Guidelines for risk management in forest planning – what is risk and when is risk management useful?

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Abstract:

Managing forest resources occurs under various sources of uncertainty. Depending on the management problem, this uncertainty may have a substantial impact on the quality of the solution. As our knowledge on the sources and magnitude of uncertainty improves, integrating this knowledge into the development of management plans becomes increasingly useful, as additional information can improve the decision making process. This adjustment requires a fundamental shift in how planning problems are viewed: instead of interpreting risk management as a technique needed only for addressing problems with natural hazards, risk management should be an integral part of most planning problems. Managing risks can be linked to a variety of adaptive planning methods: to help mitigate risk, plans should either be revised as new information becomes available or the possibility of adaptation should be accounted for in preparing the plans. We conduct a brief examination of the key topics in risk management and highlight how risk management implies trade-offs. Several decision problems which incorporate risk management are analyzed and alternative perspectives for the problem are suggested to better address risk management issues. We then provide a decision framework for considering how to integrate risk management practices into the forest planning process.

Keywords: Risk Management, Risk, Uncertainty, Conditional Value at Risk, adaptive planning

1. Introduction

Making decisions on how to manage a forest holding is a process done with imperfect information. The information regarding the current resources of a forest holding is an estimate that can be subject to substantial uncertainty. To create forest plans, the potential future resources are predicted utilizing imperfect forest growth models. In addition, the future is never certain and local growing conditions may be substantially different than those assumed in the models. Climate change (Garcia-Gonzalo et al. 2016) introduces additional uncertainty to the predictions of growth and survival. Natural hazards can considerably impact the quantity and quality of forest resources (Hanewinkel et al. 2011, Diaz-Baltiero et al. 2014). The economic situation of managing and utilizing forest resources can change quickly and dramatically over time. For instance, timber prices reflect the requirements of the industry, and changes in either demand or supply will cause a change in price. Costs associated with forest management (i.e. silvicultural activities) may change depending on the cost of labour or the development of new technology. Additionally, the political context can introduce uncertainty through the proposition of changes to legislation, or through the introduction of conservation strategies.

In forest planning, many of these sources of uncertainty are ignored as inconsequential, due to the traditions of planning or overconfidence on the accuracy of the models used. For instance, modern forest inventory methods and growth and yield models are seen as adequate enough for the task, representing the best tools we have now. In deterministic planning the effects of such small uncertainties remain unacknowledged and therefore also underestimated. The decision makers thus see no need for addressing the uncertainty in planning, except for the natural hazards. However, even though the growth models are of high quality, uncertainty introduced by these models can increase costs substantially (Borders et al. 2008; Holopainen et al. 2010; Pietilä et al. 2010). Our knowledge on the nature and magnitude of different sources of uncertainty is improving, and integrating this knowledge into the development of management plans should be an essential consideration in forest management planning.

The concepts of uncertainty and risk have a long history, and the clarification of differences between these two terms has been defined by Knight in the early 20th century (Knight 1921). The separation made by Knight was based on whether the probability distribution of possible outcomes is known (Risk) or not known (Uncertainty). In most natural systems, the precise knowledge of a probability distribution is not possible to obtain. However, through the use of statistics there is a possibility to estimate the probability distribution. If we can estimate the probability distribution of the outcome, we can use risk management tools. In this discussion, we will use the term 'uncertainty' to refer to the quality of the information, and the term 'risk' to refer to the potential of meeting the goals and expectations of the management plan, or the probability of loss due to natural hazards (see Kungwani 2014).

Management decision proposed in forest management plans should not be seen as unchangeable; rather the decisions should be adaptive (Yousefpour et al 2012). Very simply put, adaption can occur whenever new information becomes available. Such new information can be revealed when circumstances change due to unexpected events (i.e. Black Swan events (Taleb 2007)). Adapting to events that cannot be predicted (unknown uncertainty) cannot be planned for in advance, and require re-planning based on the updated circumstance. Whenever we have knowledge on the probability of possible outcomes, it is also possible to plan for adaption. New information can be obtained based on planned information collection (e.g. forest inventory), or revealed in time (e.g. expected policy shifts or changes in prices of timber). It is possible to link risk management needs to the specific timing of these events.

The actions taken to manage risk depend upon which risk element(s) is (are) to be managed. For instance, the management of wind damage can be accomplished through adjustments to the spatial patterns of harvesting (Heinonen et al. 2011). The severity of fire risks can be managed by removing fuel from the forest. Climate change is assumed to increase the growth of trees but also to increase the mortality of some tree species due to e.g. the increased probability of drought during summer or the increased probability of sub-zero temperatures after an earlier start to the growing season. Then, a subset of the impact from climate change can be mitigated by tree species and provenance selection (Forsius et al. 2013). The impact of growth model errors can be removed through the updating of information by conducting a new inventory (Eyvindson, Petty and Kangas 2017). The uncertainty related to inventory errors can be managed by using the best inventory method available. As inventories can focus on different aspects of forest attributes, the best inventory method will depend on the specific management objectives. When we cannot reduce the uncertainty, we can still prepare for it in the decision making.

Risk management is typically associated with natural hazards that introduce high losses with a low probability. However, risk management is advisable also in cases with high probability of small losses. For instance, climate change may increase the probability of mortality, this may be mitigated after clear felling by modifying the species / provenience selection for regeneration. In risk management, the problem formulation (and the interpretation of the constraints) is of more importance than the source of uncertainty. Deterministic forest planning is often designed to meet a set of constraints, but when the plan is implemented small violations of constraints are acceptable. Introducing risk management into the planning problem will force the managers to consider how important it really is to meet the constraints. Therefore, including risk management in forest planning will make forest planning closer to real-life decision making. This adjustment requires a fundamental shift in how the planning problems are viewed: reflecting how unexpected occurrences are managed in practice, allowing for the efficient handling of the deviations.

The objective of this paper is to provide guidance for integrating risk management into the forest planning process and a conceptual framework for selecting the most appropriate method for managing those risks in forest management planning. We show that introducing risk management properly into the planning process improves the decisions with reasonable effort.

2. Integrating risk management into forest planning

2.1 Measuring risk

The common feature of risk management is that specific attributes of the distribution of the outcomes can be measured and altered through varying the proposed decisions. In a very general sense, the measurement of risk relies upon the evaluation of the specific attributes of the distribution of the potential outcomes of the proposed management actions. One of the first risk measures used is variance. As a risk measure, variance simply evaluates the spread of the results from the expectation value. By measuring the spread, both outcomes which fall short or exceed the expectation value are considered unwanted. As such, the preferential interpretation of this risk measure is one where any variation away from the target is undesirable.

The late 1950's saw the introduction of downside risk measures, specifically the below mean semivariation (Markowitz 1959). Below mean semivariation (or downside mean semivariation), focuses on the unwanted deviations from the mean. From a dataset of possible outcomes, those values which fell below the mean (or specific target) were included in the evaluation of the semi-deviation. In the late 1990's, the risk measure of the Value at Risk (VaR) was developed. Following the development of the VaR, a related measure called the Conditional Value of Risk (CVaR) was developed by Rockafellar and Uryasev (2000).

Both VaR and CVaR focus on evaluating aspects of the tail of the distribution of possible outcomes. The CVaR evaluates the average loss exceeding the VaR, while VaR provides the minimum (threshold) loss with a given probability. VaR thus means that the minimum threshold is exceeded with the given probability. As a measure of risk, the VaR is well known in financial markets, and is established in policy documents (BCBS 2004). However, unlike the CVaR, the VaR is not a coherent measure of risk (Artzner 2002). Additionally when minimizing risk, the CVaR can be transformed into a rather simple linear program and optimized, while the VaR requires the use of integer programming.

In a forest management planning context, a variety of different risk measures have been applied. Robinson et al. (2016) minimized the variance of timber harvested. The shift in the variance of timber harvested involved an (implicit) trade-off in the form of an increase in the amount of forest area harvested. To evaluate the impact of managing risk on the even-flow of timber products, Hahn et al. (2014) evaluated the differences between maximizing the net present value (NPV), the maximization of the certainty equivalent (a return without risk that is equivalent to the uncertain return with risk) of the NPV and the maximization of the VaR of the NPV. To address the management of risks other than in the NPV, namely the negative deviations from a targeted even-flow, Eyvindson and Kangas (2016) used a downside risk measurement and Eyvindson and Cheng (2016) used the CVaR concept. To address both the risk of achieving a minimum targeted income flow and minimum biodiversity protection Hartikainen et al. (2016) used the VaR concept in a multi-objective forest management case. In this case, the trade-off with the objective function value was explicitly shown. For further information on risk measures for forest investments, readers are directed to Hildebrandt and Knoke (2011).

2.2 Trade-offs for risk management

Introducing risk measures into a planning problem means introducing a new objective(s) in addition to the original one(s), which makes risk management inherently multi-objective. Thus, the management of risk should be seen as a multi-objective planning problem, where the intent is to minimize the negative impacts due to uncertainty, while maximizing the benefits of managing the forest for the decision maker (i.e. society, industry or forest owner). These decision makers may consider specific uncertainties to hold more importance. A wide variety of uncertainties could be of interest to decision makers, as examples: natural hazards, economic uncertainty, future supply requirements, and conservation uncertainties. For instance, forests held by mills may focus on ensuring continual supply, investment holding companies may be sensitive to income from the holding and community / governmental held forests may need to consider a wide range of perspectives. Additionally, the size of the estate owned will impact the perceptions towards risk and management issues (Boston et al. 2015).

Risk management has often been seen as a single objective optimization problem where the costs of managing the risk is included in the optimization process and a preference towards risk is either assumed or set. From a multi-objective perspective, the trade-off is explicit; more protection from risk will be associated with a loss in the achievement of the other objectives. For the single objective optimization case, analysis of the trade-off between the willingness to accept risk and other benefits are not possible. For those cases when the risk preferences of a decision maker are explicit, the use of a single-objective optimization perspective can be justified. However risk preferences are domain and problem specific (Charness, Gneezy and Imas, 2013), and elicitation techniques may not provide estimations which have enough precision to be used as a parameter of optimization problems.

Managing the risk associated with decisions is always linked to some cost, either the cost to minimize risk, or the cost of accepting risky outcomes; efficiently managing risk strives to minimize this cost. One way to make management actions less risky is to collect better quality information. For instance, if new information enables us to narrow down the range of potential climate warming from, say, 1°-4° to 1°-2°, it would markedly reduce the risks of (monetary) losses related to tree species selection after regeneration. Likewise, better information on the future growth of a stand would reduce the risks of (monetary) losses related to harvest timing. While the improved information will reduce one or more aspects of risk (or provide an improved quantification of the risk), the cost of acquiring new information may exceed the potential benefits. If the benefits of the new information do not exceed the costs of the information, then the objective value will be degraded rather than be improved. Thus highlighting the need to conduct a trade-off analysis also with respect to acquiring new information.

One way to evaluate the benefits is through the evaluation of the value of information, measured as the value of improving the quality of information or of including the possibility to collect new information (for example chapter 4 of Birge and Louveaux 2011). In a way, this type of analysis can be compared with the cost plus loss evaluation (Eid et al. 2004, Kangas 2010). In a cost plus loss analysis, the benefits of collecting new information can be linked to the losses of the (old or new) information compared with perfect information. In forestry, this has been applied using a max NPV approach at the level of a single stand (Eid et al. 2004). When moving from a stand level to a forest holding or landscape level, approaches to evaluate the value of the information should be made using the same scale at which the decision is to be made. The value of information relates to how the problem is structured, for multi-objective problems the value of information will also consist of multiple objectives, and may not simply relate to a monetary term. In a multi-objective decision problem, the value of information can be interpreted as an improvement in the objective function value (Kangas et al. 2010, Birge and Louveaux 2011). On the other hand, in many cases just including the uncertainties into the decision problem through stochastic programming will improve the decisions. For instance in a case of inventory errors this improvement can be even larger than the improvement obtainable by collecting additional information, meaning that information on the uncertainty is in itself valuable (Eyvindson and Kangas 2014).

2.3 Risk preferences

Risk preferences identify the willingness of an individual to accept risk. While risk preferences represent a continuum, they are often segregated into three categories: risk averse, risk neutral and risk seeking (Hillson and Murray-Webster 2007). In portfolio management, the acceptability of higher risk relates to the potential for higher profits. Thus, the decision maker needs to address the trade-offs between expected profits and the safety of obtaining the profits. This is called "risk attitude". A risk neutral person weighs the different outcomes only with their probability, whereas a risk seeker gives a larger weight to the high end of outcomes and the risk averse person assigns a higher weight to the low end of the outcomes (Jarrow and Zhao 2006). One method of defining risk attitudes of a specific decision maker can be done through choice decisions (certainty equivalent, Raiffa 1968). The specific risk preferences are calculated through the presentation of a variety of gambles to a decision maker, and where they are asked the minimum amount they would accept to forgo the gamble.

The elicitation of risk preference from a decision maker provides a snap-shot of the preferences at one point in time. As with all other preferences, risk preferences will change over time and are related to other factors in the decision maker's circumstances. For instance, a forest owner, a younger owner may have a higher tolerance to risk than an older owner. These changes can be addressed through collecting new information on the risk preferences from time to time and re-planning if the attitude has changed.

By utilizing risk measures, the trade-off between the risk objectives and the other objectives of interest are made clear. These trade-offs occur irrespective if we are viewing the problem of a single stand or a landscape; and for different time horizons. Decisions made to reduce the risk with respect to one objective may negatively impact other objectives of interest which hold importance for the decision maker. If no improvements can be made to the risk measures without impacting the other objectives, an active choice by the decision makers must be made.

Making risk management explicit is always recommendable: it enables the managers to see if the proposed actions for risk management improves or worsens the outcomes of the decision in the planned way. If the costs of risk management appear unexpectedly high or low, the reason may be in flawed decision model, for instance inappropriate measures for the risk or unnecessarily strict constraints. Thus, calculating the trade-offs explicitly also enables the modellers of the decision problem to see if the analysis is useful.

This trade-off was highlighted in portfolio management in finance in the middle of the 20th century (Roy 1952; Markowitz 1952). These researchers highlighted trade-offs required between maximizing the expectation value of a portfolio and ensuring a specific level of the mean-variance ratio. Depending on the specific problem formulation, similar trade-offs between risk and return (biological or economic) can be found.

2.4 Linking risk management to specific decision problems

The modelling of a particular decision problem requires the selection of specific alternatives among several options. These modelling choices influence how risk and uncertainty can be integrated into the problem. Depending on the method used to solve the problem, some of the modelling choices are made implicitly. For a review of methods used to introduce uncertainty into forest planning readers are referred to Pasalodos-Tato et al. (2013). For some of these methods there may not be a mechanism to estimate the impacts of risk into the problem (such as the size and frequency of losses), there may be no mechanism to adjust how the feasibility of a solution is interpreted (is a problem still acceptable if the constraints are only slightly exceeded) or the incorporating the risk preferences may not be possible.

While the calculation of risk measures is not a requirement of managing risk (i.e. Robust programming (Palma and Nelson 2009) or Markov chain models (Buongiorno and Zhou 2017)), the use of risk measures can assist the decision makers by allowing for a trade-off analysis. Introducing elements of uncertainty into the decision problem requires special attention to the interpretation of constraint feasibility. For instance, the direct use of deterministic even-flow constraints under uncertainty will be interpreted as a strict requirement for a minimum flow. In a stochastic setting, such constraints are likely to have a large, negative effect on the objective function value. Thus, appropriate changes need to be made to these constraints, for instance, the threshold may be made fuzzy (Mendoza, Bare and Zhou 1993), based on a specific probability for exceeding the constraint (Bevers 2007), or through specific risk measures (such as VaR and CVaR).

If the uncertainties are not incorporated into the model in a way appropriate for the particular problem, the resulting decisions may be worse than without risk management. Special consideration should be given to how feasibility issues frame the problem: constraints that can be described as goals rather than constraints need to be modelled as goals, and only constraints that really need to be met in every condition should be modelled as strict constraints that are typical in deterministic setting. One example of appropriate strict constraints may be ecological values which should be managed with a strong sustainability perspective (Neumayer 2003); for instance maintenance of biodiversity values above a specific limit.

The value of managing risk is strongly linked to the risk preferences of the decision maker. For risk neutral decision makers, the value of assessing and managing risk may be rather small. For risk averse decision makers, the value of managing risk can be substantial. Thus, assumptions about risk preferences should be avoided as the potential value of incorporating uncertainty can be lost. At an individual forest owner level there is substantial value in appropriately determining the risk preferences of the owner (Eyvindson and Kangas 2016). For landscape level planning, biodiversity and ecosystem services may be important aspects when conducting management actions. The risk of poor performance in either biodiversity or ecosystem services may be especially undesirable, especially when considering the issue through a strong sustainability framework (Luckert and Williamson 2005). Thus, if assumptions of risk preferences must be made, they should be made with care and should still reflect the desires of the decision maker.

The possibilities to manage risk also strongly depend on the available management options for the decision makers. The modelling of forest management problems often use “schedules” to identify a single set of possible actions available to be conducted at the forest stand level (Johnson and Scheurman 1977). For each stand, a range of different schedules are simulated to reflect the alternative sequence and timing of forest operations. As new methods of conducting forest operations are developed with a focus on managing risks (i.e. wind or fire), the set of stand level schedules should be updated.

The relevance of the specific types of uncertainty may hold a variable importance dependent on the spatial and temporal scales of the decision making process. For a private forest owner, short term price uncertainties may be a key concern for near term decision making while uncertainty related to the potential growth may be of greater importance for longer term decisions. Additionally, risk preferences of a decision maker fluctuate over time, and the need for re-planning options may hold value to specific decision makers. On a national scale, the price uncertainty may hold little importance, as the focus may be on ensuring the general sustainability through changing market drivers and the impact of climatic changes. In a recent review, Yousefpour and Hanewinkel (2016) highlight the deep uncertainty of climate change, and the potential for portfolio diversification and robust decision-making to address the associated risk. Diversification of kinds of forests in a region is better adapted for a wider range of climatic conditions (Knoke et al. 2005), and robust decision-making suggests management alternatives which ensure the health and productivity of the forest for the majority of the worst case future scenarios (McInerney et al. 2012).

For regional scale planning, it is possible that neither price uncertainty nor growth rate uncertainty due to a changing climate may hold critical importance for risk management.

Regional level planning often focuses on the near term planning problems (next 5 – 10 years), and the key element of uncertainty may be the quality of the inventory information. As saw and pulp mills require a rather steady flow of specific assortments of timber, uncertainties relating to the harvesting and transportation scheduling play an important role in management of risk. The origin of these uncertainties could relate to near term climatic change, with changes in precipitation intensity (resulting in a higher number of road washouts), or a shorter period where the soil is frozen to allow harvesting activities on sensitive soils. Issues of timber prices are important for procurement managers, as a means to decrease costs. However an unscheduled mill closure (or slow down) due to limited timber supplies may not be an acceptable risk.

Selecting which species to use when regenerating a site is a decision which must be made under deep uncertainty. Considerations need to be made regarding how well the species will grow under a wide range of potential climatic conditions. This can be complicated by a lack of silvicultural knowledge at specific geographical locations (Lawrence 2017). Additionally, there is the consideration of the expected demand for different timber resources when the newly planted site is ready for harvesting. For short term management problems, our recommendation would be to include a decision rule to determine species type for regeneration, such as a probabilistic decision rule, rather than optimization techniques. For this case scenario analysis may be of value, where the uncertainty is too difficult to integrate into the optimization model completely.

If it is possible to model the site specific development (including climate change) of the different candidate species, a scenario analysis may be possible (Blythe and Young 1994). One method of coming to a decision is through reflection on which scenario the decision maker believes to be most likely. The solutions selected through this kind of decision making process may not be optimal, as information critical to the process may not be included when finding a solution (Wallace 2000). A related example to the species planting is the crop selection problem in agriculture. This problem highlights the differences between maximizing expected net profit and maximizing the conditional value at risk for a specific risk parameter (Filippi, Mansini and Stevanato 2017). Comparing the optimal solutions, as risk aversion increases, the diversity of crops selected is increased, highlighting the benefits of diversification. Interestingly, compared with what actually occurs, the crops selected by real farmers reflect the very risk averse solution provided by the model (Filippi, Mansini and Stevanato 2017). This agricultural case highlights one method which could be applicable in forestry for deciding which species (in which proportions) to plant in order to manage risk, and this information could be used as the probabilistic decision rule.

2.5 Decision problems examples:

To highlight that risk management can be viewed from a wide variety of perspectives, and to communicate the potential for risk management we examine a selection of three published examples of risk management in forestry. We will first quickly describe each example, highlight the methods used to manage risk, and discuss possible improvements for how each particular risk could be managed. The first example is from Hahn et al. (2014) which compares solutions between maximizing either the E(NPV), the certainty equivalent (CE) of NPV or the VaR of NPV. The second example is from Forsell and Eriksson (2014) where they evaluate the impacts on the E(NPV) when striving to manage the wind damage. The third example is from Eyvindson and Cheng (2016) where they evaluate the trade-off between the E(NPV) and the CVaR of obtaining a pre-set target for periodic incomes. While all examples use NPV as the objective of primary interest, it is important to note that risk management can focus on a much wider range of objectives.

The first example from Hahn et al. (2014) presents a detailed study which compares the E(NPV), CE of NPV and VaR of NPV. These objectives can be seen as a risk measures, as each objective represents a different attitude towards risk. In the analysis, they consider both production and timber price risks, using the YAFO optimization model (Härtl et al. 2013). This approach identifies the optimal timing to conduct thinnings or final harvests for each stand. The results highlight a trade-off between the E(NPV) and the standard deviation of NPV. For the extreme cases, maximizing either E(NPV) or VaR of NPV using a discount rate of 1%, a cost of 2% (i.e. a change from 23,858 €/ha to 23,370 €/ha) of the E(NPV) allowed for an improvement of the standard deviation by 34% (2,238 €/ha to 1,475 €/ha). The authors of this study indicate their surprise at these results. Rather than comparing the improvement of the standard deviation, the authors should have compare the VaR of NPV between the solutions. These results were not provided directly in the article, however it can be calculated using the E(NPV) and the standard deviation of the E(NPV). When the objective function is to maximize the VaR, the improvement in the VaR of the NPV was 6% (from 18,651€/ha to 19,938 €/ha) while the deterioration in NPV is 2%. To improve the clarity of the trade-off between the E(NPV) and the VaR, it is important to examine the values which were used in the optimization. In this case, the trade-off between these values becomes much less dramatic.

The adjustments that could be made to the Hahn et al. (2014) approach would be to increase the management options used in the analysis. The management options used in the study were rather limited, including only two decision options (to conduct either a thinning or a final felling). The inclusion of other management options which reduced the risk of hazards would have most likely impacted both the E(NPV) and VaR of the NPV positively.

The second example of Forsell and Eriksson (2014) evaluates the potential benefit from managing wind risk. No specific risk measure has been used in this example, rather their intention was to evaluate the perceived benefit towards integrating wind risk management for a risk neutral decision maker. This was done by examining the differences in E(NPV) when wind risk was addressed in the optimization model and when it was not. The authors used a graph based Markov decision process framework to find the optimal policy to maximize E(NPV). The risk of wind damage was evaluated using the tool developed by Olofsson and Blennow (2005), and it provided a stand specific probability of wind damage. By using this specific Markov decision process, the authors made an implicit decision to utilize preference of a risk neutral decision maker. The results indicated an improvement of less than 2% to the E(NPV) when wind risk was included.

A potential improvement for this analysis could be to include risk preferences other than simply a risk neutral preference. While technically challenging, risk aversion is possible using a Markov decision process (Ruszczynski 2010). By incorporating the risk preferences, it could be expected that there would be a higher use of management options which limit wind risk. This higher usage would be visible as improvements in the risk measure.

The third example from Eyvindson and Cheng (2016) evaluates the trade-off between the E(NPV) and the CVaR of obtaining a specific target for periodic income. For this case, a stochastic programming model was developed which included estimates of uncertainty relating to growth, inventory measurements and the price of the assortments of timber. By evaluating two different components of forest management (i.e. the NPV and the periodic income requirements), the trade-off between these components has a rather large span, and the use of specific risk preferences can produce rather different solutions. This approach avoids considerations of the variability in the NPV and limits the periodic income requirements to reflect an even-flow of income. Using a 3% discount rate, the range of the E(NPV) was between 350,000€ and 360,000€ while the aggregated CVaR of the periodic incomes ranged between 5,000 and 45,000€. This example demonstrates the importance of evaluating the trade-off using the values from the objective function. Additionally, this clearly communicates the potential trade-offs between the competing objectives. The changing risk attitudes can be seen clearly in the trade-off curve, increasing risk aversion for not achieving periodic incomes reduces the NPV.

This approach could be improved by directly eliciting the parameter settings from the decision maker. For this case, the specifics of the decision problem were set in advance, easing the efforts required for the trade-off analysis. For a specific decision maker, a single forest management plan is required, and this could be discovered through an interactive decision process. Through the interactive decision process the parameters of the model could be re-defined, and each time a new solution could be made available (Miettinen and Mäkelä 2000). As the decision maker reflects and learns about the potential outcomes, the forest plan can be expected to be more suitable.

3. Guidelines for managing risk in forest planning issues

When planning to manage risk, the focus should be on the value provided to the decision maker. From an application specific perspective, risk managed along a continuum from comprehensive risk management to adaptive planning. Comprehensive risk management can involve techniques which are computationally demanding, thus managers should be able to match the techniques available to the specific case. To ease the computational burden, forest planning researchers need to focus on identifying methods which capture the various sources of uncertainty in as parsimonious fashion as possible. In this way, the sources of uncertainty which are important to the decisions to be made can be incorporated into the planning model. Adaptive planning can be less computationally burdensome, as questions related to how to manage risk are delayed until specific events are observed to have happened. Alternatively, adaptive planning could be more cognitively burdensome, as the decision maker should remain aware of planning situation.

3.1 Comprehensive risk management

Developing a comprehensive approach to risk management requires a thorough understanding of the uncertainties involved in the forest management problem. The ability to manage specific types of risk depends upon the time horizon under consideration as well as the spatial scale involved. While incorporation of a majority of risk elements may be theoretically possible, the computational requirements and decision process underlying the problem may not require addressing the various risks simultaneously. Some risk can be managed independently (i.e. the choice of which species used in regeneration) and can be integrated into the planning process of other problems. Additionally, the importance of different risks depend upon the stakeholders involved in the decision making process. For a forest holding, a single forest owner may be interested in a very narrow interpretation of risk. At a regional scale, the set of stakeholders involved in making decisions may need to consider a wider variety of risks. Being able to manage risks requires both an understanding of the uncertainties involved, and an understanding of how the decision maker wishes to manage the risk.

In forest management, there are a variety of risks to consider, and a key question to ask is which risks does the decision maker want to manage (i.e. to ask the question "Risk of 'what'?"). The first two examples we examined focused on only one kind of risk: the risk associated with the NPV. Other decision problems may focus on different risks, such as the risk of achieving a specific target for periodic income (Eyvindson and Kangas 2014), the risk of low biodiversity or ecosystem provisioning occurrences, and the risk of planting a specific tree species (Hartikainen et al. 2016). The other question to ask is "How will this risk be managed?". Managing risk requires a choice and can involve a trade-off with other aspects of interest. For instance, risk can be mitigated through the improvement of the quality of information, but often this improvement comes at a specific cost. Alternatively, as Robinson et al. (2016) suggest the variance of harvested volume can be minimized by harvesting stands which have higher predicted accuracy. However, this approach requires an explicit cost of increased harvesting area (Eyvindson and Kangas 2017). Thus for this example, the trade-off is between increased harvesting accuracy and increased harvested area.

Another important aspect to consideration is how the estimates of uncertainty have been evaluated. For statistically based uncertainty estimates (i.e. inventory estimates, growth errors or price uncertainty) risk management efforts can be easily justifiable. These estimates will be unbiased and can be relatively easy to incorporate into the optimization process. For uncertainty estimates based on expert judgment (Oppenheimer et al. 2016), a more careful approach to risk management is needed. This is linked to the concept of deep uncertainty, where the actual uncertainty is unknown, and the estimates for this uncertainty is poor. We still advocate the use of this 'poorer' information, as it reflects the best information we currently have, and most likely the expert judgement will not always be completely incorrect.

3.2 Adaptive planning

Managing risk can be seen through the lens of adaptive management, decision makers should change the plan as the situation requires (Savage 2010, Yousefpour et al 2012). From a planning perspective, there are multiple approaches for planning to conduct adaptive planning. For our use, we propose three adaptive planning approaches. The simplest adaptive planning option is to create a plan based on current information using a deterministic approach (i.e. a model using a single scenario could reflect the average case, best or worst case) and re-plan as relevant new information becomes available (labelled as 1 in Figure 1). The second approach of adaptive planning is slightly more complicated which incorporates risk measures and the risk attitudes of the decision maker and then to conduct a re-planning is done as new information becomes available (labelled as 2 in Figure 1). The third approach pre-emptively suggests the optimal time to collect new information as a means to manage risk, in stochastic programming literature this is referred to as 2-stage and multi-staged problems (labelled as 3 in Figure 1). Depending on the structure of the problem, the benefit of integrating risk management will vary. For each case, we identify the potential benefits of managing risk through a simple scale: (a) high potential, (b) moderate potential and (c) low potential. These potentials refer to the ability to impact change in the objective value when risk is included in the management problem.

Selection of an approach to adaptive planning determines how risk can be integrated into the problem. Very simply put, the more restrictive approaches to adaptive planning are less computationally demanding and easier to formulate and comprehend. Thus, we are left with a need to select the planning approach which meets the needs of the decision maker with the aim of keeping the model as parsimonious as possible. To appropriately select a model for risk management, the forest planner should consider the properties of the information, the context of the management problem (what are the objectives and constraints of the problem) and the availability and benefit of obtaining updated information.

In Figure 1, we propose a decision tree for selecting an appropriate approach to managing forests under risk and uncertainty. Through a set of ordered questions, the planner is guided to systematically think through the structure of the management problem, and a suggestion for which approach to adaptive planning could be used. For two cases (5 and 9), all methods of adaptive planning could be appropriate. For case 5, a deterministic approach may be suitable, if the model requires a specific flow of timber for the worst case scenario. Alternatively, a two-staged or multi-staged model may be suitable if continual monitoring of the forest resources will be conducted to minimize the negative impacts caused by the restrictive specific flow of timber constraint. As the two-staged and multi-staged problems are rather complex, the planner should be able to clarify the benefits from its use. If the decision to collect new information will be based on other factors (new inventory conducted by governmental agency), there is little benefit from including the added complexity.

4. Conclusions

Management of risk should be done comprehensively using a parsimonious model which reflects the requirements of the decision maker. As a parsimonious model, the problem formulation should include only those key uncertainties which impact the problem at hand. For any specific problem, various sources of uncertainty may hold relevance. By including only the key uncertainties, the results should remain understandable to both the decision makers and forest managers. When developing a plan, the decision makers should be made aware that risk management should not focus on the complete elimination of risk. Nor should the plan present a complete enumeration of all potential decisions for each possible resolution of the uncertainty.

We suggest this philosophy towards risk management for two key reasons. From the planning professional's perspective, modelling risk and uncertainty in a comprehensive fashion is difficult to accomplish conceptually. In addition, finding a solution to these problems may not be tractable due to the technical challenge of finding solutions. From the user's perspective, a detailed plan with many sources of uncertainty may hold only moderate improvement in value, or maybe of less value due to the conceptual challenges of interpreting the plan. To promote usability, the planned decisions which include risk management should be as easy to understand as deterministic plans currently produced. Additional valuable information based on the risk preferences of the decision maker could be added to the plan, such as when to conduct a new inventory.

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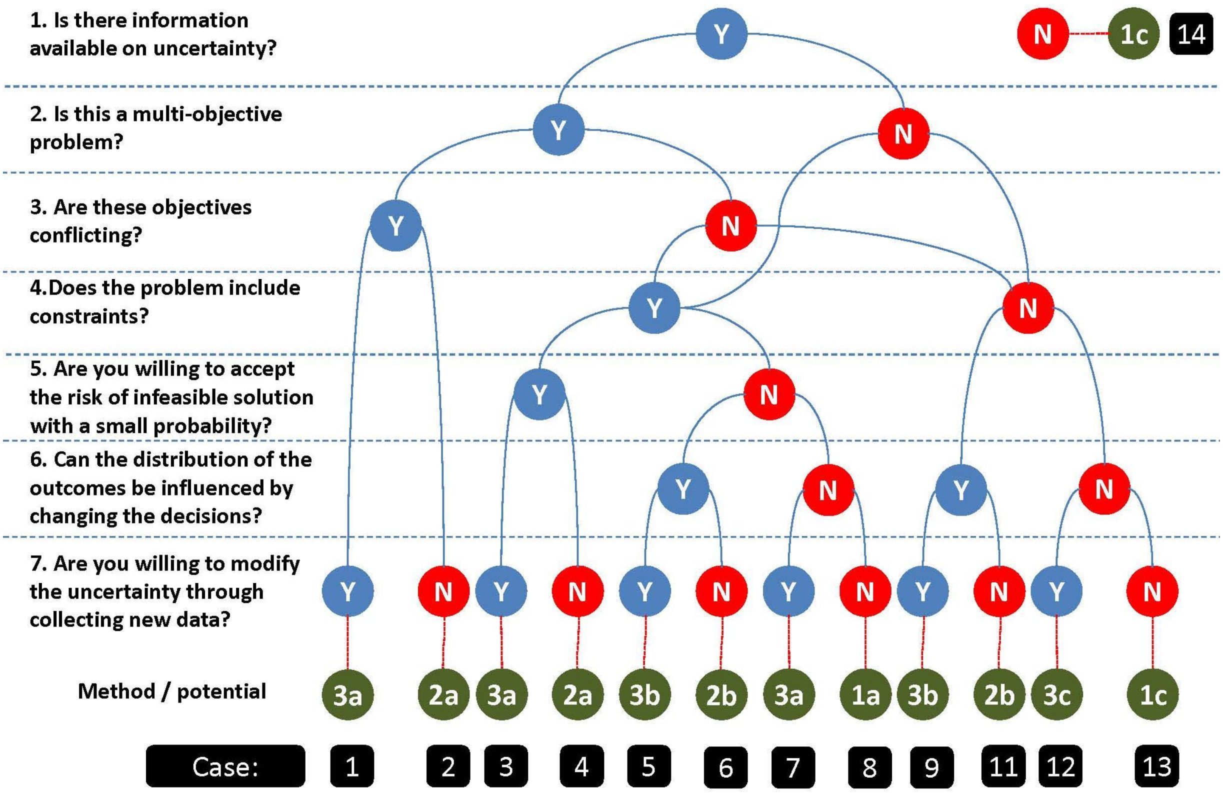

Figure 1. Decision tree for selecting a modelling framework for forest management planning. Choices for how to incorporate risk management is based on the the availability and updatability of the uncertainty information (questions 1 and 7) and the structure of the model (questions 2-6). Three alternatives for adaptive planning are highlighted, (1) deterministic planning and re-plan as new information becomes available, (2) manage risk (through risk measures, or other proxies) and re-plan as new information becomes available, (3) pre-emptively determine the optimal time to collect new information as a means to improve the management of risk (through risk measures or other proxies). The potential for risk management is highlighted by the letter after the method, (a) there is a

high potential for risk management, (b) a moderate potential for risk management and (c) a low potential for risk management.