5, Fall vs. Winter) and Low priority categories (#4, Predation). Hypotheses #8 (Fire Return Interval) and #6 (Matched Seasonality) formed the Pareto frontier. The three "Patchy Burn" hypotheses (#1, 2, 9) were clustered together with similar QVoI and Reducibility scores (Table 2).

Discussion

Our case study demonstrates that QVoI provides a rigorous and transparent approach to prioritizing research efforts as a rapid alternative to traditional VoI analyses. Furthermore, QVoI can help stakeholders structure adaptive management and guide their efforts to achieve specific management outcomes. Using the Pareto frontier as a guide, we selected the Fire Return Interval hypothesis to serve as the basis for a management experiment to accelerate learning about the effects of fire frequency on focal species in an adaptive management framework. Given that the three "Patchy Burn" hypotheses were clustered together with similar scores, participants also agreed that developing regional protocols for standardized joint learning about the ecological importance of patchy burns would be valuable moving forward.

Not only was the Fire Return Interval (#8) hypothesis Pareto optimal, but a version was also generated by each of the 3 groups, emphasizing the value of developing a region-wide experimental framework to test this hypothesis. Understanding how fire frequency impacts coastal saltmarsh plant communities and how those changes influence focal species occurrence could be an important step for both conservation and fire science. Prescribed fire is used in coastal marshes for maintaining fire regimes. Providing an ecological basis for the frequency at which to burn by designing an experiment to test fire return intervals could help to improve future management decisions. Temperature and precipitation have been identified as primary controls on wildfire occurrences (Westerling 2006; Bernard and Nimour 2007; Parisien and Moritz 2009; Krawchuk et al. 2009) suggesting that there may be regional differences in the desirable fire return interval to benefit focal species in the Gulf of Mexico. Furthermore, compared to naturally ignited wildfires, prescribed fires have been understudied (Hiers et al. 2020). In our virtual workshop and QVoI scoring, we articulated management relevant hypotheses (H_A), each with an implicit null hypothesis (H_0) that was formally stated after the workshop. We developed hypotheses following a common format that specified a threat to the focal species, described the demographic mechanism by which they were affected, and proposed a management action that may reduce or eliminate the threat (Lawson et al. 2022). We then further refined these hypotheses following the workshop to identify a null and an alternative hypothesis and the associated preferred management actions. Explicitly developing hypotheses within a paired alternative and null hypothesis framework during the workshop, rather than postworkshop, may improve the QVoI scoring process as participants carefully consider controlled management experiments that explicitly aim to falsify the alternative (H_A) hypotheses (Rushing et al. 2020, Lawson et al. 2022).

Judging the Magnitude score for each hypothesis within a workshop setting can be difficult if participants are not familiar with the number of theoretical and empirical studies from which the hypothesis was developed. This judgment can be especially difficult when the participant did not help generate and refine the hypothesis being scored (i.e., when the hypothesis is from a different breakout group). Slight changes to elicitation of Magnitude scores may improve the results. For example, a workshop discussion focused on the empirical evidence supporting each hypothesis may help participants gain a deeper understanding of the Magnitude of uncertainty prior to the scoring process. Additionally, Lawson et al. (2022) suggest a facilitator-sourced literature review or annotated bibliography to distribute and use as a guide for establishing what empirical support may exist (Sutherland et al. 2019). We further suggest a literature review could be included as part of the pre-work leading to a workshop (Cochrane et al. 2015; Appendix S1), which might also be a useful exercise for helping participants create influence diagrams and develop hypotheses as they would gain a deeper understanding of the system through the literature search.

While we were able to gain further insight through two rounds of hypothesis scoring, our process was subject to logistical constraints that did not allow everyone to be present at a single workshop. However, we recommend an iterative scoring process similar to the IDEA protocol (Hemming et al. 2018) whereby participants score each hypothesis, facilitators calculate QVoI and conduct a Pareto analysis, and the results are presented to the participants for discussion. A discussion centered around the variance of the scores, or any outlier hypotheses, could clarify any confusion regarding the scoring rubric and reduce linguistic uncertainty surrounding any of the hypotheses (Regan, Colyvan, and Burgman 2002). Following this discussion, participants would complete a second round of scoring, producing a structured, iterative process for expert knowledge elicitation (Burgman et al. 2011; Hanea et al. 2017; O'Hagan 2019). We recognize that an iterative approach can increase the amount of work for both the participants and facilitators, yet virtual meetings and web-based tools can divide the workload into multiple sessions or tasks can be completed at the individual level within a participant's own timeframe.

Our adaptive management experiments designed to accelerate learning about the effects of prescribed fire on focal species could also benefit Atlantic Coast Eastern Black Rails by providing recommendations for fire frequency and fire patchiness that could be implemented outside of the Gulf Coast region. For example, from Lawson et al. (2022) the hypothesis scoring the second highest Relevance and Reducibility scores was the "Fire vs. Other" hypothesis where prescribed burning could be compared against a separate treatment type ("Other"), such as herbicide, grazing, or mowing. Our findings for fire frequency and fire patchiness could help to provide a foundation for the type of fire treatment that may be most beneficial to Eastern Black Rails for which the "Other" treatment types can be compared. Furthermore, Lawson et al. (2022) was the first participatory application of QVoI in a workshop setting to evaluate the benefit of reducing uncertainties within an adaptive management framework for Eastern Black Rail populations along the Atlantic Coast. Our study builds on these first applications of QVoI by implementing the suggested improvements to both the facilitation and expert elicitation processes (Lawson et al. 2022).

Our case study represents a familiar conservation decision (i.e., how to best use prescribed fire) that must be made under uncertainty (i.e., not knowing how focal species are responding to fire) with limited time and resources. We demonstrated how influence diagrams can be used to identify key system uncertainties and how QVoI analysis can help to efficiently prioritize which uncertainties to reduce through research and monitoring. This case study further established how QVoI analysis can be used to guide adaptive management and improve management outcomes. As resources are limited and agencies continue to make decisions regarding research and monitoring for threatened and endangered species, VoI analyses will become increasingly important to prioritize research, avoid unfocused monitoring, and identify critical uncertainties for adaptive management.

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Tables

Table 1. List of hypotheses generated during workshop breakout group discussions aimed at reducing uncertainty around prescribed fire decisions for Eastern Black Rails (*Laterallus jamaicensis jamaicensis*), Yellow Rails (*Coterminous noveboracensis*), and Mottled Ducks (*Anas fulvigula)* in high marsh habitats along the Gulf of Mexico, USA. Hypotheses have been modified to be stated in terms of the null and alternative, and the preferred management action under each hypothesis is specified.

Hypothesis number	Hypothesis name	Null hypothesis (H_0)	Preferred management action if H_0 is true	Alternative hypothesis (H_A)	Preferred management action under H_A
	Microtopography	There is no difference in pyrodiversity at sites with low and high microtopography indices.	Apply prescribed fire to all sites.	Pyrodiversity is greater at sites with high microtopography indices because low elevation patches will remain moist and burn less severely whereas higher elevation patches will be more severely burnt.	Apply prescribed fire to sites with more microtopographic features to improve habitat quality for focal species.
2	Interspersion	There are no differences in focal species occupancy between units that are uniformly burned and units that contain a mosaic of burned and unburned areas.	Apply fire uniformly across the landscape.	Focal species occupancy is greater at units with a mosaic of burned and unburned areas because unburned areas provide refugia during fire and leave habitat on the landscape while burned areas recover.	Use fire application techniques that deliberately create a heterogenous landscape with patches of unburned, low severity burn, moderate severity burn, and severely burned areas.

	Mixed seasonality	There are no differences in vegetative response to burns conducted during both the dormant and growing seasons when compared to burns conducted during only the dormant or growing season.	Apply fire during either the growing season, dormant season, or both when fire crews are available to burn.	Vegetative response is better when both growing and dormant season burns are used because burns during the growing season control woody vegetation whereas burns during the dormant season provide the appropriate herbaceous vegetation structure.	Apply fire during both the growing and dormant seasons.
4	Predation	There are no differences in nest success and survival at infrequently and frequently burned marshes.	Use any means necessary to reduce the number of predators using coastal marshes.	As a result of reduced vegetative cover, marshes that are managed with frequent prescribed fire provide less cover for predators.	Apply fire as frequently as fuel loads will allow.
5	Fall vs. winter	All focal species will have the same response to prescribed fire.	Use prescribed fire as necessary to manage the species of interest.	Focal species will have a different response to fire depending on the season the burn is conducted due to differences in life history traits.	Burn during the season that maximizes the benefits to all 3 focal species.

Matched seasonality	There are no differences in vegetative response to burns conducted during growing season when compared to the dormant season.	Apply fire during either the growing or dormant season when fire crews are available to burn.	Fires during the growing season (at historical frequency) produce a better vegetative response than dormant season because burns during the growing season control woody vegetation.	Burn during the season that maximizes the benefits to all focal species.
Mixed management	There are no differences in vegetative response and microtopography to light grazing used with prescribed fire when compared to prescribed fire only.	Use either combined prescribed fire and grazing or prescribed fire only to provide the appropriate vegetation and microtopography.	The appropriate vegetative structure and microtopography for focal species is achieved through a combination of light-grazing and prescribed fire.	Apply both light grazing and prescribed fire to the landscape to provide the appropriate vegetation and micrography.
Return interval	There are no differences in vegetative response to fire frequency across the region.	Use prescribed fire as necessary.	Vegetative response varies with fire frequency across the region due to differences in regional precipitation.	Apply prescribed fire at the appropriate regional fire return interval to maximize the benefits to all focal species.

9	Mosaic burn	There are no differences in focal species occupancy between units that are uniformly burned and units that contain a mosaic of burned and unburned areas.	Apply fire uniformly across the landscape.	Occupancy is greater in units that contain a burned-unburned mosaic (greater pyrodiversity) because unburned areas provide refugia during fire and leave habitat on the landscape while burned areas recover.	Use fire application techniques (such as weather conditions) that provide a heterogenous landscape with patches of unburned, lightly burned, moderately burned, and severely burned areas.

Table 2. Hypothesis rankings averaged across participants (n = 30) from two workshops aimed at reducing uncertainty around prescribed fire decisions for Eastern Black Rails (*Laterallus jamaicensis jamaicensis*), Yellow Rails (*Coterminous noveboracensis*), and Mottled Ducks (*Anas fulvigula)* in high marsh habitats along the Gulf of Mexico, USA. Hypothesis rankings are listed in descending order of mean QVoI score (Magnitude x Relevance = QVoI; SE = standard error).

Hypothesis number	Hypothesis name	Magnitude (SE)	Relevance (SE)	Reducibility (SE)	QVoI (SE)
6	Matched seasonality	2.75 (0.20)	1.86 (0.17)	1.29 (0.15)	5.11 (0.59)
8	Fire return interval	2.19 (0.20)	2.30 (0.14)	2.11 (0.13)	5.03 (0.55)
9	Mosaic burn	2.69 (0.10)	1.9 (0.15)	1.62 (0.15)	4.90 (0.42)
1	Microtopography	2.57 (0.12)	1.82 (0.13)	1.75 (0.14)	4.61 (0.35)
2	Interspersion	2.37 (0.17)	2.00 (0.15)	1.67 (0.13)	4.59 (0.51)
3	Mixed seasonality	2.14 (0.20)	2.07 (0.15)	2.04 (0.12)	4.57 (0.52)
7	Mixed management	2.75 (0.14)	1.68 (0.17)	1.71 (0.11)	4.39 (0.53)
5	Fall vs. winter	2.79 (0.11)	1.32 (0.15)	1.71 (0.12)	3.64 (0.44)
4	Predation	3.07 (0.14)	1.10 (0.13)	1.39 (0.14)	3.29 (0.36)

Figure captions

Figure 1. A schematic describing the PrOACT (problem framing, objectives, alternatives, consequences, and tradeoffs) decision-making framework used during the workshop for prioritizing uncertainties related to the effects of management actions on Eastern Black Rails (*Laterallus jamaicensis jamaicensis*), Yellow Rails (*Coterminous noveboracensis*), and Mottled Ducks (*Anas fulvigula)* in high marshes along the Gulf of Mexico, USA. Rounded rectangles represent each step in the PrOACT cycle. Solid arrows represent flows of information between steps, and dotted arrows represent iteration among steps. Boxes below each of the PrOACT steps represent tools used during the workshop and at what step in the cycle each tool was used. Tools that straddle PrOACT steps combine two steps of the cycle.

Figure 2. Objectives hierarchy created during the first workshop depicting how management alternatives influence means objectives which influence fundamental objectives for Eastern Black Rails (*Laterallus jamaicensis jamaicensis;* BLRA), Yellow Rails (*Coterminous noveboracensis;* YERA), and Mottled Ducks (*Anas fulvigula;* MODU) in high marshes along the Gulf of Mexico, USA. The fundamental objectives are represented by orange boxes, means objectives represented by gray boxes, and management alternatives represented by blue boxes. An arrow from one objective to the next indicates that better achieving the former objective influences the achievement of the latter objective.

Figure 3. Example influence diagram created during the first workshop depicting the effects of management actions on fundamental objectives for Eastern Black Rails (*Laterallus jamaicensis*

jamaicensis; BLRA), Yellow Rails (*Coterminous noveboracensis;* YERA), and Mottled Ducks (*Anas fulvigula;* MODU) in high marshes along the Gulf of Mexico, USA. Green rectangles represent management actions, yellow rounded rectangles represent ecological variables, red ovals represent chance events, and blue hexagons represent fundamental objectives. Arrows represent the direction of cause and effect.

Figure 4. Combined qualitative value of information (QVoI) and reducibility scores (n=33) from workshop and webinar participants for 9 alternative hypotheses related to the effects of management actions on Eastern Black Rails (*Laterallus jamaicensis jamaicensis*), Yellow Rails (*Coterminous noveboracensis*), and Mottled Ducks (*Anas fulvigula)* in high marshes along the Gulf of Mexico, USA. Black dots represent means and black vertical (Reducibility) and horizontal (QVoI) bars represent standard errors (SE). The red line represents the Pareto efficiency frontier where options along the frontier cannot be improved upon without giving up something in terms of QVoI or Reducibility. Hypotheses that scored high in both QVoI and Reducibility were considered "highest priority", "high priority" hypotheses also scored high QVoI scores but low in Reducibility, "medium priority" hypotheses were those that had a lower QVoI score but high Reducibility, and "low priority" hypotheses were those that scored low in both QVoI and Reducibility.

Figures

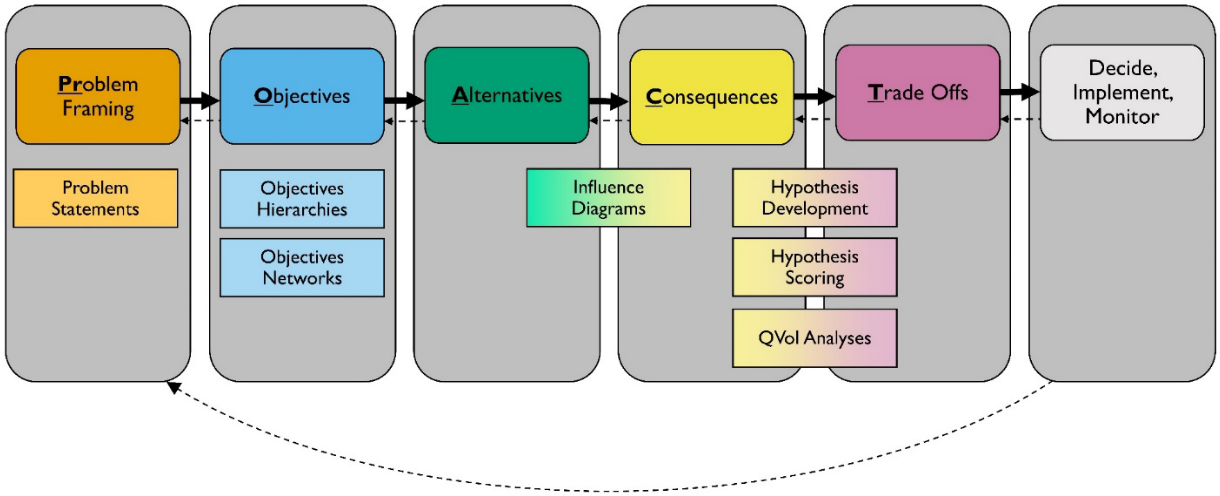

Figure 1.

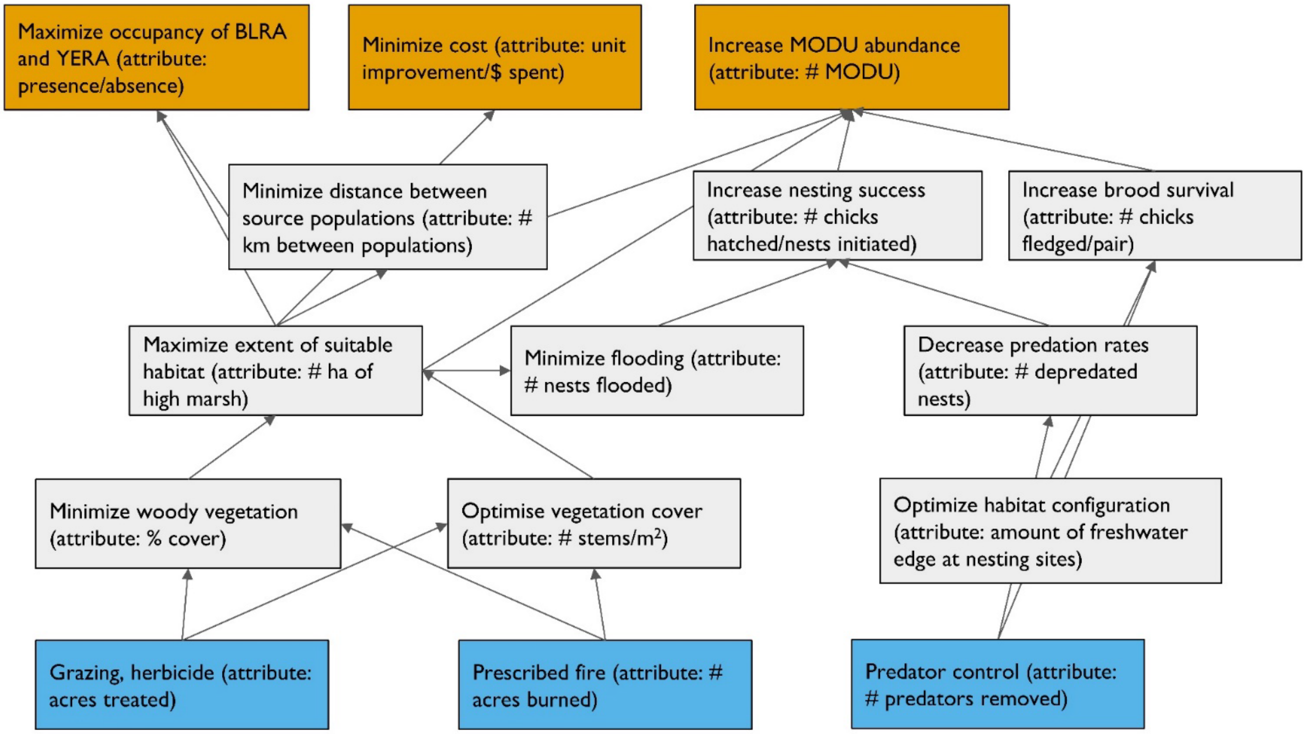
Maximize occupancy of BLRA and YERA (attribute: presence/absence)
Minimize cost (attribute: unit improvement/$ spent)
Increase MODU abundance (attribute: # MODU)
Minimize distance between source populations (attribute: # km between populations)
Increase nesting success (attribute: # chicks hatched/nests initiated)
Increase brood survival (attribute: # chicks fledged/pair)
Maximize extent of suitable habitat (attribute: # ha of high marsh)
Minimize flooding (attribute: # nests flooded)
Decrease predation rates (attribute: # depredated nests)
Minimize woody vegetation (attribute: % cover)
Optimise vegetation cover (attribute: # stems/m2)
Optimize habitat configuration (attribute: amount of freshwater edge at nesting sites)
Grazing, herbicide (attribute: acres treated)
Prescribed fire (attribute: # acres burned)
Predator control (attribute: # predators removed)

Figure 2.

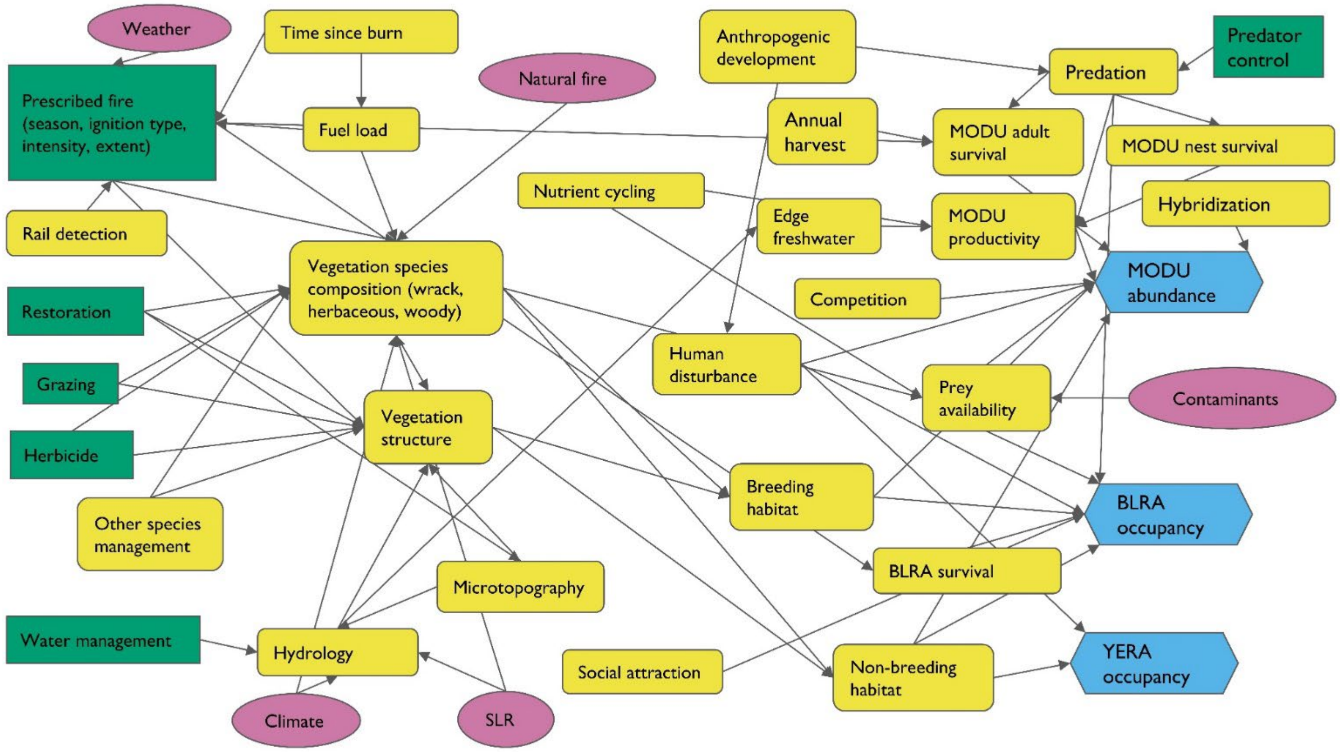
Weather
Time since burn
Prescribed fire (season, ignition type, intensity, extent)
Fuel load
Natural fire
Anthropogenic development
Predation
Predator control
Annual harvest
MODU adult survival
MODU nest survival
Nutrient cycling
Edge freshwater
MODU productivity
Hybridization
Rail detection
Vegetation species composition (wrack, herbaceous, woody)
MODU abundance
Competition
Restoration
Human disturbance
Grazing
Prey availability
Contaminants
Vegetation structure
Herbicide
Breeding habitat
BLRA occupancy
Other species management
BLRA survival
Microtopography
Water management
Hydrology
Social attraction
Non-breeding habitat
YERA occupancy
Climate
SLR

Figure 3.

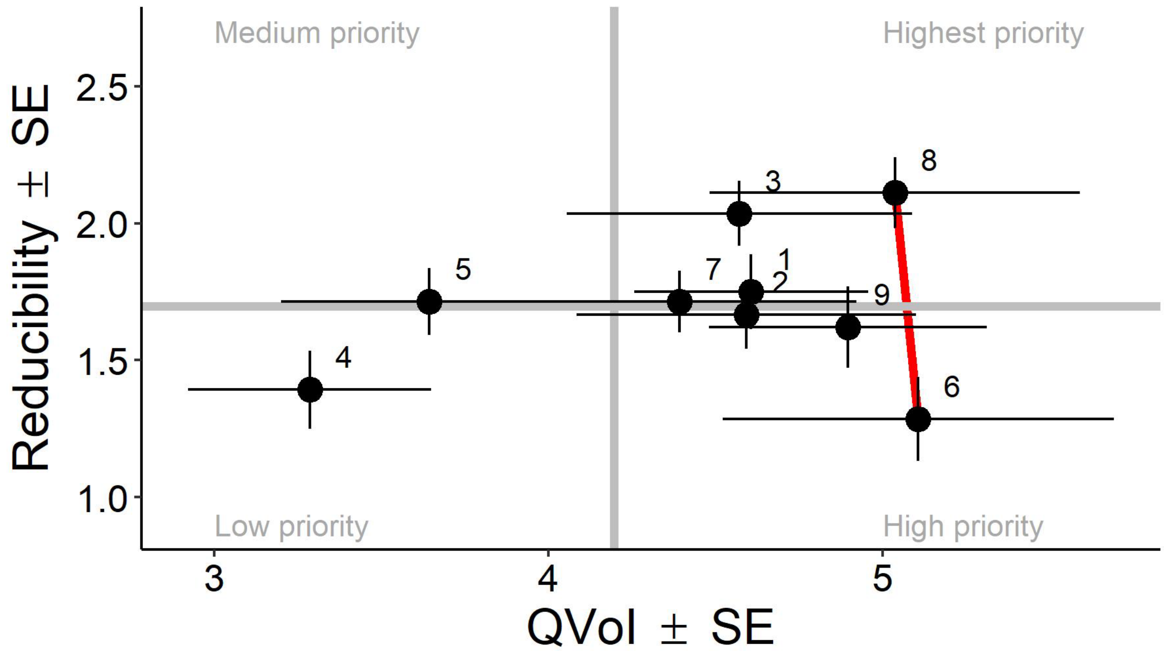
Medium priority
Highest priority
Low priority
High priority
Reducibility ± SE
QVoI ± SE
2.5
2.0
1.5
1.0
3
4
5
1
2
3
4
5
6
7
8
9

Figure 4.