Australia's National
Science Agency

Priority information needs assessment: monitoring the Coastal Integrated Forestry Operations Approval

Final report

Sam Nicol and Iadine Chadès
15 November 2019

Report prepared for the NSW Natural Resources Commission

CSIRO Land and Water

Citation

Nicol S and Chadès I (2019) Priority information needs assessment: monitoring the Coastal Integrated Forestry Operations Approval: Final Report. CSIRO, Brisbane, Australia.

Contents

List of figures

List of tables

Acknowledgments

CSIRO was funded to develop the research in this report by the NSW Natural Resources Commission. We would like to thank the expert panel who provided their time and expertise to define and prioritise the risks in this report. We would also like to thank the Technical Working Group for their oversight and constructive input to our process and the two internal reviewers who provided comments on a draft manuscript.

Executive summary

In November 2018, the NSW Government updated the rules for harvesting native forests in NSW's coastal forestry regions. These rules, called the Coastal Integrated Forestry Operations Approvals (IFOA) set out how forestry operations can be carried out on state forests and Crown timber lands in NSW. The new rules change the way in which forests are managed so it is important to conduct monitoring to ensure that the environmental, social and economic values of native forests are maintained. Chapter 8 of the Coastal IFOA conditions requires Forestry Corporation of NSW (FCNSW) to establish a monitoring program that ensures the ongoing effectiveness of the conditions in achieving the objectives and outcome statements of the Coastal IFOA.

The NSW Government has established a Forest Monitoring and Improvement Program (NSWFMIP). The Premier has asked the Natural Resources Commission (the Commission) under a terms of reference to independently oversee and advise on the program. The Commission has engaged the CSIRO to prioritise monitoring actions for a Coastal IFOA monitoring program that maximises the value of the information that it produces.

Traditionally, forest monitoring program design has focused on gathering information which in some cases has limited use for informing decisions about forest management. Since resources for monitoring are limited, it is important to ensure that monitoring is prioritised to focus on collecting information that will most benefit decision-making and change management practices to improve the sustainability of forest operations. This report outlines CSIRO's approach to prioritise a portfolio of monitoring actions that minimises the risk that the outcomes of the Coastal IFOA are not achieved, given a limited budget.

Our approach uses best-practice techniques drawn from structured decision making and expert elicitation to quantify the potential reduction in risk that could be achieved by improving the likelihood of detection through monitoring. Risks can then be prioritised either by ranking according to the potential reduction in risk or by the cost-effectiveness of monitoring strategies that mitigate multiple risks concurrently.

We found that although some risks may be of high concern, these may not be the most cost-effective risks to mitigate. Evaluating the expected ability to mitigate risks when prioritising actions provides useful context to guide monitoring decisions.

When risks are prioritised by ranking based on the potential for risk reduction, the greatest potential reductions in risk could be achieved by monitoring risks related to forest structure. The top priority risks related to loss of habitat features as a result of harvest operations, invasive species incursions and the potential effects of changes to the harvest area sizes specified in the Coastal IFOA agreement.

When prioritisation of risks considers the cost-effectiveness of monitoring, risks are grouped according to the monitoring strategies that mitigate them. If funding to implement all monitoring strategies is insufficient, further prioritisation must occur in the detailed planning of the monitoring strategies. This prioritisation can either partially implement all the monitoring strategies (prioritising which risks to mitigate within each monitoring strategy based on the expected reduction in risk) or select a reduced set of monitoring strategies which will be fully implemented (based on maximising the total risk mitigated). If partially implementing all monitoring strategies, the selection of risks depends on the incremental cost of adding or removing a risk from a monitoring strategy (for example, the cost of developing automatic acoustic detection capability for an additional species). Although our approach quantifies the expected reduction in risk, we did not estimate incremental costs and so we did not have sufficient information to develop a priority set. For the case when fully implementing a reduced set of monitoring strategies, we prioritised monitoring strategies using a cost-effectiveness metric that maximised the risk reduced per dollar spent. We found that species-based monitoring plans (Hastings river mouse, Northern Corroboree frog, Eastern Bristlebird and smoky mouse) and research projects (thermal drones for koala monitoring) could be high priorities if their costs were kept low, but that more expensive monitoring strategies needed to mitigate multiple risks to justify their costs. Of the broad-scale monitoring actions, measuring canopy height and structure with LiDAR and monitoring key habitat features were the most cost-effective strategies.

This report provides a basis to create an initial priority set of monitoring actions using estimates of the potential to reduce risk. In doing so, the approach seeks to select monitoring actions that will produce information that is relevant to management needs. The prioritised set should be viewed as an initial prioritisation based on the best available information at the current time. The risk register and the priorities should be maintained as a living document that is updated as new knowledge becomes available.

1 Introduction

1.1 Project background and context

The Natural Resources Commission (Commission) has been commissioned to independently oversee the design, implementation, review and continuous improvement of a state-wide Forest Monitoring and Improvement Program. Within the broader perspective of adaptive management of the forest estate in NSW, the NSW Government in November 2018 updated the rules for native timber harvesting in NSW's coastal forests. These rules, called the Integrated Forestry Operations Approvals (IFOA) set out how forestry operations can be carried out on state forests and Crown timber lands in NSW.

The remade Coastal IFOA is structured around high-level outcome statements that communicate the intention of the approval in regulating forestry operations to ensure ecologically sustainable forest management. Each outcome statement is supported by conditions and protocols for NSW Forestry Corporation's native timber harvesting licence, such as requirements for regeneration harvesting, koala protection, harvesting exclusion zones, stream buffers and multi-scale landscape protections.

Chapter 8 of the Coastal IFOA conditions requires Forestry Corporation of NSW (FCNSW) to establish a monitoring program that ensures the ongoing effectiveness of the conditions in achieving the objectives and outcome statements of the Coastal IFOA. Monitoring how effectively the Coastal IFOA achieves the outcome statements will support evidence-based decisions on adapting the regulatory settings for native timber harvesting under the Coastal IFOA.

Traditionally, forest monitoring program design has focussed on gathering large amounts of information that in some cases has limited use for informing decisions about forest management. To some extent, the priorities for forest monitoring have also been determined by the interest and preferences of researchers or by a sense of commitment to existing monitoring programs regardless of the value of the information that it provides. Collectively these practices have operated to direct limited monitoring resources away from gathering the information decision-makers value. The introduction of the remade Coastal IFOA presents an opportunity to rethink the priorities of monitoring and is a motivation for this report, i.e. to focus on monitoring that will most benefit decision-making and change management practices to improve the sustainability of forest operations. To oversee the preparation of the Coastal IFOA Monitoring Program the Commission convened a technical working group comprised of the Environmental Protection Authority (EPA), Forestry Corporation of NSW (FCNSW) and Department of Primary Industries (DPI). The Commission also engaged the CSIRO to help the group design a Coastal IFOA monitoring program that maximises the value of the information that it produces. This report details CSIRO's expert-driven, risk-based framework and presents a prioritised set of risks which informed the development of the draft monitoring program.

This prioritisation project fits into the broader development of a performance framework to guide the assessment of the effectiveness of Coastal IFOA conditions and protocols in meeting the outcomes stated in the Coastal IFOA. The framework will guide the development of a monitoring, evaluation, reporting and research program that best informs the adaptive management of native timber harvesting and environmental management in state forests under the Coastal IFOA. The current project identifies and prioritises risks for monitoring based on a structured, transparent and justifiable process. Risks are prioritised based in the potential reduction in risk that could be achieved by the likelihood of detection through monitoring and feasible changes in management practices to mitigate each risk. These priorities and the process to identify them will continue to be used as the detail of the monitoring program is developed with stakeholder and community involvement.

1.2 Terms of reference

This report delivers on Task 2 of CSIRO's Scope of Services, i.e.:

"Task 2: Undertake a value of information analysis to prioritise the information needs to reduce the uncertainty around the adaptive management of production forests in the Coastal IFOA region.

The objective of the project is to maximise the likelihood that the objectives of the Coastal IFOA are achieved through monitoring of a portfolio of conditions and protocols. This will be achieved by identifying which risks have most impact on achieving the outcomes, determining which interventions will most effectively reduce those risks, then choosing a portfolio of interventions that maximises the likelihood that the objectives are achieved. Finally, subject to sufficient information being available, the Service Provider (CSIRO) will investigate the level of uncertainty required to change a decision to monitor particular conditions or protocols (the value of information)."

1.3 Definition of monitoring

In this project, we take a wide definition of monitoring. Our approach assumes that monitoring is any activity that collects information to determine the effectiveness of the Coastal IFOA approval in delivering the objectives and outcome statements of the Coastal IFOA. This definition includes both traditional monitoring as well as independent evaluation and research. Hereafter we will refer to 'monitoring' using this definition.

1.4 Prioritisation logic: key considerations and objectives

Ecological monitoring programs are always limited by financial resources, meaning the focus of any ecological monitoring program needs to be carefully prioritised (Caughlan & Oakley 2001). Spreading resources too thinly by trying to monitor everything can lead to failure of the program, so it is important to make informed decisions about which risks should be monitored (Caughlan & Oakley 2001; Lindenmayer & Likens 2010). The Coastal IFOA has limited resources allocated to monitoring but many outcomes, conditions and protocols to be monitored. There is a need to prioritise the limited funds for monitoring to ensure that monitoring is effective and to maximise the benefits of investment.

The goal of the Coastal IFOA monitoring program is to "ensure the ongoing effectiveness of the approval in delivering the objectives of the approval and outcome statements" (Coastal IFOA 2018, Ch. 8). While monitoring can have many benefits other than determining the effectiveness of management, this project seeks to identify and prioritise monitoring activities that are most informative for assessing the effectiveness of the Coastal IFOA.

To achieve the objective of the monitoring program, we first need to define the relative information value of a proposed monitoring activity in assessing the effectiveness of the Coastal

IFOA (Coastal IFOA 2018). Information has 'value' if it improves the likelihood of informing management to enable meeting agreed objectives. The objective of the Coastal IFOA is to deliver ecologically sustainable forestry operations that protect the environment and conserve threatened species and biodiversity (Coastal IFOA 2018, section 14.1). Based on this objective, information from monitoring has value if it leads to changed practices that better protect the environment, species or biodiversity. Therefore, key prioritisation criteria for a proposed monitoring program should include both the likelihood of detecting whether a risk is occurring (i.e. monitoring the effectiveness of a condition in mitigating risk) and the likelihood of changed management practices.

Prioritisation requires a common metric that can be used to differentiate between options, but the Coastal IFOA regulates many unacceptable or adverse events that are challenging to compare. These adverse events can be framed as risks. Using a risk framework is useful because it facilitates prioritisation by allowing a variety of adverse events to be evaluated with a common metric.

In this framework, monitoring reduces risk by detecting that outcomes are not being met, combined with changed practices that improve the likelihood of meeting the objectives and outcomes. Note that for the purposes of this project, changed management practices were assumed to be extensions of the existing provisions of the Coastal IFOA, so the likelihood of changed management practices was assumed to be certain (for more details, see section 2.6).

In general, prioritisation seeks to select monitoring options that will provide maximum benefit given a limited budget. The benefits of monitoring can be assessed using the risk framework, but the costs of monitoring can also be considered. Our approach will evaluate the costs of monitoring, identifying cost-effective monitoring options that can be used to determine a portfolio of monitoring actions that minimises risk given an investment budget.

The remainder of this report provides details of the risk-based prioritisation approach and provides a priority list of risks for further consideration in the monitoring program design.

2 Prioritisation approach

We used an eight-step process to select an optimal portfolio of monitoring actions for the Coastal IFOA (Figure 1). These steps are adapted from the structured decision-making (SDM) protocol (Gregory *et al.* 2012; Nicol *et al.* 2018; Chades *et al.* 2019), which is an organized approach to evaluate options, clarify trade-offs and make decisions. Evaluation and feedback were not included in this prioritisation project but will be important considerations when the priority monitoring strategies are developed in detail.

We made two important scoping assumptions in this report:

1) *That the Coastal IFOA conditions would be implemented as prescribed.* The NSW EPA conducts compliance monitoring for the Coastal IFOA and receives annual reports on compliance from FCNSW. This reporting process is separate to the monitoring program being designed in this study and can be used to periodically evaluate the level of compliance with the Coastal IFOA conditions. To avoid duplication with this reporting process, we did not consider the risks associated with noncompliance or administrative

conditions, instead focusing on whether the conditions were appropriate to achieve their intended outcomes.

2) *That the value of monitoring was to inform changed management practices that could lead to reduced likelihood of adverse consequences*. Framing the value of monitoring in terms of the potential to improve management effectiveness meant that the objective of the decision problem becomes a risk minimisation problem.

The eight steps in our process are described in more detail in the remainder of this section.

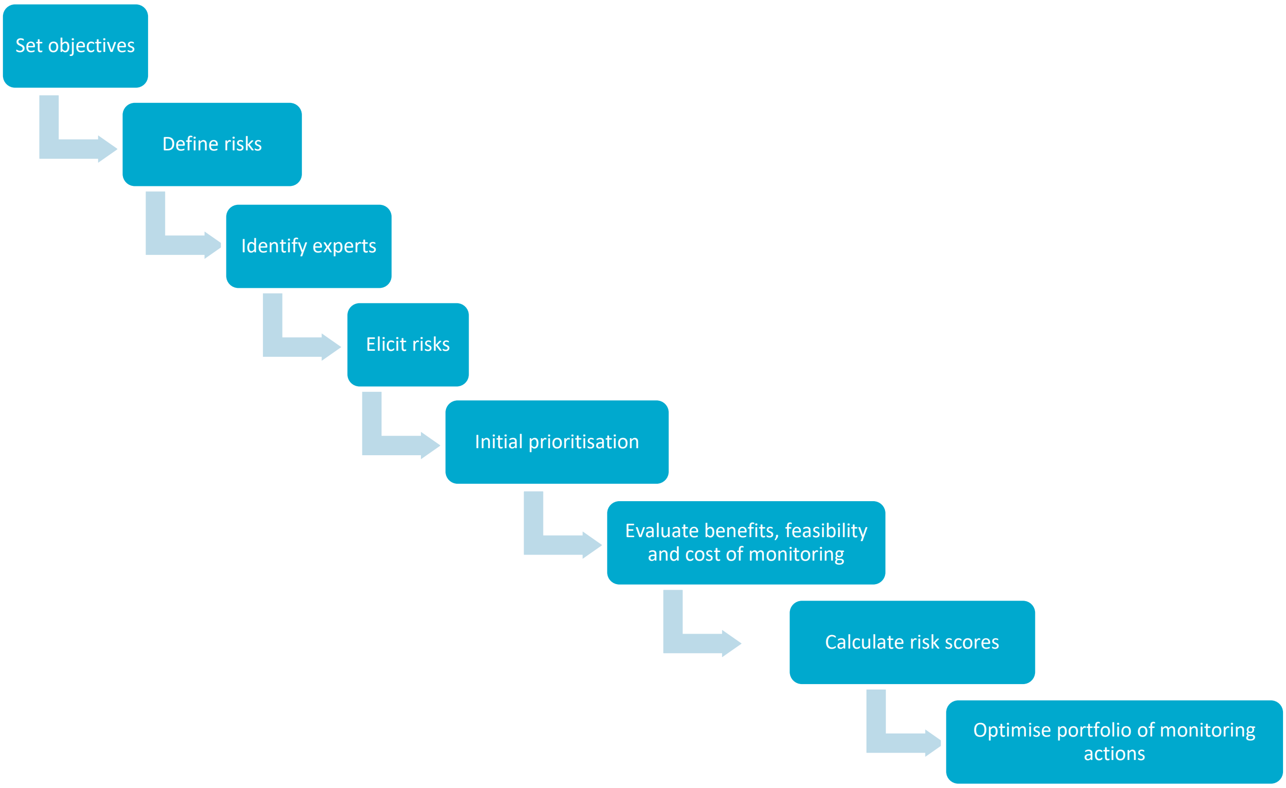

Figure 1: Diagram of steps required to select a priority portfolio of monitoring actions

2.1 Objective setting

There are several different objectives in the Coastal IFOA. Here we clarify these objectives and how they relate to the prioritisation of monitoring actions.

The overall objective of the Coastal IFOA is defined in section 14.1 (Coastal IFOA 2018), namely:

"to authorise carrying out of forestry operations… in accordance with the principles of ecologically sustainable forest management; in a manner which integrates the regulatory regimes for: (i) environmental planning and assessment, (ii) the protection of the environment; and (iii) threatened species conservation and biodiversity, and in accordance with the conditions and protocols (of the Coastal IFOA)"

This broad management objective is refined through 23 outcome statements which provide the intent of each major section of the Coastal IFOA document. These outcome statements can be used to break down the broad objective of the Coastal IFOA into more specific objectives.

The objective of the monitoring plan is defined in chapter 8 of the Coastal IFOA. The outcome statement for the monitoring plan is:

"*Monitoring programs are applied at multiple landscape scales to ensure the ongoing effectiveness of the approval in delivering the objectives of the approval and outcome statements"*

Of note are the particular matters outlined in Protocol 38 of the approval. Protocol 38 specifies that the monitoring program should monitor and evaluate the conditions of the approval, specifically including:

1) Multi-scale landscape protections;
2) Drainage feature crossing and road conditions;
3) Riparian exclusion zones and ground protection zones on class 1 classified drainage lines;
4) Exclusion zones for coastal State Environment Planning Policy (SEPP) wetlands;
5) The effectiveness of soil and water protection in intensive harvesting forestry operations;
6) Protecting and recruiting hollow-bearing trees;
7) Koala conditions;
8) The effectiveness of selective harvesting limits in achieving regeneration and stocking standards as measures of longer term regeneration; and
9) The maintenance of sufficient levels of coarse woody debris.

Finally, the decision problem objective of this project is to: *select a portfolio of priority monitoring projects that should be implemented to minimise the (cumulative) risk that the approval and outcome statements will not be achieved by the Coastal IFOA, given a limited budget*.

2.2 Defining risks

The Coastal IFOA contains outcome statements which describe the intent of the associated conditions in each section. Risks were extracted from the outcome statements and conditions in the Coastal IFOA. A risk was not assigned for every single condition; instead risks reflected the intent of groups of conditions within the Coastal IFOA document.

Although there are many conditions, there are a smaller number of policy or management mechanisms (i.e. concrete actions such as buffer areas, retention of important trees, etc.) that are used to ensure the outcomes are met. The assumptions about how the mechanisms were assumed to meet the outcome statements were then elaborated (i.e. what is the assumed link between the mechanisms in the Coastal IFOA and the achievement of the outcome?). The risks were generated by inverting the assumptions about effectiveness; i.e. the risks are that specific conditions in the Coastal IFOA will not be effective in delivering the outcome statements.

Risks were generated in consultation with representatives from the agencies in the technical working group for the project (including Forestry Corporation NSW, NSW Environmental Protection Agency, Department of Primary Industries Forest Policy and the Office of Environment and Heritage). An initial list of risks was generated by Commission staff then refined by email and during two face-to-face workshops. In addition, the NRC ran a consultation process with stakeholders and the community. Submissions to this process identified several risks (such as dieback and the incursion of invasive species) that were incorporated into the risk register.

Ninety-five potential risks were defined using this process. The resulting list of risks (see Appendix A ; sheet “Risk register”) was checked for comprehensiveness by checking that risks were listed against each outcome statement.

An assumption of this process is that the Coastal IFOA is implemented as planned, so we did not consider risks associated with noncompliance with the Coastal IFOA.

2.3 Identifying experts

Data to quantify risks were generated using an expert elicitation process. Experts were identified by snowballing, which is a technique that relies on an initial known group of experts to identify additional participants with relevant expertise from within their peer networks (Handcock & Gile 2011). In this project, the members of the technical working group constituted the initial expert group and were responsible for nominating relevant expertise within and beyond their respective agencies and organisations. We reviewed the number of experts who respond to each question and seek additional expertise where considered necessary by the project team and the technical working group.

Ethics clearance for eliciting data from human subjects was obtained from the CSIRO Social Science Human Research Ethics Committee (approval 097/19). Participants in the expert process were required to sign and submit a consent form as part of the ethics approval. Participants were able to withdraw from the study at any point up until this report was published.

Elicitation took place in two stages. In the first stage, experts provided the consequence and likelihood of each risk. In the second stage, experts evaluated the expected reduction in likelihood that was expected to occur if the risk was monitored.

2.4 Eliciting risks: consequence and likelihood

We used expert elicitation to differentiate between alternatives (Speirs-Bridge *et al.* 2010; Nicol S & Chades I 2017; Nicol *et al.* 2018; Carwardine *et al.* 2019). Formal expert elicitation follows a procedure designed to minimise expert judgement biases (Speirs-Bridge *et al.* 2010) and extract the necessary information without overloading experts (avoid expert fatigue).

Elicitation was carried out using a modified Delphi process (Hsu & Sandford 2007) that firstly makes use of assessments by individuals followed by group discussion. This process minimises bias while eliciting information from experts. Results of the elicitation were the likelihood and consequences of each alternative, which was then used to compare the relative benefits of monitoring each risk.

Experts estimated the consequence of each risk as if it occurred. Consequences were estimated relative to three categories (environmental, community and economic) using a 5-point scale ranging from insignificant to catastrophic. A rubric for each scale was included with the estimation sheets (see Appendix A for rubrics). Environmental considerations in the rubric included whether the occurrence was reversible and the potential for recovery, whether it was local or widespread and the severity of the impact. Community considerations in the rubric included the number of people likely to be affected, the extent of public outcry, media coverage and potential damage to reputation with stakeholders. Economic considerations included the impacts of the adverse event to the security of wood supply, the potential to default on contracts, and impacts to tourism, jobs and local businesses. Consequences were assigned a numerical value (1-5) based on the assigned category.

Likelihood was also estimated by experts on a 5-point scale. The likelihood scale ranged from rare to almost certain; a rubric was included with the estimation sheets. Likelihood considerations in the rubric included the history of previous occurrence, the strength of evidence in the scientific and other literatures, and whether the evidence was likely to be applicable to the current location. Each likelihood on the categorical scale was associated with a range of probabilities (each category represents a range of 0.2 so that the likelihood ranges from 0-1 for the five categories). If experts did not manually change this score in the elicitation sheets, then the category chosen by experts was assigned a default score equivalent to the middle of the range for the selected category.

After elicitation, experts were provided with summary sheets that illustrated how their consequence and likelihood estimates ranked relative to the group. Individuals were given the opportunity to change their estimates after considering the group estimates (the Delphi process; Hsu and Sandford (2007)).

2.5 Initial prioritisation

Ninety-five risks were ranked by the experts in the initial round of elicitation (Appendix A ; sheet “Risk Register”). Expert fatigue is a known risk when eliciting large quantities of information (Gosling 2018) and it was considered too taxing to elicit monitoring strategies for all risks from our expert group. Because of the difficulty of developing and evaluating monitoring strategies for so many risks, we undertook an initial prioritisation process.

Risks were prioritised based on their expected risk score. Expert scores for likelihood and consequence were multiplied to generate an expected risk score for each expert and for each criterion (environmental, community and economic criteria). To create a more compact set of risks for further analysis, we selected the top 30 ranked risks according to environmental, community and economic criteria. This process resulted in 42 unique risks (i.e. some risks were ranked in the top 30 for more than one criterion, e.g. for both environmental and community reasons). Two of these risks related to compliance conditions (i.e. “Maintenance of data layers for forestry operations are not maintained and not publicly available” and “That the monitoring strategy fails to provide appropriate information on the effectiveness of the IFOA conditions, leading to information-poor decisions”) that were outside the scope of this project. These two conditions were removed from the process as compliance was assumed to be monitored via a separate process to the effectiveness monitoring program being developed in this project.

After this initial prioritisation process was complete, the risks were cross-examined against protocol 38 criteria to ensure that all protocol 38 criteria were included in the list (the monitoring program must comply with protocol 38—see condition 122.3). Five additional risks were added as a result of comparison with protocol 38, resulting in a list of 45 risks for which monitoring strategies were developed (see Appendix A , sheet “Monitoring strategies” for a list of the risks included in the initial prioritisation).

Although the initial prioritisation reduced the number of risks from 95 to 45, the monitoring strategies that we developed were broad and address a range of risks within each strategy. Many of the risks that were not included in the initial priority set will be addressed by the monitoring strategies arising from the initial prioritisation.

2.6 Evaluating the benefits, feasibility and costs of monitoring

Monitoring actions are activities that must be undertaken to identify whether the outcomes of the Coastal IFOA are being achieved. After the initial prioritisation, monitoring actions were developed to determine which risks would be most effective to monitor to deliver the objectives and outcomes of the Coastal IFOA. This translates to determining which monitoring actions would most reduce risk.

Monitoring itself is unlikely to reduce risk—monitoring may detect that a risk is being realised (i.e. that a condition is not leading to the expected outcomes being achieved), but mitigating the risk requires changed management practices to avert the risk. Because of this, we must specify both the monitoring strategies to detect risks as well as the expected changed management practices that would potentially occur if monitoring showed that risks were being realised.

Monitoring strategies were developed to a level of detail that was sufficient for prioritisation, but detailed designs were not developed. Monitoring strategies were developed in consultation with an expert panel during a workshop. Experts were asked to provide:

1) The goal of the monitoring strategy and the monitoring question;
2) What the monitoring strategy is trying to detect, the assumptions being made and the accuracy required;
3) The monitoring study design: the method, spatial and temporal scale, sampling density and frequency, replication and stratification;
4) A ‘ballpark’ cost estimate for implementation, establishment and operation of the monitoring strategy;
5) The likelihood that the monitoring would be successfully implemented and detect change if it occurred (using a 5-point likelihood scale), and
6) The likelihood that the risk would occur if the monitoring (and associated changes in management practices) were implemented (using a 5-point likelihood scale).

Our approach assumes that both the monitoring strategy successfully detects the risk if it is realised (item 5 above) and that management practices will change. Due to the large amount of data that had to be elicited through the workshop process, we did not elicit which management practices would change in response to monitoring nor the likelihood of successfully changing management practices. Instead we assumed that the most likely changes to management practice would be adaptations of the existing IFOA conditions. For example, if a condition specifying a minimum buffer distance from a stream was included in the IFOA and monitoring demonstrated that the buffer was insufficient, the most likely management action would be to further increase the buffer. Similarly, changed management practices relating to exclusion zones would most likely result in further extensions to exclusion zones. As these management actions are already in place, we assumed that the likelihood of extending them in response to evidence of risks being realised from monitoring would be certain.

It became apparent during the workshop that many of the risks could be monitored simultaneously using a common monitoring strategy. For example, a passive acoustic monitoring array could be used to monitor hollow-dependent bats (risk 33 in Appendix A) and the population of hollow-dependent birds (risk 35), as well as other risks relating to species that vocalised such as forest owls and some arboreal mammals. Some risks can also be monitored using multiple strategies—for example ensuring that there are adequate winter flowering trees requires both that they are conserved (Monitoring key habitat features) and that they form part of regenerating forests (Monitoring regenerating forests). The expert groups also identified types of risks that were difficult to monitor in the traditional sense and information was best gathered through other means such as through targeted research or independent evaluation programs.

The likelihood of the risk being realised after monitoring should be less than or equal to the likelihood of the risk being realised without the monitoring strategy. The reduction in likelihood is an indicator of the potential to avert the risk using the monitoring strategy. Experts were given an opportunity to review their consensus estimates relative to the initial likelihood estimates for each risk (averaged over experts) to ensure that the likelihood reductions were positive and that the magnitude of the reduction in likelihood was credible.

2.7 Calculating a risk score

Risk is defined as the effect of uncertainty on objectives (ISO 2018), often expressed as the product of consequence and likelihood. For the case with monitoring, the likelihood combines two events (i.e. we monitor and if we detect change, management practices are changed to mitigate the event). Here we show how the risk was generated for this case and provide an expression for the reduction in risk that results from monitoring and changed management practices.

Assume that the adverse event (i.e. the Coastal IFOA outcome is not realised using existing mechanisms) has consequence C. Let the likelihood of the adverse event be L_0, so that the risk in the absence of any monitoring is $R_0 = CL_0$. If the risk is detected by monitoring and changed practices are implemented, then the likelihood of the adverse event is reduced to L_1 (where $L_1 \leq L_0$).

Let the likelihood of detecting the adverse event occurring with monitoring be p_{mon} and the likelihood of changed management practice be p_{manage}.

There are four possible outcomes:

1) The adverse event does not occur (likelihood is $1 - L_0$). This has consequence 0, since the risk was not realised. The risk of this outcome is 0.
2) The adverse event occurs but is not detected and therefore not managed, in which case the risk is $CL_0(1 - p_{mon})$.
3) The adverse event occurs and is detected, but the changed management practices are unsuccessful in mitigating the event; in this case the risk is $CL_0 p_{mon}(1 - p_{manage})$.
4) The adverse event occurs, is detected, and management practices are successful; so that the risk is $CL_1 p_{mon} p_{manage}$.

The total risk of the adverse event with monitoring and changed practices is:

$$R_1 = 0 + C\left(L_0(1 - p_{mon}) + L_0 p_{mon}\left(1 - p_{manage}\right) + L_1 p_{mon} p_{manage}\right)$$

Which simplifies to:

$$R_1 = C\left(L_0 - p_{mon} p_{manage}(L_0 - L_1)\right)$$

The reduction in risk from monitoring and changed practices is then:

$$\Delta R = R_0 - R_1 = Cp_{mon}p_{manage}(L_0 - L_1)$$

i.e. the reduction in risk from monitoring is the difference in risk with and without monitoring, modified by the likelihoods of successful monitoring and successful changed management practices. In our case, we assumed that the likelihood of extending existing management actions in response to evidence of risks being realised from monitoring would be certain, i.e. we assumed that $p_{manage} = 1$ for all strategies.

The change in risk as a result of monitoring and changed management practices was computed for environmental, community and economic criteria. An overall risk reduction was computed by averaging across the three criteria.

2.8 Prioritisation and portfolio optimisation

It could be tempting to prioritise monitoring strategies by directly ranking the reduction in risk values using ΔR, or cost-effective reduction in risk values (using $\Delta R/cost$). However, this assumes that the objective of the problem is to maximise the reduction in risk rather than minimising the total risk that could be occurred by applying the Coastal IFOA. In Appendix B , we prove that these two problems are mathematically equivalent, meaning that the optimisation process becomes a simple ranking exercise, where risks are selected in descending order of risk reduction until the budget is exhausted.

We proposed two ways to use the risk reduction scores to select a portfolio of risks to monitor.

Approach 1: Risk reduction (individual risks)

The most basic way to prioritise risks is using the expected reduction in risk ΔR as a metric of priority. In this approach, risks with a high ΔR are high priorities for inclusion in the monitoring portfolio. We computed the expected risk reduction for each risk (Appendix A ; sheet "Monitoring strategies").

Approach 2: Cost-effectiveness of monitoring strategies (combined risks)

In the case where decision makers must choose which monitoring strategies to implement, it is necessary to evaluate the total benefits of implementing a monitoring strategy. We assume that risks affected by monitoring and mitigation strategies are independent and that risks can be mitigated using a single monitoring and mitigation strategy. Under these assumptions, the total risk reduction from implementing a monitoring strategy is given by the sum of risk reductions of affected risks. To account for cost-sharing, the cost-effectiveness of a monitoring strategy (CE_j) is then given by:

$$CE_j = 100000 \times \frac{\sum_{i \in J} \Delta R_i}{cost_j}$$

Where J is the set of risks that can be monitored and mitigated with monitoring action j; $cost_j$ is the cost of implementing monitoring action j. Scores are multiplied by 100,000 to avoid very small numbers caused by dividing risks (0-1 scale) by large cost (dollar values ranging from $10-1500k). Cost-effectiveness scores have units of risk reduced per hundred thousand dollars.

According to this prioritisation approach, monitoring strategies with high cost-effectiveness scores would be high priorities for inclusion in the Coastal IFOA monitoring strategy. Consistent with the proof in Appendix B , a priority list of monitoring actions can be generated by simply selecting monitoring actions in decreasing order of cost-effectiveness until the budget is exhausted.

To implement this approach, we designated which risks would be likely to share costs, then computed the cost-effectiveness of each of the monitoring strategies (Appendix A ; sheet "Monitoring_strat_cost_effect").

3 Results

3.1 Initial Risk Assessment and Prioritisation

3.1.1 Consequence and likelihood estimates

A plot of the risk assessment scores is included in Figure 2 (see also Appendix A for a list of all risks). Most risks were considered possible or unlikely to occur. The most outstanding exception was the risk of population declines for the Eastern Bristlebird (risk 60 in Figure 2), which was estimated to be “likely” to occur. The risk that “Harvesting operations change the structure of regenerating forest (particularly giant, hollow-bearing, sap and feed trees) so that it does not provide suitable habitat for dependent species” was rated as the next most likely to occur. The estimated likelihood for this risk was between “possible” and “likely”. None of the risks were considered “rare”.

Environmental and community consequences were more frequently rated as Major or Catastrophic than economic consequences. Most environmental and community risks were most frequently rated either Moderate or Major, while most economic risks were most frequently rated Minor or Moderate. Catastrophic rankings most frequently occurred for risks to forest regeneration and structure (risks 1-29), but at least one expert also ranked several species and water-related consequences as potentially catastrophic. Conditions relating to dust, waste and administrative conditions were generally ranked with lower risk than other risks, except for risk 95 (the risk that the monitoring strategy fails to provide information on the effectiveness of the Coastal IFOA, leading to information-poor decisions), which was most frequently ranked Major for all three consequence categories.

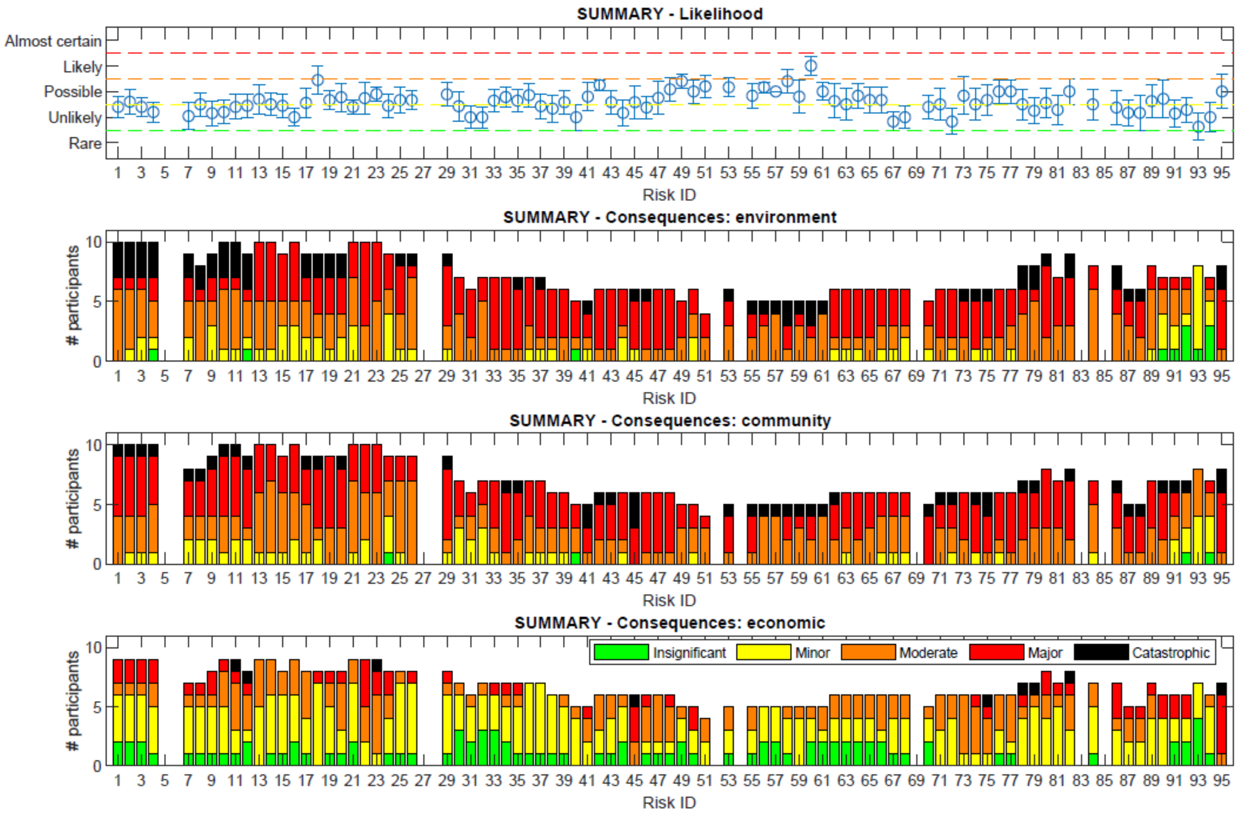

Figure 2: Summary plot of expert assessment for the risks affecting the Coastal IFOA. Risk descriptions for each risk ID are included in Appendix A . As a rough guide, risks 1-29 relate primarily to forest regeneration and structure; risks 30-77 relate to biodiversity; risks 78-89 relate to aquatic habitat and water quality; and risk 90-95 relate to dust, waste and administrative risks. Missing bars are risks that were consolidated or removed (e.g. risks relating to compliance conditions) during the expert consultation phase.

3.1.2 **Risk estimates**

Risk scores for each risk are shown in Figure 3. The full list of risks is included in Appendix A .

Similar to the pattern in the consequence results, environmental and community risks were generally ranked as higher risk than economic risks by the experts, although it is noteworthy that our analysis excluded the economic risks posed by the possibility of interruptions to timber supply as a result of the new conditions. This assumption caused some experts to comment that the economic risks were difficult to score or artificially low, particularly for the forest structure risks (risks 1-29 in Figure 3).

There was broad agreement about the 30 highest risks across the three categories (environment, community and economic). Of the risks that were in the top 30 of one of the three categories, the majority (54%) of risks were also in the top 30 of another category. Of these distinct risks, the majority (74%) ranked in the top 30 for more than one criterion, and 40% ranked in the top 30 for all three criteria. This meant that many of the highest-ranked risks were major issues for more than one criterion.

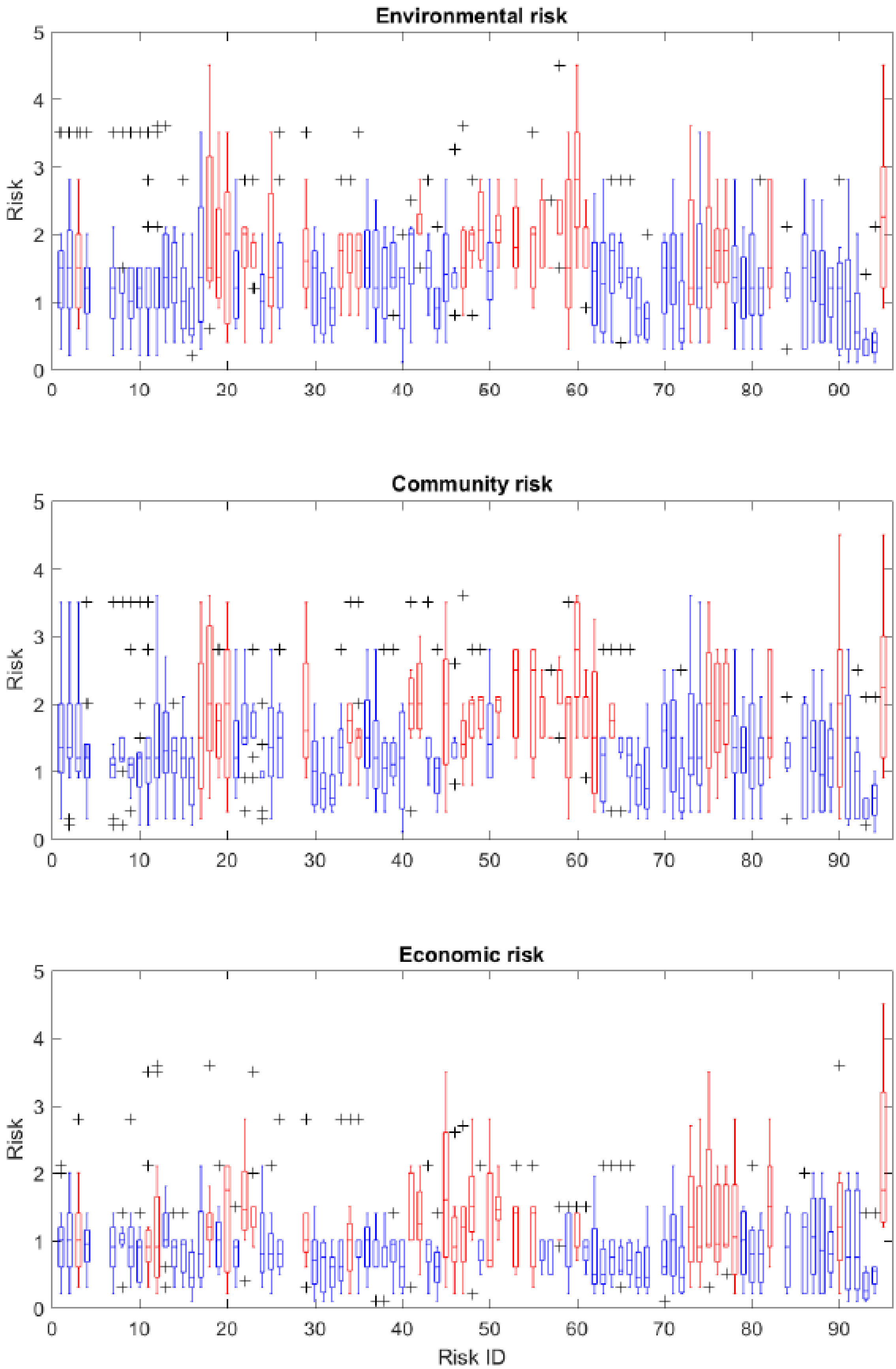

Figure 3: Summary plot of risk scores for environmental, community and economic criteria. Boxplots indicate the median expert scores and the 25th and 75th percentiles. Boxplots coloured red illustrate the top 30 risks from each criterion that were selected by the initial prioritisation. Risk descriptions for each risk ID are included in Appendix A

. As a rough guide, risks 1-29 relate primarily to forest regeneration and structure; risks 30-77 relate to biodiversity; risks 78-89 relate to aquatic habitat and water quality; and risk 90-95 relate to dust, waste and administrative risks.

The highest ranked risks averaged over each criterion are given in Table 1. The risk that the monitoring plan fails to provide appropriate information on the effectiveness of the IFOA conditions was the highest ranked risk overall and was the only risk that was ranked in the top 5 for all three criteria (ranked 1,2 and 3 for economic, community and environmental criteria respectively).

The risk of population declines in the Eastern Bristlebird population was the highest risk under both environmental and community criteria. The risk of population declines in the Smoky Mouse population was also very highly ranked under these two criteria. Risks relating to koalas were ranked highly by the economic criterion (risks relating to koalas ranked 2 and 5 according to the economic criterion) but were not in the top 5 overall as they were ranked lower according to the environmental and community criteria.

Table 1: Five highest-ranked risks when averaged over environmental, community and economic criteria. Risk scores are measured on a scale from 0 (lowest) to 5 (highest).

Risk ID	Risk description	Environmental risk	Community risk	Economic risk	Average risk
95	That the monitoring strategy fails to provide appropriate information on the effectiveness of the IFOA conditions, leading to information-poor decisions.	2.34	2.34	2.33	2.34
60	*Dasyornis brachypterus monoides* Eastern Bristle Bird Upper North East Subregion (SMP area) - That the conditions of the species-specific management plan are not effectively supporting the persistence of the species in the planning area (30% decline in 10 years)	2.88	2.70	1.18	2.25
18	Harvesting operations change the structure of regenerating forest (i.e. insufficient giant, hollow-bearing, sap and feed trees) so that it that does not provide suitable habitat for the range of dependant species.	2.16	2.13	1.44	1.91
58	*Pseudomys fumeus* Smoky Mouse Eden Subregion (SMP	2.50	2.14	1.08	1.91

	Area) - That the conditions of the species specific management plan are not effectively supporting the persistence of the species in the planning area (30% decline in 10 years or three generation whichever is the greater)				
42	72. Hastings River Mouse, *Pseudomys oralis* - IFOA conditions fail to protect micro-habitat. Habitat senescence changes habitat from suitable to unsuitable over medium term, habitat definition inappropriate, disturbance exclusion inappropriate. That the species specific conditions are ineffective in supporting the persistence of the population in the location. Occupancy at the site(s) declines by 30% over 10 years.	2.12	2.13	1.32	1.86

3.2 Monitoring strategies

The expert group developed monitoring actions to cover all risks. These monitoring strategies could be categorised into 9 broad categories, i.e.:

1) Species-specific monitoring—Flora
2) Species-specific monitoring—Fauna
3) Research programs
4) Monitoring species occupancy (Passive Acoustic Monitoring)
5) Monitoring Key Habitat Features
6) Monitoring Regenerating Forests
7) Monitoring Forest Structure and Health
8) Independent Evaluation of Forestry Practice
9) Catchment-based Waterway Health Monitoring

Some of the monitoring strategies can be used to monitor multiple risks simultaneously. Each of the risks was mapped to a relevant monitoring strategy during the expert workshop.

For the purposes of prioritising monitoring strategies (see approach 2 in section 2.8), it is necessary to assign each risk with a cost sharing identifier to enable risks to be grouped according to shared costs. After the workshop, the monitoring goals and design descriptions were used to estimate which risks could share costs. Key considerations in determining whether risks could share costs were:

1) Monitoring design for risks was the same;
2) Monitoring design for risks were in the same geographical location;
3) Monitoring actions could occur simultaneously in time.

Descriptions of each of the monitoring strategies and the cost identifiers that were assigned to each risk are included in Appendix A (sheet: "Monitoring strategies"). After assigning cost sharing identifiers, there were 25 monitoring strategies.

3.3 Prioritisation of risks

Risks can be prioritised using the expected risk reduction (see approach 1 in section 2.8; risk reductions for each risk are included in the spreadsheet "Monitoring strategies" in Appendix A). Using risk reduction as the prioritisation criteria, the five highest risks in each criterion (environmental, economic, community) are given in Table 2. When ranked by potential for risk reduction, the top three risks were related to aspects of forest structure and regeneration. Specifically, the top risks related to loss of habitat features as a result of harvest operations, invasive species incursions and the size of coupe sizes in the Coastal IFOA agreement. The remaining risks in the top 5 related to the effectiveness of tree retention and wildlife habitat clumps, and the appropriateness of the exclusion zones for species needs.

Ranking the risks according to risk reduction (Table 2) resulted in different ranks than ranking according to raw risk (Table 1). Only one of the top 5 risks was shared when ranking according to these two methods (risk 18, loss of habitat features as a result of harvest operations). Although some risks may be of high concern, mitigating these risks may not be the most cost-effective actions. Evaluating the expected ability to mitigate risks when prioritising actions provides useful context when choosing what to monitor.

Table 2: List of the 5 risks with the greatest expected risk reduction as a result of monitoring and changed management practices. Risks are measured on a scale between 0 and 5, so the maximum possible risk reduction is 5.

Risk ID	Risk description	Enviro risk reduction	Comm risk reduction	Econ risk reduction	Average risk reduction
18	Harvesting operations change the structure of regenerating forest (i.e. insufficient giant, hollow-bearing, sap and feed trees) so that it that does not provide suitable habitat for the range of dependant species.	0.89	0.89	0.60	**0.79**
22	That the regeneration standards are insufficient and forestry	0.67	0.57	0.58	**0.61**

	operations increase the risk of invasive species in the landscape; measured by incursion of new invasive species into features.				
20	That the maximum coupe size of intensive or alternate coupe harvesting enables harvesting of areas that are too large to enable species to persist in the landscape and recolonise following timber harvesting within a landscape management area.	0.58	0.61	0.42	**0.54**
53	That tree retention and wildlife habitat clumps in the landscape (combined with harvest settings and other protected habitats) are ineffective in supporting the persistence of priority species i.e. populations decline over 30% in 10 years or three generations which ever is the greatest.	0.60	0.65	0.36	**0.54**
51	Identified protection is not appropriate for the species - e.g. protection radius insufficient or excess to species needs, protection of mature individuals only does not provide sufficient recruitment or protection from forestry disturbances inconsistent with species life cycle needs. That flora road management plan settings are inconsistent with species life cycle needs	0.588	0.546	0.42	**0.518**

The risk reduction scores provide a common metric with which to evaluate risks and this enables prioritisation to be carried out in different ways. For example, instead of prioritising risks in an overall sense, decision makers may choose to prioritise risks within monitoring strategies. This would be useful if all monitoring strategies were funded, but there was a need to decide which risks to monitor within each strategy (assuming that monitoring more risks results in higher costs). Risks are ranked within monitoring strategies in Appendix A (sheet “Monitoring strategies”).

3.4 Prioritisation of monitoring strategies

Monitoring strategies were prioritised based on their cost effectiveness and the assumed cost sharing identifiers that specified which risks could be mitigated by the monitoring strategy (Table 3; see approach 2 in section 2.8). From this process, the most cost-effective strategies were a research program to detect koalas and other species using thermal drones, implementing species monitoring programs for Hastings river mouse and Northern Corroboree frogs, monitoring forest structure and health (using LiDAR measurements of canopy structure and height), and monitoring key habitat features (recording the condition of key features over time). The koala research program and the two species monitoring plans had relatively low risk reduction but had high cost-effectiveness due to their very low costs (these three monitoring strategies had the lowest estimated cost of all strategies considered). These strategies are 'easy wins' that offer limited risk reduction but are cheap and easy to implement.

In contrast, the strategies to monitor forest structure and key habitat features had two of the highest risk reductions of all the strategies considered. These strategies were moderately expensive but mitigated multiple highly ranked risks simultaneously (mitigated 7 and 5 risks respectively). Of the other broad-scale monitoring strategies that targeted many risks simultaneously, the acoustic monitoring array ranked highly in the prioritisation, but the monitoring regenerating forests ranked very low due to its high expected cost of implementation.

In general, species-specific risks had lower total risk reduction than broad-scale monitoring actions that mitigated multiple risks. For some species, such as the Hastings River mouse, Eastern Bristlebird, Smoky mouse and a number of threatened flora species, the potential risk was large in isolation (Table 1), but was low compared to the aggregated risk reductions from broad-scale actions which mitigated multiple risks. Although the overall risk for these species was high, the ability to mitigate the risk using the Coastal IFOA was often constrained. Low likelihoods of successful monitoring and changed management practices also hampered expected risk reductions for Smoky mouse and Eastern Bristlebird[1], while the potential to reduce risks to the Corroboree frog and Hastings River mouse were constrained because the main threats facing the species is not clearly related to forestry practices. Despite these issues, species monitoring actions for Corroboree frogs, Hastings River mouse, Smoky mouse, Eastern Bristlebirds and threatened flora species were all relatively cost-effective strategies because the low costs associated with their implementation meant that even a low risk reduction represented good return on investment. More expensive species monitoring programs with similar expected risk reduction (e.g. yellow-bellied glider and greater glider monitoring programs) were less cost-effective, while monitoring for other species (southern brown bandicoots, giant burrowing frogs and bat camps and roosts) were considered unlikely to have any significant impact on risk to the species due either to impracticalities of monitoring or the impacts of threats not primarily related to forestry.

[1] Smoky mice are ephemeral species, with numerous examples of unsuccessful attempts to locate the species at sites where it had been recently observed. For this species, predation by cats and foxes was considered a greater threat than the direct impacts of forestry operations. Hastings river mice are thought to prefer a medium level of disturbance, so the impacts of forestry operations are uncertain. Competition with bush rats may be a greater threat than forestry operations. Eastern Bristlebirds had a low probability of monitoring success due to difficulty detecting the species, but management was considered likely to succeed if habitat was improved through appropriate burning regimes and weed control. Corroboree frogs are primarily threatened by chytrid fungus, which is difficult to manage solely using the exclusion provisions in condition 71 of the Coastal IFOA.

Among the research programs, research to improve koala detection using thermal drones was very cost-effective due to its extremely low cost. This research is already underway and requires little additional investment to realise the expected risk reduction. Of the other research programs, research to better understand koala nutrition and how koalas interact with browse trees had moderately high cost-effectiveness, while the research programs to better understand the impacts of exclusion zones around class 1 streams and SEPP wetlands had low cost-effectiveness, largely due to the difficulty of meaningfully detecting change and attributing change to forestry practices.

Table 3: Prioritisation of monitoring strategies based on cost-effectiveness. Cost effectiveness has units of risk reduced per $100,000. Larger values of cost effectiveness represent higher priorities according to this process. Cost effectiveness is calculated by summing the risk reductions for risks mitigated by the monitoring strategy. Average values are generated by taking a mean risk reduction over the three criteria (environmental, community and economic risks).

Monitoring strategy	Strategy Descriptor	Indicative Cost ($)	Average risk reduction	Average cost-effectiveness	Monitoring strategy rank
Research program	Thermal drones for koala survey	10000	0.36	3.59	1
Species-specific monitoring--Fauna	Hastings River Mouse	10000	0.19	1.94	2
Monitoring Forest Structure and Health	LiDAR measurement of canopy height and structure	100000	1.87	1.87	3
Species-specific monitoring--Fauna	Northern Corroboree Frog	10000	0.14	1.42	4
Monitoring Key Habitat Features	Monitor key habitat features	250000	2.95	1.18	5
Species-specific monitoring--Fauna	Eastern Bristlebird	25000	0.19	0.77	6
Passive Acoustic Monitoring	Passive acoustic monitoring array	300000	1.81	0.60	7
Species-specific monitoring--Fauna	Smoky Mouse	25000	0.15	0.59	8

Species-specific monitoring--Flora	Species-specific monitoring	70000	0.41	0.59	9
Research program	Research: koala browse trees	100000	0.37	0.37	10
Species-specific monitoring--Fauna	Yellow Bellied-Glider species persistence	100000	0.35	0.35	11
Species-specific monitoring--Flora	Survey of exclusion areas	150000	0.52	0.35	12
Independent evaluation of forestry practice	Independent review: water quality	200000	0.43	0.21	13
Independent evaluation of forestry practice	Independent review: harvest burning	200000	0.42	0.21	14
Research program	Research: effectiveness of conditions for Coastal SEPP wetlands	50000	0.09	0.18	15
Species-specific monitoring--Fauna	Greater Glider species persistence	200000	0.36	0.18	16
Species-specific monitoring--Fauna	Southern Brown Bandicoots	50000	0.07	0.13	17
Species-specific monitoring--Fauna	Greater glider dens	200000	0.25	0.13	18
Monitoring Regenerating Forests	Monitoring regeneration forests	1500000	1.87	0.13	19
Catchment based waterway health monitoring	Catchment scale BACI macroinvertebrate assemblage	300000	0.13	0.04	20

Research program	Research: effectiveness of class 1 drainage lines exclusion zones	200000	0.06	0.03	21
Species-specific monitoring--Fauna	Giant Burrowing Frog	20000	0	0	22
Species-specific monitoring--Fauna	Bat camps and roosts	50000	0	0	22
Independent evaluation of forestry practice	Independent review: cryptic flora protection	200000	0	0	22
Independent evaluation of forestry practice	Independent review: conservation of habitat features	200000	0	0	22

4 Discussion

There are various approaches to prioritise monitoring strategies using the risk framework. Selecting a priority set of risks to monitor is dependent on:

i) the expected consequence and likelihood of a risk occurring;

ii) the likelihood of mitigation of the risk (including both likelihood of detection with monitoring and likelihood of changed practices);

iii) the cost of monitoring; and

iv) whether monitoring strategies can be customised by adding or removing relevant risks to vary the cost of monitoring (the other case requires implementing a fixed monitoring strategy that covers all affected risks).

In this section we discuss three different approaches to prioritisation based on the four factors above. In the first approach, we assume that risks can be prioritised based on risk reduction alone. This prioritisation approach is straightforward but does not consider the cost of monitoring nor the potential for mitigating multiple risks with a common monitoring strategy. The second approach assumes that all monitoring strategies will be partially implemented, and that individual risks will be prioritised within each monitoring strategy. As with the first approach, we do not include cost in this prioritisation, as we did not elicit the incremental costs of including or excluding risks from monitoring strategies. The third approach assumes that monitoring strategies will be implemented in full, but resource constraints may mean that not all strategies can be implemented. In this case, we use cost-effectiveness to prioritise each of the strategies. We conclude the discussion with some thoughts on using our prioritisation approach in practice.

4.1 Prioritising all risks

We prioritised based on maximising the expected risk reduction from monitoring and mitigation actions in the Coastal IFOA. Our prioritisation showed that some of the highest-risk events were not equivalent to the events that were most effective to manage. In general, while many individual species had relatively high-risk scores (Table 1), the greatest reductions in risk could be obtained by monitoring and managing regeneration aspects of forest structure (Table 2). In particular, the highest risk reductions could be obtained by monitoring important trees (giant, hollow-bearing, sap and feed trees), invasive species incursions and the maintenance of a suitable mosaic of forest age classes in intensive and alternate coupe areas. The high expected reductions in risk for regeneration were driven largely by a high expert confidence that monitoring regenerating forest was almost certain to detect change. In contrast, many of the high-risk species were either difficult to detect and manage on forestry estate or threatened by threats that were not directly related to forestry (e.g. chytrid fungus, predation, competition with invasive or other native species), so monitoring and increasing the existing Coastal IFOA management provisions was considered unlikely to result in significant reductions in risk to species.

For these threatened species impacted by threats other than forestry, targeted threat-based management is required. Although these management actions were not priorities for the monitoring of the Coastal IFOA, the high-risk species that are unlikely to benefit from forestry management may need to be considered elsewhere, for example in threatened species recovery plans managed by State and Federal environment departments. By ranking adverse events based on the raw risk scores developed in this project and comparing with the top priorities based on risk reduction, decision-makers can: (i) identify species and other risks that are of high importance but will not be effectively managed using the mechanisms in the Coastal IFOA, and (ii) determine whether these risks can be effectively monitored and managed using other policy or departmental instruments.

4.2 Prioritising within monitoring strategies

If all monitoring strategies are likely to be implemented, but not all risks will necessarily be monitored, prioritisation is needed to determine which risks each strategy should monitor. In this situation, risks should be prioritised within each monitoring strategy based on the potential for risk reduction, but the prioritisation process does not evaluate the trade-offs between risks from different monitoring strategies.

Four monitoring strategies would mitigate a notably large number of risks simultaneously if implemented (Appendix A , sheet "Monitoring strategies"). If implementing the full monitoring strategy was cost-prohibitive, then prioritisation within these strategies may be required to reduce the cost. To address this, the top priorities within these four strategies are discussed below.

1) *Monitoring forest structure and health: LiDAR measurement of canopy height and structure:*

   LiDAR measurements would directly mitigate 6 priority risks. Of these, the greatest risk reduction would result from monitoring canopy cover to test the appropriateness of the maximum coupe size. The least effective risk to monitor was the risk of dieback via declines in canopy health.

2) *Monitoring key habitat features: survey of feature condition, use etc:*

   Monitoring key habitat features would directly mitigate 8 priority risks. Of these, the greatest risk reduction would result from monitoring selected features for priority species. The least effective risk to monitor was reductions in the abundance of winter flowering trees.

3) *Monitoring regenerating forests: Structure, composition and coarse woody debris benchmarks with plot-based monitoring*

   Monitoring regenerating forests would directly mitigate 5 priority risks. The greatest risk reduction would result from monitoring the structure of regenerating forest (particularly giant, hollow-bearing, sap and feed trees) to ensure that sufficient habitat is available for dependent species. The least effective risk to monitor was reductions in coarse woody debris levels for dependent species.

4) *Passive acoustic monitoring array:*

A passive acoustic monitoring would directly mitigate 6 priority risks. The greatest risk reduction would result from monitoring the abundance of hollow-dependent arboreal species (excluding birds and bats). The least effective risk to monitor was whether the Coastal IFOA conditions protected sufficient habitat for large forest owls.

These relative priorities should also be considered in the context of the total risk reduction—it may be worth monitoring all risks affected by some monitoring strategies at the expense of excluding other risks elsewhere. This decision will depend on the incremental costs of including risks, as well as other factors such as the relative budget assigned to each monitoring strategy.

4.3 Prioritising between monitoring strategies

A third prioritisation approach assumes that only some of the monitoring strategies will be implemented, but that the monitoring strategies will be implemented to monitor all affected risks if selected. This approach assumes that implementing a monitoring strategy can mitigate multiple risks and that each risk is mitigated by a single monitoring strategy. Using this approach, the highest priority monitoring strategies were either broad-scale strategies that mitigated multiple risks (i.e. large risk reduction) or species-specific monitoring strategies or research projects that could be implemented with very low cost (Table 3).

Although there was some variation in risk reduction for different species-specific risks, most of the variation in cost effectiveness for monitoring related to species appeared to be due to variation in cost. There was a notable drop in cost-effectiveness for species monitoring plans costing more than $10000, and another drop for plans >$70,000 (Appendix A , sheet "Monitoring strat_cost_effect"). Species monitoring tends to have limited risk reduction potential because it only mitigates risk for a single species and often must overcome impediments such as low probability of success or external threats. To balance the limited benefits of single-species monitoring compared to strategies that mitigate multiple risks species monitoring plans should be conducted at low cost where possible to make them competitive in a cost-benefit ranking approach.

In contrast to the results for species-specific monitoring strategies, broad-scale monitoring strategies have greater potential to have high benefit because they mitigate multiple risks. This allows broad-scale monitoring strategies to justify higher costs in some cases. The three broad-scale monitoring actions that had high cost effectiveness (monitoring forest structure and health; monitoring key habitat features; passive acoustic monitoring) balanced high risk reduction with moderate costs ($300,000 or less; Table 3). A fourth broad-scale action, monitoring regenerating forests, had similar expected risk reduction but was cost-prohibitive ($1.5 million; an order of magnitude higher than all other strategies).

Research projects varied in their cost-effectiveness. Research to improve detection of koalas using thermal drones was the most cost-effective strategy, combining a moderate expected risk reduction with very low cost of implementation. However, this strategy is already in progress, so some of the implementation costs may have already been borne, providing an artificially low estimate of cost for this strategy. A research project to understand koala nutritional requirements had moderate cost-effectiveness due to a higher cost of implementation despite having a similar expected risk reduction to the thermal drone project. Both research projects about the impacts of the IFOA conditions on water quality (SEPP wetlands and class 1 drainage lines) had low cost-effectiveness due to low expected risk reduction from the research. These results suggest that research projects should be prioritised cautiously, and that care should be used to ensure that: (i) the research will target a risk where uncertainty reduction will benefit management; and (ii) that the full costs of the research are included in the estimates for prioritisation, particularly for studies that are already underway.

None of the four independent reviews had high relative cost-effectiveness. Two of the reviews (water quality and harvest burning) had moderate potential for risk reduction, but the high implementation cost ($200,000) largely nullified the expected benefits. For these two review proposals it may be worth investigating cheaper ways to implement the main elements of the reviews to improve cost-effectiveness. The other two reviews (cryptic flora protection and conservation of habitat features) were not expected to reduce the likelihood of the relevant risks. For the cryptic flora review monitoring, it is possible that the number of flora species and their cryptic nature means that it is unlikely that changes could be detected. The justification given for the conservation of habitat features review was similar, i.e. that even with improvements in survey modelling, evaluation of a sample of habitat features would not be certain to detect broad-scale changes in the quality or abundance of habitat features.

Although the independent reviews had comparatively low cost-effectiveness compared to other monitoring actions, independent reviews are an important mechanism for generating trust between stakeholders. Appointing a mutually agreeable and trusted third party to review forestry operations provides assurance that conditions are being met and generates constructive feedback for improvement if and where required. Because the benefits from this trust do not directly lead to reduced risk of adverse events occurring, they are not captured by the cost-effectiveness analysis, but these benefits are important and should be considered when prioritising monitoring actions.

4.4 Interpreting and using the results

The analysis provides priority sets of risks that should be monitored to maximise the likelihood of meeting the objectives of the Coastal IFOA given the available resource constraints and the assumptions of our analysis. Our prioritisation should be treated as a guide and not as an actual investment decision; the final decisions about what monitoring strategies to invest in are likely to include other factors such as the outcomes of public consultation, more detailed cost estimates, and departmental/agency needs not covered by this analysis.

By documenting and quantifying the expected risks, the risk register provides the technical information required to inform prioritisation in different ways while allowing scope for decision makers to refine the objectives through different prioritisation approaches. For example, public consultation may result in some monitoring strategies being implemented even if they did not rank highest in the prioritisation. Our approach can inform these conversations by providing an initial priority set and a logic for why and how it was selected.

While the risk register represents the state of knowledge at the current time, we expect that the understanding of risks will evolve as more detailed information becomes available and additional stakeholders become involved in the monitoring process. As such, the risk register should be viewed as a living document that needs to be regularly updated and adapted to ensure that it remains relevant to decision-making. As monitoring strategies are developed in more detail after the first round of prioritisation, the updated likelihoods and costs can be updated in the risk register. Once the strategies are implemented, monitoring and evaluation strategies should be implemented to evaluate and update the predictions of the register so that future prioritisation decisions make use of the best available information.

The next step in implementing the monitoring plan is to select a priority set of risks and monitoring actions based on our risk analysis, available funds and other considerations such as information gathered through public consultation. After selection of these risks, the relevant monitoring actions must be developed in more detail. Our risk register outlines the goals and methodology of each monitoring action as well as ballpark cost estimates. This information provides a starting point to develop more detailed strategies, such as the statistical methods that will be used, the number of replicates (spatial and temporal) required, the power of each monitoring strategy to detect change over time, and more detailed cost estimates. Most of the proposed monitoring strategies have strong precedents and should not require considerable methodological development, however an exception is the strategy to monitor regenerating forests, which relies on establishing benchmark conditions for structure, composition and coarse woody debris for different harvested forest types over time. Agreeing on these benchmarks early will greatly facilitate the implementation of this monitoring strategy.

Conclusions

This report uses a decision-science approach to prioritise monitoring actions to assess the effectiveness of the conditions of the Coastal IFOA. Our approach assumes that the key risks to prioritise are those that are most likely to be mitigated if adverse events are detected. Although the highest raw risks included many single species-based risks, the greatest potential reductions in risk could be achieved by monitoring risks related to forest structure.

The monitoring strategies that were developed mitigated multiple risks simultaneously, so that a comparatively small set of monitoring strategies would be required to mitigate the top thirty ranked environmental, social and economic risks. If funding to implement all monitoring strategies is insufficient, prioritisation can either partially implement all monitoring strategies by prioritising risks within each monitoring strategy or fully implement a reduced set of monitoring strategies. In the former case, the selection of risks depends on the incremental cost of adding or removing a risk from a monitoring strategy, so although adverse events could be ranked according to their expected reduction in risk, we did not have sufficient information to develop a priority set. In the latter case, we prioritised monitoring strategies using a cost-effectiveness metric that maximised the risk reduced per dollar spent. We found that species-based monitoring plans (Hastings river mouse, Northern Corroboree frog, Eastern Bristlebird and smoky mouse) and research projects (thermal drones for species monitoring) could be high priorities for risk if their costs were kept low, but that more expensive monitoring strategies needed to mitigate multiple risks to justify their costs. Of the broad-scale monitoring actions, measuring canopy height and structure with LiDAR and monitoring key habitat features were the most cost-effective strategies.

Our report provides the basis to create an initial priority set of monitoring actions based on the potential to reduce risk. In doing so, the approach seeks to select monitoring actions that will produce information that is relevant to management needs. The prioritised set should be viewed as an initial prioritisation based on the best available information at the current time, and the risk register should be maintained as a living document that is updated as new knowledge becomes available.

References

Carwardine, J., Martin, T.G., Firn, J., Reyes, R.P., Nicol, S., Reeson, A., Grantham, H.S., Stratford, D., Kehoe, L. & Chadès, I. (2019) Priority Threat Management for biodiversity conservation: A handbook. *Journal of Applied Ecology,* **56,** 481-490.

Caughlan, L. & Oakley, K.L. (2001) Cost considerations for long-term ecological monitoring. *Ecological Indicators,* **1,** 123-134.

Chades, I., Ponce Reyes, R., Nicol, S., Pascal, L., Fletcher, C., Cresswell, I. & Carwardine, J. (2019) An integrated spatial prioritisation plan for the Saving our Species program. Report prepared for the NSW Office of Environment and Heritage. CSIRO, Brisbane.

Coastal IFOA (2018) Coastal Integrated Forestry Operations Approval-- Conditions. Available at: https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/forestagreements/18p1177-coastal-ifoa-conditions.pdf.

Gosling, J.P. (2018) SHELF: The Sheffield Elicitation Framework. *Elicitation: The Science and Art of Structuring Judgement* (eds L.C. Dias, A. Morton & J. Quigley), pp. 61-93. Springer International Publishing, Cham.

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T. & Ohlson, D. (2012) *Structured decision making: a practical guide to environmental management choices.* . Blackwell Publishing Ltd.

Handcock, M. & Gile, K. (2011) Comment: On the concept of snowball sampling. *Sociological Methodology,* **41,** 367-371.

Hsu, C.-C. & Sandford, B.A. (2007) The Delphi technique: making sense of consensus. *Practical assessment, research & evaluation,* **12,** 1-8.

ISO (2018) *Risk management-- Guidelines*. International Organization for Standardization, Switzerland.

Lindenmayer, D.B. & Likens, G.E. (2010) The science and application of ecological monitoring. *Biological Conservation,* **143,** 1317-1328.

Nicol S & Chades I (2017) A preliminary approach to quantifying the overall environmental risks posed by development projects during environmental impact assessment. *PLoS One,* **12,** e0180982.

Nicol, S., Ward, K., Stratford, D., Joehnk, K.D. & Chadès, I. (2018) Making the best use of experts' estimates to prioritise monitoring and management actions: A freshwater case study. *Journal of Environmental Management,* **215,** 294-304.

Speirs-Bridge, A., Fidler, F., McBride, M., Flander, L., Cumming, G. & Burgman, M. (2010) Reducing Overconfidence in the Interval Judgments of Experts. *Risk Analysis,* **30,** 512-523.

Appendix A Risk register, monitoring actions and cost-effectiveness prioritisation

The full risk register, the monitoring strategies and the cost-effectiveness prioritisation of the monitoring strategies is contained in the attached Excel spreadsheet “Appendix A1- Risk Register.xlsx”.

Appendix B Proof of optimality for the greedy ranking heuristic

Prioritising monitoring strategies for the Coastal IFOA is a combinatorial optimisation problem. In this appendix we show that the combinatorial optimisation problem can be reduced to a simple ranking exercise, where risks are selected in descending order of risk reduction until the budget is exhausted.

The first step in defining an optimisation problem requires defining the objective. The objective of the project is to minimise the risk of an adverse outcome under the Coastal IFOA.

We assume that the consequences of an adverse event (C) can be estimated from an economic (C_1), societal (C_2) and environmental (C_3) perspective. Assuming these consequences can be additive, in absence of monitoring, the risk of event *i* can be expressed as:

$$R_{i_0} = L_{i0}C = L_{i0}\sum\nolimits_{k=1..3} C_{ik}$$

We assume that the risk of consequences occurring can be mitigated through monitoring and changes in management (R_{i_1}). Formally:

$$R_{i_1} = \left[\left(1 - p_{i,mon}\right)L_{i0} + p_{i,mon}\left(1 - p_{i,management}\right)L_{i0} + \left(p_{i,mon}p_{i,management}L_{i1}\right)\right]\sum\nolimits_{k=1..3} C_{ik}$$

$$R_{i_1} = \left(L_{i0} - p_{i,mon}p_{i,manage}\left(L_{i0} - L_{i1}\right)\right)\sum\nolimits_{k=1..3} C_{ik}$$

Monitoring comes at a cost (c_i) which must not exceed a total budget B.

The optimal decision problem can be formulated as choosing the monitoring investment x_i={0,1} to minimise the cumulative risk of incurring consequences under budget constraints. Formally,

Optimisation problem (1):	$\min_{x_i} \sum_i R_{i_0} - x_i(R_{i_0} - R_{i_1})$	with x_i={0,1} binary decision variables for all *i* in the list of risks (see Appendix)
Subject to:		
(constraint 1)	$\sum_i x_i c_i \leq B$	The total cost of monitoring strategies selected is less than or equal to a given budget B

Interestingly, the objective of optimisation problem (1) can be reformulated as:

$\min_{x_i} \sum_i R_{i_0} - x_i \Delta R_i = \min_{x_i} \left(K - \sum_i x_i \Delta R_i \right)$ with K=$\sum_i R_{i_0}$, a positive constant that we can discard for the purpose of solving the optimisation problem. Optimisation problem 1 can therefore be reformulated using the following dual formulation:

Optimisation problem (2)	max $\sum_i x_i \Delta R_i$	with x_i={0,1} binary decision variables for all *i* in the list of risks (see Appendix)
Subject to:		
(constraint 1)	$\sum_i x_i c_i \leq B$	The total cost of monitoring strategies selected is less than or equal to a given budget B

Optimisation problem (2) is an efficient formulation as it will allow us to quickly evaluate the most cost-effective solution by ranking the values $\Delta R_i / c_i$.

Note that the formulation can include complementarity (cost sharing) if a matrix of complementarity benefits is provided. For all but one of our risks (winter flowering trees; see section 2.6), implementing a single monitoring strategy is considered sufficient to mitigate the risk (i.e. risk mitigation was not assumed to be dependent multiple monitoring strategies). Since only one risk was dependent on multiple strategies, we assumed that the simple ranking approach in optimisation problem 2 was an optimal way to select a portfolio of priority risks and/or monitoring strategies.

As Australia's national science agency and innovation catalyst, CSIRO is solving the greatest challenges through innovative science and technology.

CSIRO. Unlocking a better future for everyone.

Contact us

1300 363 400
+61 3 9545 2176
csiroenquiries@csiro.au
csiro.au

For further information

Land and Water
Sam Nicol
+61 7 3833 5751
sam.nicol@csiro.au
https://people.csiro.au/n/s/sam-nicol.aspx

Iadine Chadès
+61 7 3833 5683
Iadine.chades@csiro.au
https://people.csiro.au/C/I/Iadine-Chades