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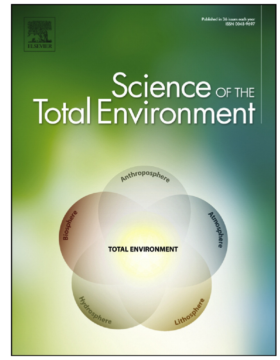

The value of perfect and imperfect information in lake monitoring and management

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The value of perfect and imperfect information in lake monitoring and management

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Abstract

Uncertainty in the information obtained through monitoring complicates decision making about aquatic ecosystems management actions. We suggest the value of information (VOI) to assess the profitability of paying for additional monitoring information, when taking into account the costs and benefits of monitoring and management actions, as well as associated uncertainty. Estimating the monetary value of the ecosystem needed for deriving VOI is challenging. Therefore, instead of considering a single value, we evaluate the sensitivity of VOI to varying monetary value. We also extend the VOI analysis to the more realistic context where additional information does not result in perfect, but rather in imperfect information on the true state of the environment. Therefore, we analytically derive the value of perfect information in the case of two alternative decisions and two states of uncertainty. Second, we describe a Monte Carlo type of approach to evaluate the value of imperfect information about a continuous classification variable. Third, we determine confidence intervals for the VOI with a percentile bootstrap method. Results for our case study on 144 Finnish lakes suggest that generally, the value of monitoring exceeds the cost. It is particularly profitable to monitor lakes that meet the quality standards a priori, to ascertain that expensive and unnecessary management can be avoided. The VOI analysis provides a novel tool for lake and other environmental managers to estimate the value of additional monitoring data for a particular, single case, e.g. a lake, when an additional benefit is attainable through remedial management actions.

Keywords: decision making, environmental management, imperfect information, lakes, perfect information, value of information.

1 Introduction

Human-induced stress and disturbances threaten inland and coastal waters more severely than many other ecosystem types (Sala et al., 2000). Therefore dedicated legislation, such as the Clean Water Act (CWA) in the U.S and the EU Water Framework Directive (WFD) (European Parliament, 2000) have been adopted to protect the ecological structure of inland and coastal aquatic ecosystems, to secure their functioning and provisioning of ecosystem services. In the European Union, the WFD aims at ensuring good status in rivers, lakes, coastal and ground waters by 2027. The WFD status classification of water bodies into five ecological status classes (high, good, moderate, poor and bad) is primarily based on regular and long-term monitoring data of parameters representing biotic structure, supported by the physical and chemical properties of water and hydrological and morphological features (European Communities, 2003). For each classification variable, the status class is assessed against the degree of deviance from the pre-determined reference conditions.

Under the WFD, assessing the ecological status that identifies possible management needs and subsequent restoration measures, requires extensive monitoring programs that produce reliable data for decision making. For cost-efficient decision making in water management, the use of relevant information is important. However, it is often challenging to know when these information criteria have been optimally met to achieve the most profitable outcome. In addition, in ecological monitoring the uncertainty is an inevitable part of the data (Carstensen and Lindegarth, 2016). The value of information (VOI) analysis can be a useful approach to control for that uncertainty and to assess concretely how much it is profitable to pay for monitoring.

The VOI is a concept of decision theory that assesses the value of additional information to solve a decision making problem. One of the earliest references is by Schlaifer and Raiffa (1961) and a modern presentation is given e.g. by Eidsvik et al. (2015) and Canessa et al. (2015). A tenet of the VOI is that while additional information can help reduce uncertainty, it is profitable to gather only if it affects the conclusion. More specifically, the VOI analysis aims to assess and compare the expected outcomes in the decision situation. Making a decision implies that one of all the possible alternatives must chosen to achieve the specified objectives. The uncertainty in the decision situation affects the expected outcomes of each alternative. To calculate the VOI, one needs to specify the decision to make, the random variables that affect the decision situation, the scenarios formed from these decisions and random variables, and the monetary value of each scenario to the decision maker. The VOI is commonly divided into two categories:

1. The value of perfect information (also known as the expected value of perfect information, EVPI) is the value of data that provide exact information on the state of the system.
2. The value of imperfect information (also known as the expected value of sample information, EVSI) expresses the value of data providing less than perfect information.

In the literature, EVPI and EVSI are frequently used terms for the same concepts. However, we use the definitions of value of perfect and imperfect information according to Eidsvik et al. (2015).

The VOI analysis framework is already widely applied in the fields of economics, finance and medicine (Eidsvik et al., 2015) and the potential of the approach also in environmental and ecological decision making has been recognized and increasingly applied in recent years (Bolam et al., 2019, Eyvindson et al., 2019). Perhaps surprisingly, the VOI is still seldom applied to environmental monitoring data, despite the increasing demand (Colyvan, 2016) for such analysis. As far as we know, Nygård et al. (2016) is the first one to apply VOI analysis with perfect information to assess the value of marine monitoring data. They developed a conceptual model of the components that needed to be established when calculating the VOI of monitoring data. In the present study, we follow their model but as the major novelty, we extend the VOI analysis also to imperfect information in the context of surface water monitoring.

So why has the use of the VOI still remained limited with environmental monitoring? A major difficulty in applying the VOI approach to environmental management and monitoring is to define the monetary value of the present and targeted ecological status of the environment. Some economic evaluation studies for fresh waters (e.g. Atkins and Burdon (2006)) exist, but these estimates do not directly translate to our context. Here, we build on the valuation study by Ahtiainen (2008) who used the contingent valuation method (Carson et al., 2004) to study the economic benefits attributable to improvement of ecosystem status from moderate to good in the Finnish lake Hiidenvesi. Secondly, the high computational cost prevents the more common use of the VOI, especially for the value of imperfect information (Steuten et al., 2013).

In the present work, we want to fill the gap of missing real-life applications of VOI analysis concerning environmental monitoring data and propose a method to further the more frequent use of VOI. We aim to use the VOI analysis to assess the worth of the additional information needed to gain a more reliable estimate of the ecological status of a water body when there is already a preconception about its true status. We show that both perfect information as well as imperfect information approach can be used to evaluate the value of additional monitoring data. First, we aim to form an analytical solution for the value of perfect information in the case of two ecological status classes and two alternative decisions. Second, we propose how to calculate the value of imperfect information empirically using simulation methods. In addition, our aim is to evaluate the uncertainty of the value of imperfect information with confidence intervals. Third, we conduct a sensitivity analysis to study how different assumptions affect the VOI. The assumptions are related to: i) the monetary value of a lake meeting the quality requirements of good status, ii) the cost of the management action and iii) the outcome of the implemented management option, i.e. whether or not the target ecological status is achieved. Lastly, we compare the VOI to the realized costs of the monitoring data.

2 Materials and methods

2.1 The methodology for estimating the value of information

This section follows the concepts and notations by Eidsvik et al. (2015). All notations are summarized in Table 1. In a decision situation, there are two types of variables, 1) decisions and 2) variables with uncertainty. If the decision maker can control the value of a variable, the variable is categorized as a decision. We refer to the values of a decision as alternatives or actions and denote the set of them by *A*. The decision maker can choose any alternative $a \in A$. Moreover, if the decision maker cannot control a variable value, it is classified as a variable with uncertainty. The value of a random variable is called a state or a realization and is denoted by *x*. A discrete random variable is defined based on its sample space Ω, with the probability $p(x) \geq 0$ of the state $x \in \Omega$ such that $\sum_{x \in \Omega} p(x) = 1$. For example, in an environmental framework we can have two alternatives: i) a management action to a water body ($a = a_1$) or ii) no action ($a = a_0$), whilst water bodies may have two states: i) a target status ($x = x_1$), and ii) a non-target status ($x = x_0$).

Table 1: Definitions of used notations.

Notation	Definition
$x \in \Omega$	Discrete variable, direct measurement of status
$a \in A$	Alternative or action
(x, a)	Scenario
c	Cost of implementing alternative *a*
r	Ratio of target status obtained after actions
$v(x, a)$	(Monetary) value of the scenario (x, a)
y	Continuous variable, indirect measurement of *x*
p(x)	Prior knowledge of *x*
p(y)	Marginal density of *y*
$p(x \mid y)$	Posterior probability of *x* given *y*
PV	Prior value
PoV(x)	Posterior value of perfect information
PoV(y)	Posterior value of imperfect information
VOI(x)	Value of perfect information
VOI(y)	Value of imperfect information

A scenario is an instantiation of every variable in the decision situation. The decision situation always involves a total of $|\Omega| \times |A|$ different scenarios. Each scenario with the decision *a* and the uncertainty *x* has an outcome with a value function $v(x, a)$ given by the decision maker. It is equal to the value of the realized outcome for the decision maker when also the costs of the action and the change of the value due to the action are taken into account. For example, we could have a cost for a management action ($c = c_1$) and for no actions ($c = c_0$). The effectiveness of an action may be specified by a parameter $r \in [0,1]$. It is the ratio from value $v(x, a)$ of how much an action can affect the monetary value compared to a situation where an action is not performed. The utility function $u(\cdot)$ is an extension of the value function that also measures the decision maker's ability to tolerate risk (von Neumann and Morgenstern, 1944). Risk seeking or risk averse decision makers could be taken into account by measuring the expected utility of outcomes instead of the expected value. In our set-up, we assume that the decision maker is risk neutral, so $u(v(x, a)) = v(x, a)$.

The value of information (VOI) is the price threshold at which the decision maker is indecisive about whether or not to acquire additional information to make a decision on an action, for example on a management action. In other words, the VOI is the maximum price, yet still profitable to invest into additional information. The decision making has two steps:

1. Make a decision about whether or not to obtain additional information.
2. Make an actual decision, either based on prior knowledge alone or on prior information and on the additional information.

The flowchart for decision making progress is shown in Fig. 1. The VOI is calculated in the first step.

Figure 1: The decision making progress for lake management.

The value of perfect information can be written as

$$VOI(x) = PoV(x) - PV, \tag{1}$$

where

$$\begin{aligned} PV &= \max_{a \in A} \{\mathbb{E}(v(x,a))\} \\ &= \max_{a \in A} \left\{ \sum_{x \in \Omega} v(x,a)\, p(x) \right\} \end{aligned} \tag{2}$$

and

$$\begin{aligned} PoV(x) &= \mathbb{E}\left(\max_{a \in A} \{v(x,a)\} \right) \\ &= \sum_{x \in \Omega} \max_{a \in A} \{v(x,a)\}\, p(x). \end{aligned} \tag{3}$$

Above, *PV* (prior value) is a priori the maximum expected benefit of all expected benefits, given all available alternatives. A rational decision maker should choose the alternative that maximises the average benefit. Secondly, *PoV(x)* (posterior value) is the updated expected benefit after new information is gained, i.e. the average maximum benefit. The *VOI(x)* is the difference between these benefits. If the *VOI(x)* exceeds the price of the information, the decision maker should invest in collecting the data. The *VOI(x)* is always non-negative, since the averaging of the maximum benefit of states is always at least as large as the maximum benefit of averaging over states.

In Eq. (3) it is assumed that the additional information is perfect, providing a certain knowledge of the state *x*. The *VOI(x)* is then the absolute maximum, at which it is still profitable to pay for additional information. However, in many cases additional information cannot provide a completely accurate knowledge about the state *x*. Instead, we observe, for example, the value *y* of a continuous random variable with the density *p(y)* reflecting, but imperfectly, the state *x*. Then, the observed information is referred to as imperfect information.

The value of imperfect information is given as

$$VOI(y) = PoV(y) - PV, \tag{4}$$

where *PV* is as in Eq. (2) and

$$\begin{aligned} PoV(y) &= \int_y \max_{a \in A} \{\mathbb{E}(v(x,a) \mid y)\}\, p(y)dy \\ &= \int_y \max_{a \in A} \left\{ \sum_{x \in \Omega} v(x,a)\, p(x \mid y) \right\} p(y)dy. \end{aligned}$$

The posterior distribution $p(x \mid y)$ above can be calculated with Bayes' rule, see Eq. (5).

A major source of complexity in the VOI problems is the need to model continuous probability distributions (Yokota and Thompson, 2004). To simplify the decision situation and problem solving, a continuous input is often categorized . Categorization of a continuous variable is normally a bad idea since it leads to loss of information. In addition, the results are depending on arbitrary cut points set by the decision maker (Royston et al., 2006). Our aim is to avoid categorization , but an analytic solution for *VOI(y)* is rarely available because of a continuous sample space and hence, integration. To obtain an approximate solution, we utilize a Monte Carlo type of approach to the integration using empirical data (Robert and Casella, 2005). We approximated the posterior value for imperfect information by

$$\hat{P}oV(y) = \frac{1}{n}\sum_{i=1}^{n}\max_{a\in A}\{\mathbb{E}(v(x,a)\,|\,y_i)\}$$
$$= \frac{1}{n}\sum_{i=1}^{n}\max_{a\in A}\left\{\sum_{x\in\Omega}v(x,a)\,\hat{p}(x\,|\,y_i)\right\},$$

where n is the number of observations, and in our case, $y_i, i = 1,\ldots,n$, are the values sampled from distribution $\hat{p}$ fitted to the data of chlorophyll concentration and x is the ecological status. Furthermore, the posterior distribution is given by Bayes' rule

$$\hat{p}(x\,|\,y_i) = \frac{\hat{p}(x)\,\hat{p}(y_i\,|\,x)}{\hat{p}(y_i)}, \tag{5}$$

where we estimated $\hat{p}(y_i\,|\,x)$ by gamma distribution (see an example in Fig. 2). The marginal distribution of y_i is defined for states of x as follows:

$$\hat{p}(y_i) = \sum_{x\in\Omega}\hat{p}(x)\,\hat{p}(y_i\,|\,x).$$

For example, for two environmental states $x_j, j = 0,1$, in the following we use $\hat{p}(x_1) = 0.48$, which is the estimated proportion of water bodies in the target status.

We estimate confidence intervals of $\hat{P}oV(y)$ using the parametric percentile bootstrap method (Efron and Tibshirani, 1993). The simulation is implemented as follows:

1. Random samples $y_1,\ldots,y_{n_0}$ and $y_1,\ldots,y_{n_1}$ are drawn from gamma distributions of target and non-target water bodies fitted to the original data, with respect to the original proportions.
2. Gamma distributions $Gamma(\alpha_0^*, \beta_0^*)$ and $Gamma(\alpha_1^*, \beta_1^*)$ are re-fitted to the random samples.
3. The posterior value $\hat{P}oV(y^*)$ is calculated using the re-calculated fits.

We repeated this $B = 1000$ times in the spirit of bootstrap and obtained bootstrap replicates $\hat{P}oV(y^{*(b)})$, $b = 1,\ldots,B$. Confidence intervals of $\hat{V}OI(y)$ can be derived from these confidence intervals by substracting the prior value *PV*. All the calculations were implemented with R (R Core Team, 2018).

2.1.1 Conceptual model

Nygård et al. (2016) developed a conceptual model that sums up the components that are needed when evaluating the VOI of monitoring data. We applied and extended their model to inland water monitoring using imperfect information. After identifying the variables connected to monitoring, the following steps need to be performed:

1. List the alternative monitoring activities that could be carried out to gain additional information. The list can include several variables and several strategies. In our application, we considered two alternatives; either to implement monitoring of chlorophyll data or not to implement it, depending on the price of monitoring compared to VOI (see Section 3.1).

2. Estimate the costs of these monitoring alternatives, which can subsequently be compared to the VOI (comparison in Section 3.1).

3. Assess the status (prior information $\hat{p}(x)$) based on expert judgment. The existing past data or knowledge can be used to obtain the prior, the subjective probability. For several status classes, the relative likelihood approach, for example, could be used, see French et al. (2010). We defined the priors in our case study in Section 2.3.

4. Assess the status after the selected monitoring activity has been carried out. If imperfect information (*y*) is used, the assessment of the status can be based on the statistical classification. See Section 2 and Eq. (5).

5. List the alternative management actions (*a*) depending on the status of the system. We applied two alternatives; either implement (a_1) or do not implement actions (a_0) (Table 2).

6. Estimate the costs (*c*) of these management actions (examples of costs, c_1 and c_0, presented in Table 2).

7. Estimate the change in the state of the system if the management options are implemented. We used the ratio *r* for describing the degree of change (see Table 2.)

8. Estimate the monetary values $v(x,a)$ of different states of the system. In our case, defining the monetary value of reaching a target ecological status in the water body was sufficient. (Section 2.4).

After implementing the steps 1-8, the formula (1) was applied to calculate the *VOI(x)* and formula (4) for the *VOI(y)*.

2.2 Monitoring activity on imperfect information

According to the WFD, the overall ecological status assessment of a water body is based on data collected for several biological quality elements and indicators. However, we limit our VOI analysis to the biological quality element phytoplankton, or more specifically to chlorophyll *a*, one of the many indicator variables in lake status assessment. Chlorophyll *a* content is indicative of water body productivity and therefore generally correlates well with the ecological status of lentic water bodies mainly suffering from human-induced eutrophication. Lentic water bodies are also subject to other major anthropogenic stress, such as intense water level regulation, were not included in this analysis.

The data that we used in the analysis are produced by the official Finnish lake monitoring program and stored in the open source database of the Finnish Environment Institute (http://www.syke.fi/en-US/Open_information). We used chlorophyll *a* data from the second assessment period of the river basin management plans (years 2006–2012). Our data contain 144 lakes and 166 water bodies within them: a water body is either a whole lake or more rarely, a limited, homogeneous part of a lake. In the following, we refer to water bodies sometimes simply as lakes for brevity. We selected the most frequently sampled water bodies with at least 3 summertime observations per year. Overall we included 6742 observations from 166 water bodies. We aggregated annual and local observations into means of annual medians per water body. This is the standard current approach in ecological status assessment of water bodies (Aroviita et al., 2019) . The lakes are divided into 14 lake types with 1–31 lakes per type. We accounted for lake type in status classification, as types naturally differ in chlorophyll concentration. We note that joining all lake types in our analysis may overestimate the uncertainty of chlorophyll as an indicator of status resulting in a more inaccurate VOI. However, the sample size is insufficient to allow for a closer study by lake type.

Since the overall ecological status of a water body determines the need for management actions, we categorized water bodies into those that either met the target status during the second classification period, or those that did not. Of the total of 166 water bodies, 79 (48%) met high or good status while 87 (52%) did not, i.e. belonged to either the moderate, poor or bad status class. We assume that the chlorophyll content indicates the status of a water body and represents the value *y*. Thus, the *VOI(y)* is estimated by using the empirical distribution of chlorophyll. Fitting gamma distributions, we estimated the distribution of aggregated values of chlorophyll over time and monitoring locations separately for water bodies in both good and in less than good status (Fig. 2).

Figure 2: Histograms and fitted gamma distributions of chlorophyll *a* concentration of 166 water bodies based on monitoring. The water bodies are categorized into two classes, in target status (blue) and not in target status (red). The value on the horizontal axis is the aggregated value of the chlorophyll *a* concentration over seven years (2006 to 2012) and monitoring locations in water bodies.

2.3 Priors

We used three distinct priors for the distribution of the ecological status, to illustrate how the prior knowledge about the status affects the VOI. Without more detailed knowledge about the ecological status of a given water body, a prior was estimated from the data: the proportion of water bodies in target status to the total number, i.e. $\hat{p}(x_1) = 79/166 = 0.48$. We also have more detailed prior information on some lakes, for example, as in the case of lake Hiidenvesi, which is currently assessed to be in moderate status with high degree of certainty. So, we set the prior to $\hat{p}(x_1) = 0.20$ and also to $\hat{p}(x_1) = 0.80$.

2.4 Monetary value of lakes

Evaluation of the monetary values of lakes $v(x,a)$ is challenging because a valuation of the environment is not straightforward. Reynaud and Lanzanova (2017) conducted a meta-analysis on the economic value of ecosystem services delivered by lakes and their value to the private properties located next to lakes. According to Reynaud and Lanzanova, the mean value of a lake to an adjacent property in Finland was USD 265.9 (in 2010) per property per year. However, these estimates do not directly translate into the benefit achieved by management, i.e. the monetary value between the two status categories treated here.

We used a valuation study by Ahtiainen (2008) that studied the economic benefits attributable to the improvement of the status of a single lake, Hiidenvesi, with an area about 3000 hectares, currently in moderate condition. She assessed the willingness of residents to pay for management actions to reduce the eutrophication of the lake. As the described target status in the poll broadly corresponds to the definition of good status under the WFD, her results are appropriate for our purposes. Based on the poll, the mean sum residents were willing to pay ranged between EUR 4.08–54.48 per property per year. Furthermore, the overall estimated willingness of properties to pay ranged between EUR 3 and 5.7 million over the course of the five-year management implementation period. For generality, we used the VOI of a water body per hectares to combine it with the estimated average cost c_1 of a management action cost of EUR 200 per ha (source: Finnish Environmental Institute). In doing so, our results apply to water bodies of all sizes.

We first chose to use the most conservative value of EUR 3 million per 3000 ha = EUR 1000 per ha as the value $v(x_1,a_0)$ for a water body in target status with no performed actions. When constructing the value for the scenarios, summarized in Table 2, the monetary value of ecological status was estimated by subtracting the cost c of each management option from a value of a scenario by each row. Therefore, if a water body indeed needs and receives management (average EUR 200 per ha) and its status also improves to the target status, the value of the water body increases to EUR 1000 per ha. However, the value of a water body is only EUR 800 per ha after taking into account the cost of management. For simplicity, we first assumed that the target status is achieved as a result of management actions. Later, we also released this assumption so that the target status is not always reached after implementing a management action (Table 4) . Here, the VOI is insensitive to the absolute monetary value; only the increase in monetary value when the status of a lake increases, is significant.

In the preceding example, the value $v(x,a)$ of a water body in target status ($x = x_1$) with no restoration ($a = a_0$) is fixed to EUR 1000 per ha. As this estimated value is uncertain and may vary substantially among lakes, we also performed a sensitivity analysis, to examine the effect of a variable monetary value on the VOI by varying the value of $v(x,a)$ from EUR 200 to 2000 per ha.

Table 2: A summary of costs *c* and the monetary values $v(x, a)$ for an example lake Hiidenvesi, where the value of the target ecological status equals EUR 1000 per ha (Ahtiainen, 2008). The costs of the management action were set to EUR 200 per ha. The monetary value takes the cost of a management alternative into account. See text for more details.

		Monetary value (EUR/ha)	
		Ecological status *x*	
Alternative *a*	Cost *c* of alternative (EUR/ha)	x_0 : non-target status	x_1 : target status
a_0 : no actions	c_0 = 0	0	1000
a_1 : actions	c_1 = 200	1000-200=800	1000-200=800

3 Results

First, using four monetary values $v(x, a)$ given in Table 2 and when a priori we are more certain that a lake is indeed in target status ($\hat{p}(x_1) = 0.8$), the expected values of two alternative actions a_0 and a_1, $E(v(x, a_0))$ and $E(v(x, a_1))$, are equal. Thus, maximum expected value (*PV*, Eq. (2)) has the same value, EUR 800 per ha (Table 3, first row). However , additional information is profitable to gather and worth paying for up to a maximum of EUR 160 per ha for perfect information (Eq. (1)). For imperfect information, it is worth to pay up to EUR 100 with 95% CI (85.7, 115.1) per ha (Eq. (4)) to ascertain the ecological status of the lake .

If in turn we are a priori more certain of the water body to be in non-target status ($\hat{p}(x_1) = 0.2$), i.e. it likely needs restoration, then it is profitable to implement the restoration to achieve the expected value of EUR 800 per ha (Table 3, second row). Furthermore, it is worth paying a maximum of EUR 40 per ha for perfect information and EUR 0 with 95% CI (0, 3.5) per ha for imperfect information.

When the proportion of lakes in target status, as estimated from the data, is used as the prior, i.e. $\hat{p}(x_1) = 0.48$, the highest expected return is obtained by management: the expected value is then EUR 800 per ha (Table 3, third row). Moreover , it is worth paying EUR 95 per ha for perfect information and EUR 15 with 95% CI (0, 33.2) per ha for imperfect information to ascertain the true status of the lake .

Table 3: VOI analysis for an example lake, Hiidenvesi, when the monetary value of the target status is EUR 1000 per ha. The prior value is based on the maximizing alternatives, i.e. implement management actions (a_1) or not (a_0). VOI should be compared with the monitoring cost of EUR 4.9 per ha obtained by dividing the monitoring cost EUR 14766 by the area of Hiidenvesi 3030 ha.

	Prior $\hat{p}(x)$		Prior value,	Perfect information		Imperfect information	
	Not in target status	In target status	*PV* (€/ha)	*PoV(x)* (€/ha)	*VOI(x)* (€/ha)	*PoV(y)* (€/ha)	*VOI(y)* (€/ha) (95% CI)
Prior given by the manager	0.2	0.8	800 (a_0 / a_1)	960	160	900	100 (85.7, 115.1)
	0.8	0.2	800 (a_1)	840	40	800	0
							(0, 3.5)
Prior estimated from data	0.52	0.48	800 (a_1)	895	95	815	15 (0, 33.2)

3.1 Monitoring costs

If the VOI exceeds the price paid for gathering the information, the additional information is profitable for decision making. We compared the obtained VOI to actual monitoring costs, based on the information from the Finnish Environmental Institute (personal communication). One sample of chlorophyll *a*, from collection to analysis, currently costs EUR 138. Thus, costs for the entire data, i.e. the 6742 samples equals EUR 930 396. In our data, 107 chlorophyll *a* observations were taken from Hiidenvesi over the years 2006–2012, which equals EUR 14 766.

Depending on the prior knowledge presented, *VOI(x)* ranges between EUR 40–160 per ha and *VOI(y)* between EUR 0–100 per ha on average, when the monetary value of target status was fixed to EUR 1000 per ha. If we assume that the ecological status meets the target ($\hat{p}(x_1) = 0.8$) and that additional information provides imperfect knowledge about the status, the *VOI(y)* equals EUR 100 per ha. Hiidenvesi has an area of 3030 ha and thus a *VOI(y)* of EUR 303 000. If we assume that the ecological status does not meet the target ($\hat{p}(x_1) = 0.2$), *VOI(y)* for Hiidenvesi equals EUR 0. If we assume the prior $\hat{p}(x_1) = 0.48$, *VOI(y)* for Hiidenvesi equals EUR 45 450. When the prior $\hat{p}(x_1)$ equals either 0.8 or 0.48, the realized monitoring cost are significantly smaller than the estimated *VOI(y)* for Hiidenvesi. Hence, in both cases, it would be profitable to gather additional information. Similar calculation can be performed for any prior.

3.2 Sensitivity analysis

Since the most uncertain assumption is the monetary value of the ecological status of the lake, we modelled the effect of different monetary values on VOI of both perfect and imperfect information. Instead of using a fixed value of EUR 1000 we varied the value of $v(x_1, a_0)$ from EUR 200 to 2000 per ha. Table 4 presents a generalization of Table 2 for the purpose of sensitivity analysis. For further comparison, three different priors for ecological target status x_1 were used as earlier : $\hat{p}(x_1) \in \{0.80, 0.20, 0.48\}$, where the first two were provided by an expert and the third was estimated from data. In addition, the cost of management c_1 was either EUR 100 or EUR 200 per ha and a value of non-target status lake after choosing management alternative was reduced with ratio $r \in \{0.70, 1\}$. Any other proper values for the prior, cost and ratio could be used as well.

Table 4: The monetary values $v(x,a)$ in a four scenario management decision-making situation, i.e. with two possible decision alternatives and two states for the uncertainty. The cost c of a management alternative is taken into account, as well as the possibility that implementing a management option does not necessarily help to reach the target status. This is implemented with the ratio *r*.

		Monetary value $v(x,a)$	
		Ecological status *x*	
Alternative *a*	Cost *c* of alternative	x_0: non-target status	x_1: target status
a_0: no actions	$c_0 = 0$	$v(x_0, a_0)$	$v(x_1, a_0)$
a_1: actions	c_1	$v(x_0, a_1) = r \cdot v(x_1, a_0) - c_1$	$v(x_1, a_1) = v(x_1, a_0) - c_1$

The *VOI(x)* can be shown to be a piecewise-defined function of monetary value $v = v(x_1, a_0)$ that consists of three different functions. If $v \le c_1 / r$, gathering additional information would be useless because management activities are too expensive to implement, thus *VOI(x)* equals zero. If $v > c_1 / r$, it is useful to calculate VOI. If $c_1 / r < v < c_1 / (r - rp)$ with $p = \hat{p}(x_1)$, *VOI(x)* is an increasing function of *v*. After the change point $v = c_1 / (r - rp)$, *VOI(x)* is a positive constant. The derivation of these results is presented in Appendix A. According to Fig. 3, also the *VOI(y)* is an increasing function of value *v* until the same change point. After the change point, *VOI(y)* starts to approach zero. If the monetary value is large compared to the costs, it is always profitable to implement management actions to ascertain good ecological status, and any additional information is then unprofitable. For the expectation that a water body does not need management ($\hat{p}(x_1) = 0.80$), the cost equals EUR $c_1 = 200$ per ha and the ratio $r = 1$ (Fig. 3, top left panel), *VOI(x)* starts to increase from zero when the monetary value of the target status of a water body equals EUR 200 per ha. The maximum of VOI is reached when $v = 1000$. Then, the *VOI(x)* is EUR 160 per ha and that of imperfect information EUR 121 per ha, respectively. The same pattern for *VOI(x)* and *VOI(y)* is repeated for other assumptions of prior $\hat{p}(x_1)$, cost c_1 and *r*.

The maximum value of *VOI(x)* increases on average when it is increasingly certain that the lake is in the target status, i.e. the value of $\hat{p}(x_1)$ increases (Fig. 3). In turn, the more certain it is that the lake is in non-target status, the faster *VOI(x)* reaches its maximum value. The *VOI(x)* is the absolute maximum worth paying for additional information. The *VOI(y)* depends on the priors and the data, but it is always less than the *VOI(x)*.

Figure 3: The effect of the value of a water body in target status on the VOI. *VOI(x)* is the value of perfect information and the maximum value of VOI. *VOI(y)* with 95% confidence intervals is the value for imperfect information. The prior is fixed from left column to right: $\hat{p}(x_1) = 0.8$, $\hat{p}(x_1) = 0.2$ and $\hat{p}(x_1) = 0.48$, respectively. The cost of management is fixed from top row to bottom: $c_1 = 200$, $c_1 = 100$ and $c_1 = 200$. The ratio *r* is also fixed from top row to bottom: $r = 1$

, $r = 1$ and $r = 0.7$.

4 Discussion

According to our knowledge, this study is the first attempt to implement *VOI(y)* to lake monitoring data. From a methodological point of view, the main results are shown in Fig. 3, where the VOI is presented as a function of monetary value. The results for perfect information are derived theoretically while the results for imperfect information are based on simulations. *VOI(x)* naturally exceeds *VOI(y)* for all monetary values, and the change point seems to be the same for perfect and imperfect information. In the case of perfect information, *VOI(x)* first increases linearly until the monetary value reaches the change point, and then remains constant. Thus, in this setup if the monetary value is known to exceed the change point, it is not necessary to fix the monetary value more exactly. In contrast, for imperfect information, *VOI(y)* first increases linearly until the monetary value reaches the change point and then decreases. Thus, the situation differs essentially from the case of perfect information because the exact determination of the monetary value is always needed to calculate *VOI(y)*.

From the environmental management point of view, the main result is that the monitoring is most often cost-efficient. When comparing the realized monitoring costs and the estimated VOI, costs are significantly smaller and thus still profitable to invest in. Interestingly, even with a good a priori understanding of the ecological status of the lake, it may still be profitable to gather additional information. We found, perhaps somewhat counter-intuitively, that the VOI is highest when the ecological status is expected to meet the target, and the decision maker is fairly certain that there is no need for management actions. In this case, it is worth gathering additional information to unequivocally confirm that the lake meets the quality standards, in order to avoid unnecessary and expensive management actions, while minimizing any risks of losing the expected benefits of good ecological status. Indeed our results suggest that while river basin management strives to be more cost-efficient (Carvalho et al., 2019), the monetary investment in the current lake monitoring is often actually profitable.

We related the benefit of additional information to chlorophyll *a* in this work . However, a one year intensive sampling of a lake using all required biological quality elements includes also 5 annual physico-chemical samplings, and the sampling of phytoplankton on three occasions. Moreover, in fully compliant WFD assessments, littoral and/or profundal macroinvertebrates should be sampled twice and a single fish and macrophyte survey should be conducted in the course of each river basin management period of six years. Based on the information from Finnish Environmental Institute the estimated cost for all the aforementioned is around EUR 6000 per year per lake (personal communication). But even using EUR 6000 per year as the true monitoring cost per lake, our calculations suggest that monitoring is financially profitable for lakes within the size criteria monitored under the WFD.

We recognize that much uncertainty is associated with the estimated monetary value of status improvement. The economic value of lakes has been studied quite intensively (Reynaud and Lanzanova, 2017) , but the results are difficult to generalize especially for our specific purposes. Also, results of valuation studies are context specific: Hjerppe et al. (2017) recently estimated that the recreational value of the Finnish lake Pien-Saimaa in its present moderate ecological status is EUR 21 100 000 per year. However, the comparable value for our purposes is the difference in the recreational value between the lake in current moderate status and good status (EUR 21 560 000) and it is only EUR 38 per ha per year , the area of Pien-Saimaa being 120 km^2 . This would mean only EUR 190 per ha for a 5 year period, which is much smaller than the wholesale value of EUR 1000 per ha provided by Ahtiainen (2008), that we used in our analyses. Interestingly, if indeed the monetary value in EUR/ha is as small as Hjerppe et al. (2017) suggest our study indicates that in most scenarios, collecting any additional information on the status of the lake would be useless from the decision-making point of view (Fig. 3). Another study by Artell and Huhtala (2017) estimated that owners of a lakefront property were willing to spend up to EUR 5400 for the improvement of the lake status from moderate to good. Economic value of a lake being this inconsistent, we performed a sensitivity analysis to evaluate the influence of changes in monetary value on the VOI.

In this work , we scaled the value to the size of a lake in an attempt to generalize results to different size water bodies, thus implicitly assuming that the costs and value of status improvement per unit area remain constant. The results on the effects of size on the lake value are inconsistent, but the recent meta-analysis by Reynaud and Lanzanova (2017) suggests a positive relationship between the value per property and lake area. Larger lakes might be more highly valued than smaller lakes, since they might underpin a wider range of ecological functions (Brander et al., 2006) and perhaps a greater variety of valued water uses. We do not have any data on the dependency of per unit area management costs on the lake size. However, in practise relative monitoring costs per unit area are smaller for large water bodies, where fewer samples per area are taken for status assessment. Therefore, in reality the cost of one sample is greater in smaller water bodies.

Lastly we see great potential in the use of the VOI in environmental management and guidance of when to commit more resources to monitoring and when not to. The decision about whether to monitor or not is particularly applicable in the context of adaptive management of natural resources (e.g. Canessa et al. (2015), Williams et al. (2011)). Adaptive management is an iterative process where uncertainties can be reduced and management improved by monitoring the management outcomes and learning from them (Holling, 1978). A future challenge will be to extend the VOI analysis to other environmental monitoring alongside growing support for a wider adoption of the concept of adaptive management.

5 Conclusion

The main aim of this paper was to demonstrate that the concept of VOI analysis can be successfully applied to monitoring in a lake management decision making context. To do so, we applied VOI analysis to lake monitoring data on chlorophyll *a* concentrations. As a baseline for the analysis, we first proposed the analytical formulas for the value of perfect information in the case of two ecological status classes and two alternatives. Second, we proposed how to calculate the value of imperfect information from the monitoring data by using a Monte Carlo type of simulation method and how to evaluate the uncertainty with confidence intervals based on the percentile bootstrap method. Third, we implemented a sensitivity analysis to study how the monetary value of a water body in target status affects the VOI in the case of perfect and imperfect information. The main restrictions we needed to take into account were choosing one ecological indicator, aggregating sampling data over seven years, assessing the effect of the monetary value on the calculations and scaling the monetary value to the size of a lake. From an environmental management point of view, the main results are that the monitoring is cost-effective especially when the lake is a priori in target status.

The VOI analysis provides a novel tool for lake and other environmental managers to estimate the value of additional monitoring data for a particular, single case, e.g. a lake, when an additional benefit is attainable through remedial management actions. In such a case, decision makers should have a prior knowledge about the present status of e.g. a lake and about the value of the desired outcome, e.g. good ecological status. Further, knowledge on the *VOI(y)* in management scenarios is useful and can be extended also to other environmental contexts thus expanding the work of e.g. Nygård et al. (2016).

While we gained important insights, in our study we focused on traditional water sampling data. However, there are emerging techniques of collecting environmental data (e.g. remote sensing) which have been hailed as potential alternatives for future monitoring. Assessing the VOI of these alternative data sources is important and would allow to identify the most effective and cost-efficient ways to monitor and assess the state of European inland and coastal waters.

Appendix A: The change point at value of perfect information with respect to the monitoring value

Let a_0 and a_1 be two alternatives of a decision situation and the uncertainty $x \in \{x_0, x_1\}$ be discrete, $p = p(x_1)$ is constant. Values of scenarios can be chosen for example as in Table 4: $v = v(x_1, a_0) \geq 0$ is the value of lake in target ecological status set by decision maker, $r \in [0,1]$ is the ratio from value *v* of how much a management improves a status of lake not in target status and $c_1 \geq 0$ is the (constant) cost of implementing alternative a_1. In some situations, *r* could be alternatively interpreted as the probability of achieving the target status after the management. The cost of implementing alternative a_0 is $c_0 = 0$. In this case, the posterior value *PoV(x)* is an increasing function of *v*.

According to the Eq. (3), the posterior value in our situation is

$$PoV(x) = \max\{0, rv - c_1\} \cdot (1-p) + \max\{v, v - c_1\} \cdot p$$

$$= \begin{cases} 0 + pv, & \text{if } rv - c_1 < 0 \Leftrightarrow v < \dfrac{c_1}{r} \\ (rv - c_1)(1-p) + pv, & \text{otherwise.} \end{cases} \tag{6}$$

Furthermore, the prior value *PV* is a piecewise-defined linear function, as follows. According to the Eq. (2), the expected values (prior values) of the two alternatives are

$$\begin{aligned} \mathbb{E}(v(x, a_0)) &= (1-p) \cdot 0 + p \cdot v \\ &= pv \end{aligned} \tag{7}$$

and

$$\begin{aligned} \mathbb{E}(v(x, a_1)) &= (1-p) \cdot (rv - c_1) + p \cdot (v - c_1) \\ &= (r - rp + p)v - c_1. \end{aligned} \tag{8}$$

The prior value is the maximum of these two expectations:

$$PV = \max_{a\in A}\{\mathbb{E}(v(x,a_0)),\mathbb{E}(v(x,a_1))\}$$
$$= \max_{a\in A}\{pv,(r-rp+p)v-c_1\} \qquad (9)$$
$$= \begin{cases} pv, & \text{if } v \le \dfrac{c_1}{r-rp} \\ (r-rp+p)v-c_1, & \text{otherwise.} \end{cases}$$

Thus, the value of perfect information is

$$VOI(x) = PoV(x) - PV$$
$$= \begin{cases} 0, & \text{if } v \le \dfrac{c_1}{r} \\ (r-rp+p)v-(1-p)c_1, & \text{if } \dfrac{c_1}{r} < v \le \dfrac{c_1}{r-rp} \\ pc_1, & \text{if } v > \dfrac{c_1}{r-rp} \end{cases} \qquad (10)$$

The change point of *VOI(x)* can be found at the change point of the piecewise-defined function of *PV*, and it is $v = c_1/(r-rp)$.

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Declaration of competing interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Credit Author Statement

Vilja Koski: Methodology, Software, Formal analysis, Investigation, Writing, Visualization
Niina Kotamäki: Conceptualization, Verification, Investigation, Resources, Writing, Visualization
Heikki Hämäläinen: Verification, Investigation, Writing
Kristian Meissner: Verification, Resources, Writing
Juha Karvanen: Conceptualization, Verification, Formal analysis, Writing, Visualization
Salme Kärkkäinen: Conceptualization, Formal analysis, Writing, Visualization , Supervision

Graphical abstract

Highlights

- Knowledge on the value of monitoring can assist decision-making in lake management.
- We calculate value of perfect information theoretically.
- We estimate value of imperfect information with Monte Carlo type of approach.
- Generally, monitoring is profitable to invest in if VOI exceeds the cost.
- Additional monitoring is profitable even if the lake is in good condition a priori.

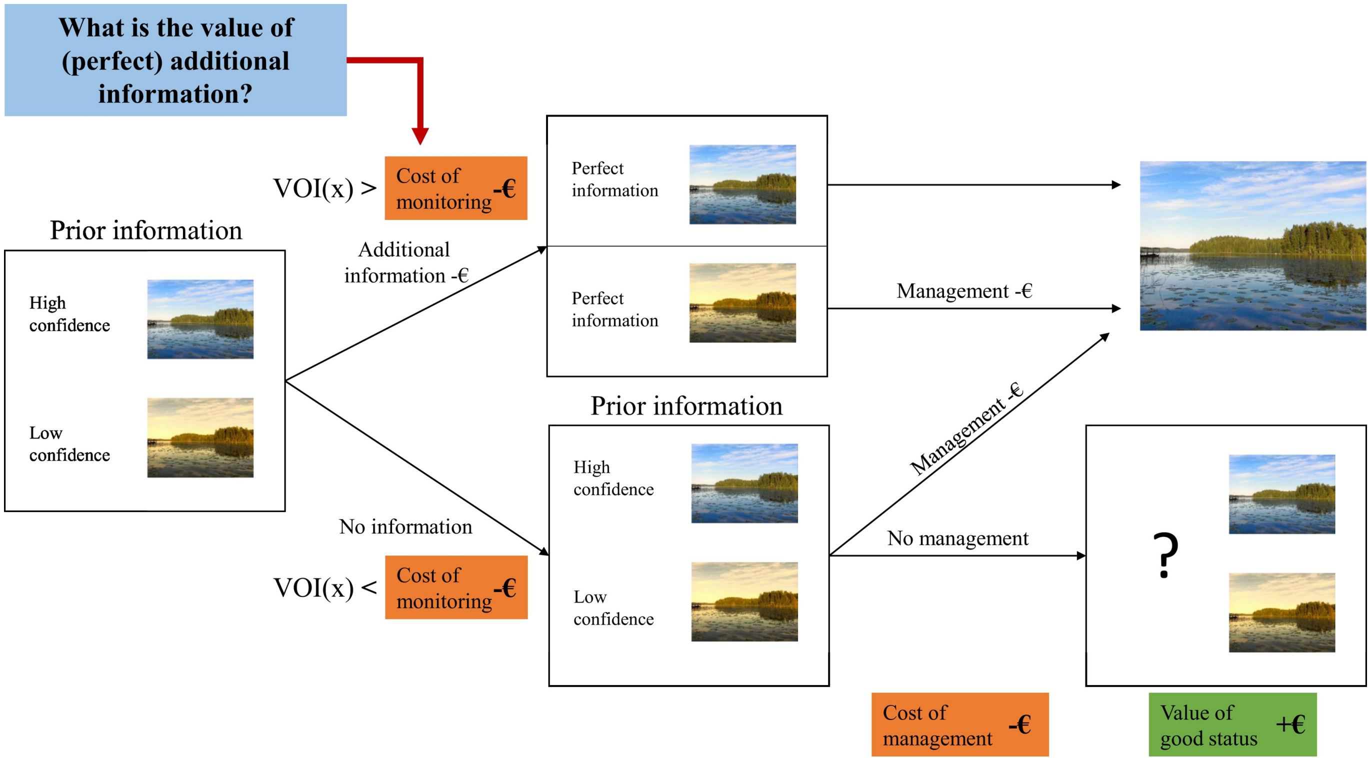
What is the value of (perfect) additional information?
VOI(x) >
Cost of monitoring -€
Prior information
High confidence
Low confidence
Additional information -€
Perfect information
Perfect information
Management -€
Prior information
High confidence
Low confidence
No information
VOI(x) <
Cost of monitoring -€
Management -€
No management
?
Cost of management -€
Value of good status +€

Figure 1

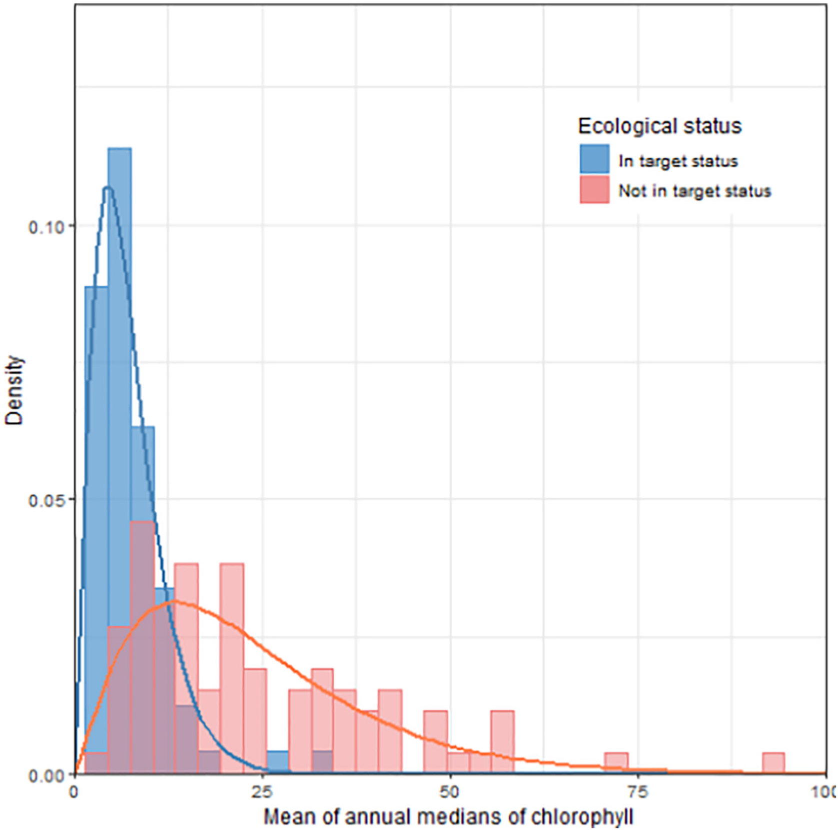
Ecological status
In target status
Not in target status
Density
0.10
0.05
0.00
0
25
50
75
100
Mean of annual medians of chlorophyll

Figure 2

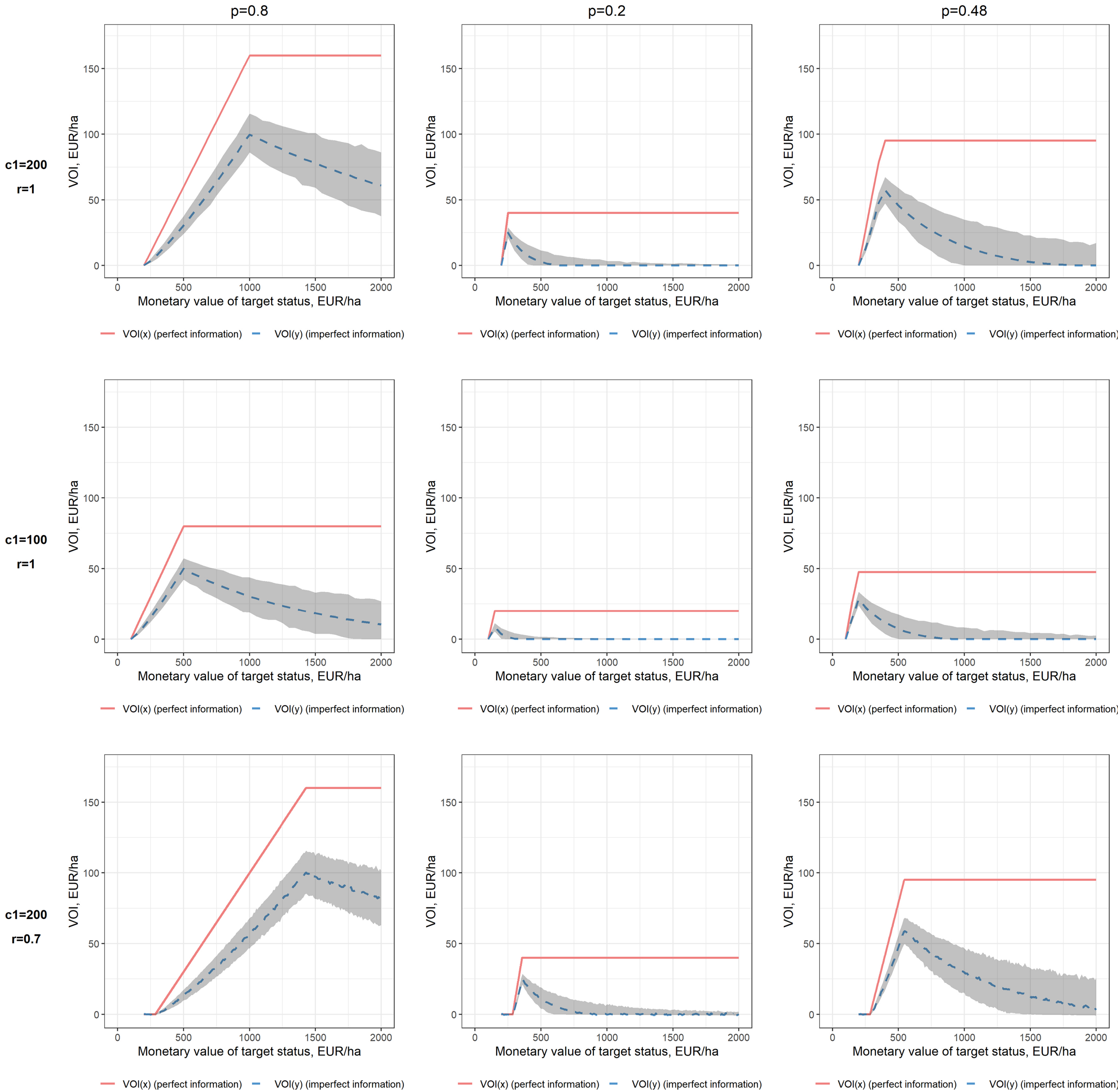
p=0.8
p=0.2
p=0.48
c1=200
r=1
c1=100
r=1
c1=200
r=0.7
VOI, EUR/ha
Monetary value of target status, EUR/ha
VOI(x) (perfect information)
VOI(y) (imperfect information)

Figure 3