Economics of Prioritising Environmental Research: An Expected Value of Partial Perfect Information (EVPPI) Framework

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22 February 2013
Working Paper 1303
School of Agricultural and Resource Economics
http://www.are.uwa.edu.au

Citation: Jeffrey, S.R. and Pannell, D.J. (2013) *Economics of Prioritising Environmental Research: An Expected Value of Partial Perfect Information (EVPPI) Framework*, Working Paper 1303, School of Agricultural and Resource Economics, University of Western Australia, Crawley, Australia.

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Abstract

Significant public funds are spent on projects designed to improve environmental quality. Design and implementation of these initiatives is contingent on knowledge generated from environmental research. Funding agencies have many demands for research dollars while having limited research budgets. A prioritisation process is required for efficient and effective allocation of research funds. A review of research prioritisation literature suggests that ad hoc approaches are often used for ex ante analyses examining the value of environmental research (e.g., Delphi techniques, information gaps from literature reviews). This paper characterises environmental research prioritisation in the form of an economic decision problem, formulated using expected value of information concepts. An implicitly Bayesian modelling approach is developed with research priorities being made based on estimates of expected value of partial perfect information (EVPPI). Considerations and challenges associated with empirical implementation of EVPPI are discussed and a hypothetical example is provided to illustrate use of this approach in informing environmental research funding decisions.

Keywords. Environmental Research; Research Prioritisation; Value of Information; Expected Value of Partial Perfect Information

JEL Classification. Q50, Q51, Q57

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Introduction

In response to society's interest in environmental quality and the impacts of human behaviour, public institutions and other organizations have implemented large scale environmental policies and projects. These are designed to enhance ecosystem service[1] (ES) production by directly mitigating environmental damage and/or encouraging or requiring individuals to exhibit behaviour that reduces or prevents such damage. These projects and policies are typically costly[2]. It is therefore important for decision makers to have accurate information regarding the relationship between the intended change in behaviour and the resulting production of ES in order to ensure that available project/program funds are invested efficiently. This information is generated by undertaking environmental research[3].

Environmental research itself is a costly undertaking. For example, the Australian federal government has committed $68.5 million over four years to fund five research hubs through the National Environmental Research Program (NERP).[4] Agencies that fund environmental research typically have limited budgets. As a result, not all proposed research can be undertaken. Further, at any given point in time it is likely not possible to fund all environmental research with the potential to contribute significantly towards public policymaking. As a result, some type of prioritisation process is required in order to determine what areas of environmental research should be funded so that limited research funds are allocated in an efficient and effective manner. To maximise the benefits of investment in research the prioritisation process should reflect both the costs associated with the research activities and the potential value of research results. The value of the research is a function of the potential value of associated ES production.

There are a number of challenges in prioritising environmental research activities. These include complexity and stochasticity in the relevant biophysical systems being studied, multiple objectives motivating research activities (e.g., multiple types of ES being affected),

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[1] Ecosystem services are "components of nature, directly enjoyed, consumed, or used to yield human well-being" (Boyd and Banzhaf 2007, p. 619).

[2] An example of this is the Caring for our Country program in Australia. From 2008 to 2013 this program provides funding of more than $2 billion for environmental initiatives in six priority areas; natural resource management in remote areas of the country, enhanced biodiversity, protecting coastal environments and aquatic habitats, sustainable agricultural practices and community skills (Commonwealth of Australia 2011).

[3] Here the term "environmental research" is used in a generic sense. It may refer to research designed to study the relationship between human activities and ES production. In other cases, it may simply refer to research designed to study the natural biological, chemical or physical relationships that co-exist and interact to produce ES within an ecosystem.

[4] With cofunding sources included, the total funding invested in NERP is over $150 million.

along with uncertainty regarding the outcomes from the research. Also problematic is the fact that values for many ES are non-market in nature. However, a significant obstacle is the lack of a rigorous framework within which to undertake the prioritisation process. Evidence from the literature indicates that environmental research prioritisation and ex ante analysis of the value of environmental research, if undertaken at all, is typically conducted using ad hoc methodologies with no formal basis in economic theory or concepts. In order to ensure that good environmental policy and program decisions are made, it is essential that research activities focus on areas of high priority (i.e., greater value to society).

This paper addresses the issue of positioning the environmental research prioritisation problem in an economic modelling framework. Within this overall goal, the specific objectives of this paper are to:

i) Review the literature on research prioritisation within the environmental sciences as well as relevant literature from other fields of study (i.e., agriculture and medicine/health) to gauge the state of knowledge;
ii) Characterise research prioritisation as an economic decision making problem;
iii) Propose a framework that can be used to prioritise environmental research; and
iv) Outline how this framework may be empirically implemented to prioritise environmental research activities.

Literature Review

There is an extensive literature, particularly within agriculture, that examines the value of research. Much of this literature, however, evaluates research from an ex post perspective (e.g., Brethour and Weersink 2003; Fan et al. 2005; Maredia and Raitzer 2010; Srinivas 2009). The analysis used within this body of literature typically involves estimating the impact of research on economic surplus, using various methods such as cost-benefit analysis. Alston et al. (1995) provide a review of concepts and techniques used in this literature.

A growing literature also exists that examines the value of agricultural research, and specifically research prioritisation, from an ex ante perspective. This literature is the focus of the discussion here. In some cases, methodologies commonly used in ex post studies are used to estimate ex ante value of research. Estimates of costs and potential benefits from research are obtained from available literature or expert opinion and then used to quantify potential research benefits within a demand and supply model (e.g., Balagtas et al. 2003; Alene et al. 2006). This approach (i.e., standard economic surplus measurement) is consistent with economic principles but may be of limited value in terms of evaluating environmental research. Much of the agricultural research examined in these studies relates to new technologies that result in potential market supply curve shifts. For environmental research, often there is no formal market for the ES being affected and many of the benefits resulting from the research are non-market in nature. This makes it difficult to formally examine research benefits within an economic surplus framework.[5]

Within the economic development literature there are studies that undertake to identify cropping research priorities (e.g., Rusike et al. 2010; Diagne et al. 2012). These analyses start from a conceptual economic model of an agricultural household. An empirical model of household demand is derived that incorporates the effects of crop traits on variables such as income and poverty. Once the empirical model is estimated statistically, expert opinion is used to identify and quantify potential improvements that might arise from research activities. These results are then used to estimate the ex ante value of research required to generate these improvements. The methods in these studies are rooted in standard economic concepts but again the context is often not directly applicable to an environmental research setting.

There is a limited literature addressing research prioritisation within the environmental sciences. The majority of studies in this area take one of two empirical approaches in their analyses. Some make use of “expert opinion” to identify priority areas for future research (e.g., Braunisch et al. 2012; Rudd et al. 2011). Typically, this is done through either a formal ranking process (e.g., surveys asking for ratings of topics using Likert scale responses or use of Delphi techniques) or through informal discussion amongst experts with the intent of reaching a consensus of research priorities. For example, Braunisch et al. (2012) use a two stage process. In the first stage, a small group of experts is asked to provide a set of relevant research questions related to biodiversity conservation. These questions are then used to create a survey that was completed by a larger group of scientists. Likert scale ratings are solicited and utilised in a statistical analysis in order to identify biodiversity research priorities

The alternative approach is to review current literature to identify gaps in research which are then identified as potential research priorities. Lima et al. (2011) use this approach to identify research priorities for conservation of bird species. Databases of published studies

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[5] If the outcomes from the research are considered in terms of identifying and quantifying the value of externalities associated with production and/or consumption of market goods and services, however, then an economic surplus framework is potentially feasible (e.g., Kutschukian 2008).

are used to catalogue the allocation of research resources by combination of species and location. Based on this analysis, species/locations that have not received much research attention are identified as research priorities. In some cases, a combination of both methods is used. Weinberger et al. (2012) use a literature review to identify potential research gaps, which are then presented to a set of disciplinary experts as the starting point for rating/ranking potential areas of priority for future research.

These environmental research prioritisation studies make use of relevant information in the various analyses. Taking advantage of disciplinary expertise to identify potential research directions is likely essential in any prioritisation process. However, this body of literature suffers from some significant limitations. First, in most cases there is no explicit recognition of the scale of benefits (i.e., value of resulting increased ES production) that may be generated from the different avenues of research. While economic value may influence the ratings of research topics by individual experts in those studies using expert opinion, the formal evaluation procedures used to ultimately identify research priorities do not incorporate any economic analysis. These studies typically do not consider relevant factors such as research costs, probability of research success, or time lags for benefits and associated discounting. The other limiting characteristic of these studies is that the empirical methods used are ad hoc and do not have a basis in theory, economic or otherwise. The main contribution of this literature is in identifying information gaps.

Economics of Information

One way of considering the value of research is to think of research as the process of generating new information. This allows the problem to be placed within the context of the economics of information. There is a rich history of economics literature that addresses the value of information, beginning with Stigler's (1961) paper which considers information in terms of marginal benefits and costs. Much of the work in this area has focussed on the economics of asymmetric information in decision making (e.g., review by Stiglitz 2002); that is, situations where relevant information is known by some but not all individuals involved in a transaction. This line of research typically examines the relationship between asymmetric information and market failures (e.g., adverse selection or moral hazard). While this is not directly relevant to research prioritisation, the basic idea of considering marginal benefits from additional information versus marginal costs of obtaining that information does apply to the decision problem addressed in this paper.

The value of information has been empirically estimated for different types of decision makers (e.g., producers, consumers, policy makers, resource managers). Within the literature concerning the economics of agriculture and food, studies have examined the expected value for varied types of information, including (for example) climate variables (e.g., Letson et al. 2009), disease risk associated with livestock imports (e.g., Disney and Peters 2003), weed populations in crops (e.g., Pannell 1994), and product label information about genetically modified food attributes (e.g., Hu et al. 2005). Most of these studies proceed by first determining the optimal action or decision with currently available information. The analysis is then repeated, assuming that new or updated information is available at the time that the relevant decision is made. The difference in outcomes between the two decisions (i.e., with versus without the additional information), defined in terms of the decision maker's objective (e.g., profit, utility, welfare), represents the expected value of the additional information.

The empirical methods used vary by study but often involve simulation or optimisation techniques. While these studies do not explicitly deal with questions of prioritising research decisions, they are relevant in that they conceptualise the value of information using economic theory, with empirical methods being developed from these theoretical models. Often, the framework is based on an "implicit" Bayesian approach to the use of additional information. Rather than explicitly deriving posterior probabilities using Bayes theorem, the updated probabilities are obtained and applied directly in the empirical analysis.

A somewhat similar literature also exists for the value of "environmental information". A number of studies examine the expected value of new information in making improved environmental management decisions (e.g., Bouma et al. 2011; D'Evelyn et al. 2008; Liu et al. 2012; Runge et al. 2011; Sung and Shortle 2006; Williams et al. 2011). These papers follow a similar pattern in terms of methodological approach; that is, calculating the expected value of information using an implicit or explicit Bayesian approach. The motivation for this analysis tends to be recognition that there is often a lack of information available for making environmental management decisions (i.e., policies, programs and/or projects).

The environmental management topics addressed in this literature range from pollution abatement strategies for coral reefs (Bouma et al. 2011) to control of invasive species (D'Evelyn et al. 2008) to groundwater remediation (Liu et al. 2012). In these papers, the value of the additional information is often defined in terms of cost. For example, a reduction in the cost of meeting abatement targets may be used as the means to value additional information. There are exceptions to this, however, with some papers explicitly considering impacts on benefits and costs. One example of this is the analysis of watershed nutrient pollution by Sung and Shortle (2006), in which social net benefits associated with water quality management decisions are estimated. Pannell and Glenn (2000) present and discuss a Bayesian framework for estimating the value of additional information related to agricultural sustainability. The empirical methods used in these analyses vary as well, including applications of Monte Carlo simulation, stochastic dynamic programming and multi-criteria decision analysis.

Concepts from the economics of information have also been applied in studies to explicitly examine research priorities within the medical and health literature.[6] Examples include Ades et al. (2004), Coyle and Oakley (2008), Fleurence (2007), Welton et al. (2008) and Woods et al. (2011). The analyses in these papers usually address questions of whether it is worthwhile to pursue particular research activities to develop new medical or health treatments.

The methods used in these studies are consistent with the agricultural and environmental value of information papers noted above. A model is developed to represent the decisions to be made regarding alternative treatments for the medical or health research problem of interest. The decision model incorporates relevant parameters and relationships that contribute to net benefits associated with the treatments. Available (i.e., prior) information is used to “populate” the model parameters. There is usually uncertainty associated with at least some model parameters. Net benefits may incorporate research costs along with any impact of treatments on medical or health costs (e.g., cost of treatment itself, increases or decreases in associated medical costs). Also typically included are estimates of treatment benefits which are often quantified as the change in quality adjusted life years (QALY)[7], valued using decision maker willingness to pay for additional QALY (i.e., the non-market value of a life).

The model is simulated with the prior probabilities to determine optimal treatment and associated net benefits. Simulation is often done using Monte Carlo methods (e.g., Ades et al. 2004). The model is then re-simulated, assuming that perfect information is available for

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[6] Similar to the environmental research studies mentioned earlier, there is also an extensive literature within the medical/health discipline that uses ad hoc methods to prioritise research directions (e.g., Anstee et al. 2011; Blackwood et al. 2011; Ranson et al. 2010; Thariani et al. 2012).

[7] Quality adjusted life years is a measure of the value of health and is used to quantify the impact of health interventions on both the quantity and quality of health (Hirskyj 2007).

a subset of parameters (i.e., those parameters for which uncertainty would be reduced through the research), with the optimal treatment being identified given the level of those parameters. The expected net benefit with the partial perfect information is then calculated and compared to the "prior" net benefit estimate to determine the value of information.

In summary, environmental research prioritisation has received attention within the current literature. However, most of the analysis has been ad hoc in nature with no basis in relevant theory. As well, little emphasis is given in this literature to the economics of the issue, either with respect to the economic value of the research output or to the constrained nature of the problem; that is, the need to allocate limited resources (i.e., research budgets) among multiple uses.

One area that does show potential for the study of research prioritisation is the value of information literature. These studies are grounded in relevant economic theory (i.e., economics of information). This approach has largely been applied within agricultural, environmental and medical studies to quantify the value of updated information for decision making. Studies commonly use a Bayesian framework combined with Monte Carlo simulation or stochastic dynamic optimisation methods. Limited attention has been paid in the ecological literature to research prioritisation using this approach. However, there are a significant number of studies within the medical/health literature that use expected value of information methods to identify areas of priority for future research. Based on the review of literature, summarized above, value of information concepts are used as the basis for proceeding in the current analysis.

Theoretical Model

In this section, economic principles that underlay the value of information (VOI) literature are used to formulate a conceptual model that represents research prioritisation as a decision making problem for a research funding organization. There are different versions of this problem that may be considered as relevant, depending on the nature of the funding agency's mandate and the scale/scope of the potential research directions. In some cases, funding allocation decisions are made by choosing among research project proposals that target a specific area of interest. An example of this scenario might involve an agency that is interested in funding research with an overall goal of improving ES production associated with agricultural wetlands.

In these cases, there are multiple avenues of research that can be used to generate information of value in the specific area and the prioritisation process is used to identify the most “profitable” path or paths to explore within this area. In the case of the agricultural wetlands example, the result of the prioritisation process might be to decide whether it is better to conduct research examining the impact of agricultural practices on water quality attributes (e.g., nutrient and/or pesticide concentrations) versus pursuing research that explores the effects of those attributes on ES production in the form of aquatic populations.

Alternatively, a “bigger picture” research prioritisation problem may be considered, where the research funding decisions are on a much larger scale with respect to the environmental issues or problems. In particular, research may be undertaken to address a wide variety of environmental problems or issues, and prioritisation of funding to those different issues is also important. For example, a funding agency may need to decide whether research that investigates the impact of agricultural chemical use on marine life within coral reefs is of higher or lower priority than research that examines the effects of forestry management practices on biodiversity. Both larger and smaller scale prioritisation problems are important and, in principle, can be addressed through the use of the same type of conceptual VOI model. For the purposes of the discussion here, the focus is on “smaller scale” problems of allocating research funding resources amongst potential activities that are all directed towards the same environmental issue or problem.

Consider a decision maker who has limited funds that are to be allocated amongst alternative environmental research projects. The objective of the decision maker is assumed to be one of maximizing net benefits derived from the available research funds. Here the net benefits are defined in expected terms, since funding decisions are made ex ante and research outcomes are stochastic in nature. The decision maker’s problem may be characterised as choosing some combination of research projects from among R project proposals, as follows:

$$\begin{gathered}\max_{I} \sum_{r=1}^{R} I_r E[BEN^r - CST^r] \\ subject\ to \sum_{r=1}^{R} I_r(CST^r) \leq BDGT\end{gathered} \tag{1}$$

where BEN^r and CST^r represent benefits and costs, respectively, associated with the r^{th} research project and I is a vector of binary variables, I_r, representing whether a particular project is undertaken ($I_r = 1$) or not ($I_r = 0$).[8] The decision maker's "problem" is then to choose the set of projects that maximizes the expected benefits from the research, net of research costs. The constraint ensures that the total amount allocated for research funding does not exceed the decision maker's budget (BDGT).

Of course the prioritisation problem is not as simple or straightforward as might be suggested by the optimisation problem specified in (1). For example, it is likely that both benefits and costs arising from research activities will accrue over time, meaning that BEN and CST have a dynamic dimension and would therefore require consideration of time in their valuation. This suggests the need to discount future values to present values with the associated requirement of having to decide on an appropriate discount rate. Further, the valuation of benefits from environmental research may be problematic, given the non-market nature of many of the benefits that might arise because of information generated from research activities (e.g., value of biodiversity, improved aesthetics, etc.).

Another potential complication related to the optimisation problem identified in (1) is the uncertainty associated with benefits and costs of research. As noted earlier, funding decisions are made prior to the research being undertaken and so at the time both research costs and benefits are unknown. Setting aside any uncertainty associated with research costs, there may be a significant amount of uncertainty surrounding research benefits. This is probably true of any type of research but is particularly relevant for environmental research given the stochastic nature of biophysical systems/relationships and the degree of interaction between relevant parameters. The analysis of benefits arising from research activities will undoubtedly be probabilistic in nature, with estimates of prior probabilities for research benefits being required and then updated either through additional information (i.e., "priors" being converted to "posteriors") or by assuming that perfect information is available from research results (i.e., uncertainty is resolved to certainty). Further, it is likely that research would provide updated or perfect information for some stochastic parameters, but not all; that is, information available for some uncertain parameters will remain unchanged.

Based on this discussion it is apparent that much of the focus and effort should be allocated to further specification of the expected benefits associated with potential research

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[8] In formulating the decision problem as in (1), the implicit assumption is that research funding decisions are yes/no decisions; that is, either the research is funded or not. This is only one possible representation of the prioritisation problem. For example, another "model" of this decision problem would be to specify the decision variable I_r as a continuous variable with upper and lower bounds of 1 and 0, respectively. The interpretation here is that research projects may be partially or fully funded. Another alternative would be to have the decision variable defined as funds allocated to individual research projects (i.e., CST^r defined as a decision variable rather than a pre-determined parameter).

projects; that is, E[BEN^r]. As well, the analysis is one of examining the value of partial improvement in information. To begin the process of "extending" the optimisation problem from (1) to incorporate dimensions of uncertainty and partial improvement in information, consider a potential area of environmental research where alternative "actions" are being examined in terms of their impact on environmental quality. There are N potential actions, indexed n=1,2,…,N. The net benefit (NB) associated with the nth action may be defined as follows:

$$NB(n,\theta,\alpha) = P_B \cdot B(n,\theta,\alpha) - C(n,\theta,\alpha) \qquad (2)$$

where B is the degree of improvement in environmental quality (e.g., ES levels) attributable to action n, P_B is the "unit value" of environmental quality, and C is the cost associated with the action. The nature of B and C will be specific to the type of environmental research being examined. For example, if the effects of agricultural practices on water quality attributes are being studied, B() might represent the improvement in aquatic populations (however that is measured). P_B is then the value of that improvement and C is the cost associated with implementing the action (e.g., the opportunity cost of foregone agricultural returns on land set aside as a buffer).

Benefits and costs are assumed here to be a function of the particular action n and other influencing factors θ and α; θ is a vector of stochastic parameters and α is a vector of deterministic parameters. Further, θ is assumed to be structured as:

$$\theta = (\theta^R, \theta^O) \qquad (3)$$

where θ^R is the subset of stochastic parameters that are affected by the potential research activities and θ^O are the other stochastic parameters. Using the agricultural wetland research example, components of θ^R might include reduction in chemical runoff and/or sediment resulting from establishing a buffer while θ^O might include weather conditions such as precipitation that are not affected by the research but do affect the benefits from the alternative actions. Note that components of θ^R and θ^O may or may not be statistically independent. The vectors of stochastic and deterministic parameters may include both economic and non-economic elements.

Based on currently available information, the problem may be considered as choosing the best action in order to maximize the net benefits to society:

$$\max_n E_\theta[NB(n,\theta,\alpha)]$$

or

$$V_{current} = \max_n \iint NB(n,\theta,\alpha)f(\theta^O)d\,\theta^O f(\theta^R)d\theta^R \qquad (4)$$

$$V_{current} = E_\theta[NB(n^*,\theta,\alpha)]$$

assuming continuous distributions for individual elements of θ. The outcome from this optimisation is the best action (n^*) to undertake, given current information, and the level of expected net benefits associated with that action ($V_{current}$).

The ex ante value of information generated by research activities is obviously unknown. However, one way to consider and quantify the value is to calculate the expected value of partial perfect information, or EVPPI. EVPPI is the additional net benefit that would be generated if elements of θ^R (i.e., those stochastic parameters affected by the research) were known with certainty at the time that a decision was made regarding the action to be undertaken; that is, the uncertainty associated with θ^R was resolved prior to decisions being made.

Under conditions of partial perfect information, the level of expected net benefits resulting from the research being undertaken is:

$$E_{\theta^R} \max_n E_{\theta^O|\theta^R} NB(n,\theta,\alpha) \qquad (5)$$

The maximization problem contained within (5) may be expressed as:

$$\max_n \int NB(n,\theta,\alpha)f(\theta^O)d\theta^O \Big|_{\theta^R} \qquad (6)$$

In other words, the optimal action is chosen to maximize expected net benefits, given values for the elements of θ^R. The result is a set of optimal actions given perfect information about the values for those stochastic parameters affected by the research ($n^*|_{\theta^R}$), and associated expected net benefits for those actions, or $NB^*(n^*,\theta,\alpha)$. Equation (5) may then be restated as:

$$V_{PPI} = \int NB^*(n^*, \theta, \alpha) f(\theta^R) d\theta^R \quad (7)$$

that is, the expected value of net benefits, given optimal actions, calculated over all values of θ^R. This represents the expected net benefits given availability of partial perfect information (V_{PPI}).

The value of the research may then be calculated as the difference between the expected net benefits before (i.e., based on current information) and after (i.e., based on partial perfect information) the research activities:

$$EVPPI = V_{PPI} - V_{current} \quad (8)$$

For a particular research project r, the benefits $E[BEN^r]$ from (1) are equal to the EVPPI calculated in (8). Research prioritisation then requires estimates of EVPPI for each potential research project, or $EVPPI^r$.

The prioritisation process outlined here is implicitly Bayesian in nature. The new information generated through the process of research is assumed to completely resolve uncertainty associated with relevant parameters at the time of decision making. However, the procedure can be made explicitly Bayesian if considered in the context of using new information generated by research to update the prior probabilities from the optimisation problem in (4); that is, expected net benefits based on current information. Using the updated probability information, revised EVPPI can be calculated to determine if the present research priorities are still valid or whether revised prioritisation should be undertaken.

The results from this analysis may be considered as an upper bound on the value of information provided by any particular research project. It is unlikely that uncertainty for elements of θ^R will be completely "resolved" by the program of research. In recognition of this, another approach is sometimes proposed within the medical literature on research prioritisation; expected value of sample information (EVSI). While the role of EVSI in medical literature is often to inform with respect to optimal sample size in research, it can also be thought of as a means to quantify the impact of updated probability information within a Bayesian analysis. While not the focus of the discussion here, a brief review of EVSI is provided in an appendix to this paper.

Steps in Empirical Implementation

This section presents an outline of the steps required to empirically implement the EVPPI research prioritisation framework. The intent is to provide some perspective and understanding regarding the nature of the information required to carry out these procedures. There are four general stages in the process, discussed below; define the biophysical system and related ES, calculate the expected value of current information, calculate the EVPPI associated with the alternative research activities, and finally calculate the marginal value of each area of research for use in establishing research priorities.

Defining the "System"

1. Characterise the components of the biophysical system and the relevant relationships between elements of the system.
2. Identify the relevant ES being generated and the relationships between biophysical system functions and processes and ES production. Here, relevance of ES is defined in terms of the degree to which they are influenced or affected by the potential research activities.
3. Quantify the value of human benefits resulting from ES production. These are the functional relationships between the level of ES and their associated "social" and market values.
4. Identify and quantify linkages to "external" factors. These are elements that affect the biophysical system in terms of the nature of the functional relationships, ES production, etc. Some of these may in turn be influenced by the potential areas of research.
5. Identify the potential actions to be considered within the context of the biophysical system and quantify the effects of these actions on the system and relevant environmental outcomes (i.e., ES and related human benefits).

Calculating the Expected Value Associated with Current Information

6. Solve the optimisation problem outlined in (4). The structural details of this optimisation are case-specific as is the appropriate empirical optimisation procedure but the process can be considered "generically", as follows:
    a. For each state of nature, calculate net benefits associated with each potential action, given current information about relevant parameters and functional

relationships. Here, a "state of nature" is defined as a set of specific values for all stochastic parameters (θ).

   b. Calculate the expected net benefits to society for each action over all states of nature, and identify the action that maximises these expected benefits. This maximum expected value represents the value of current information.

Calculating the Expected Value of Partial Perfect Information (EVPPI)

7. Identify the impact(s) of the potential research activities on the biophysical system (and influencing factors); what parameters/relationships are affected and how are they potentially changed by the research?
8. Solve the optimisation problem outlined in (5) and (6) for a proposed area of research. A generic representation of this optimisation process is as follows:
   a. Identify a "research state of nature", which is a set of specific values for stochastic parameters affected by the research activities (θ^R).
   b. For that research state of nature, determine the expected net benefits to society for each action, calculated over all states of nature for other stochastic parameters (θ^O). Identify the action providing the greatest expected net benefit and the associated value of that maximum net benefit.
   c. Repeat step b for all research states of nature.
   d. Calculate the expected value, over all research states of nature, of the maximum expected net benefit values determined in steps b and c. This represents the value associated with partial perfect information.

Value of Research

9. The expected value of the potential research activities is calculated as the difference between the expected value of partial perfect information (i.e., from step 8d) and the expected value of current information (i.e., from step 6b).
10. Repeat steps 1-9 for all potential areas of research activities. The expected value of research for each potential area can then be compared to the costs of research CST^r from (1) to determine the area with the greatest net expected value and thus the "greatest" priority.

Additional Empirical Considerations

While the steps outlined above for research prioritisation are relatively straightforward, the actual empirical implementation process may be very involved. There are a number of empirical considerations of significance. Three of these are briefly reviewed here; information sources, stochastic parameters and optimisation procedures.

Information Sources

Several types of information are required in order to estimate the expected value of research using the approach outlined above. Estimates are required for ecosystem functions and processes that are relevant for the particular environmental issue or problem being studied. These form the basis for the model of the biophysical system and associated ES production. Also needed are estimates of the impact that research activities may have on these relationships.

In order to assess the potential value of environmental research, estimates of economic costs and benefits are also required. Values of human benefits derived from ES production are used to quantify the value of partial perfect information generated from environmental research. In many cases these values will be non-market in nature, adding to the challenge of obtaining the needed information. Costs include any costs associated with the impact of research activities (i.e., negative net benefits) and the costs of undertaking the research activities.

Obtaining estimates of these parameters and/or functional relationships is not a trivial step. In many instances, the necessary information is not readily and easily available. Estimates of non-market values for ES may be difficult to obtain, or empirical estimates of relationships between elements of the biophysical system may simply not exist. The review of literature on research prioritisation in the medical/health fields, presented earlier in this paper, suggests that in most cases the necessary parameters are "engineered" using a combination of expert opinion and information from available literature. In the case of environmental research, similar sources are likely to be used to develop the necessary functional relationships.

Stochastic Parameters

As noted earlier in the discussion of the theoretical model, it is likely that many of the relevant relationships and parameters needed for the prioritisation process are stochastic. In these cases, probability distributions associated with the relationships/parameters (i.e., θ from the theoretical model discussion) are required in order to properly model the biophysical system and the effects of potential research activities. If there are correlations between important stochastic parameters, estimates of these are needed as well. Potential sources of this information are as discussed above; available literature and expert opinion, although correlations are likely to represent a particularly significant challenge. Information for these parameters may range from simple point estimates (i.e., no probability information) to discrete values distributions to continuous distributions (e.g., mean and standard error or variance or confidence interval).

Optimisation Procedures

As discussed in the review of literature, a variety of empirical optimisation techniques have been used to identify research priorities. These include, for example, ad hoc ranking procedures based on Likert scale responses or more formal optimisation tools such as linear programming or dynamic programming. Monte Carlo methods are commonly used in EVPPI studies, particularly in the medical/health literature on research prioritisation.

Given discrete distributions for the relevant stochastic parameters (i.e., for research related variables, θ^R, and other parameters, θ^O), the optimisation problems specified in (4) and (6) simplify to summations over discrete parameter values (and associated probabilities). However, with continuous distributions for some or all of the stochastic parameters, more involved procedures are required. In many cases, the resulting optimisation problem does not have a closed form solution and so Monte Carlo techniques are used.

Ades et al (2004) provide a discussion of alternative Monte Carlo algorithms for calculating expected net benefits of research, using the EVPPI approach. The complexity of the Monte Carlo procedures depends on the nature of the net benefits function (NB) contained within the integration (i.e., whether or not it is linear in the stochastic parameters) and whether elements of θ^R are correlated with elements of θ^O. Generally speaking, however, the Monte Carlo simulation proceeds by making iterative draws from the various distributions of stochastic parameters. Those values are used, along with any deterministic parameters (denoted by α earlier), to calculate the net benefits. The integration is done by calculating the expected values using the iteratively calculated net benefit values. Various software platforms (e.g., @Risk; Palisade 2010) are available to operationalize the Monte Carlo algorithm.

Hypothetical Empirical Example

To illustrate the empirical process outlined in the previous section, a hypothetical research prioritisation example is provided for illustrative purposes. It is supposed that a research granting agency is interested in prioritising funding for research related to agricultural wetland water quality. In particular, the potential areas of research include examining a) the relationship between agricultural field practices associated with chemical application and water quality attributes (i.e., nutrient and pesticide levels), or b) the relationship between water quality attributes and aquatic population ES. The interest in these areas of research arises from a need to have better information to inform the policymaking process as it relates to adoption of agricultural beneficial management practices (BMPs); specifically, establishing buffer strips versus incorporating perennial legumes into rotations.[9] Both of these practices have been demonstrated to have positive effects on water quality and associated ES (e.g., Blanco and Lal 2008; Hilliard et al. 2002; Putnam et al. 2001).

To begin, the biophysical system associated with the research problem is characterised in terms of relevant factors and relationships. Figure 1 provides a simplified illustration of the biophysical relationships for the system used in the example here; that is, an agricultural field with associated wetland. The system itself is considered to include the biophysical processes present in the agricultural field and the adjacent wetland. The components of the biophysical system of interest, given the research prioritisation question, are levels of erosion, chemical (nutrient and pesticide) runoff and plant growth in the agricultural field, along with levels of sediment and agricultural chemicals in the wetland.[10]

Next, ES generated by the biophysical functions and processes are identified. There are many potential ES that may be considered, given the constituents of the biophysical system. For the purposes of the illustration here, the ES of interest are aquatic populations, soil and water quality, biodiversity and crop populations.

Human benefits derived from ES production in this example are varied. While not an exhaustive list, Figure 1 provides examples including aesthetics, recreation (e.g., hunting or fishing depending on the nature of the wetlands), damage avoidance (i.e., reduced likelihood

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[9] This results in two potential actions to consider in the empirical analysis. An alternative scenario would involve defining a third potential action; implementing both BMPs simultaneously. This is not considered in the discussion of the hypothetical example here. However, in principle the process used would not change. What would be required is additional information concerning the impacts of adopting both BMPs at the same time.

[10] This is obviously a simplified version of the biophysical system in question, as there will be other biological and physical processes going on in the field (e.g., downward movement of nutrients and chemicals through the soil, growth in weed populations, etc.) that are not considered here. The implicit assumption is that these are sufficiently “minor” in terms of their relationship with the proposed research activities to be safely ignored.

of flooding), health (e.g., effects of water quality) and harvests (i.e., marketable outputs from crop production). For the examples of human benefits provided in Figure 1, only harvests would have an easily determined market value. The economic values for other benefits are largely non-market in nature, and would represent a challenge for estimation (e.g., what is the value of aesthetics associated with wetlands?).

Consideration is next given to identifying external or exogenous factors that may affect the biophysical system. Examples of these are illustrated in the bottom left corner of Figure 1. Topography (e.g., slope of the field) will affect the likelihood of chemical runoff and soil erosion, as well as potential plant growth. Agricultural practices include any decisions made by a producer related to crop production, including choice of crop, tillage practices, seeding rates, fertiliser and pesticide application decisions, etc. Weather (i.e., precipitation and temperature or heat) has obvious effects on plant growth, and precipitation (amount and timing) affects the likelihood and rate of erosion and chemical runoff.

Once the system represented in Figure 1 is identified, the relationships between the various components must be defined and quantified. These are represented, in very simplified form, by the “thick” arrows in Figure 1. For instance, the green (checkerboard) arrow represents the relationship between agricultural field conditions and relevant wetland environmental conditions. As an example, the rate of erosion will heavily influence wetland sediment levels. A quantitative estimate of this relationship would be needed; for example, a functional expression relating rate of erosion to wetland sediment levels).

Required relationships also include links between the biophysical system and ES; this is represented by blue (diagonal striped) arrows. For example, the level of aquatic populations, along with soil and water quality, is affected by wetland sediment and chemical levels. Similarly, there is a relationship between plant growth and crop populations that would be required to model the biophysical system. The red (dotted) arrows represent functional relationships between ES and associated values of human benefits, also needed for the analysis.

In quantifying these relationships, effects of the exogenous influencing factors must also be considered; this is represented by the black (solid) arrow. For example, the relationship between pesticide runoff and wetland pesticide levels would be influenced by the slope of the field (i.e., topography), the amount and timing of precipitation (i.e., weather events) and producer decisions concerning the type of crop, rate and timing of pesticide application (i.e., agricultural production practices), etc.

Also affecting the biophysical system and resulting ES production in this example are BMPs; that is, buffer strips and perennial legumes in rotation. These relationships are represented in Figure 1 by the dashed arrows. Implementation of one or other of the BMPs is hypothesised to affect the relationship between agricultural field conditions and the resulting wetland environmental conditions, which in turn affects the level of ES production generated by the wetlands. It should also be noted that implementation of either of the BMPs also affects the relationship between plant growth and crop populations; establishing a buffer strip reduces the field area available for crop populations and the use of perennial legumes changes the "mix" of crop populations in the field.

As discussed earlier, it is likely that many of the relationships identified here are uncertain (i.e., probabilistic) in nature. This aspect would also need to be quantified. For example, a functional relationship for wetland sediment level could be specified as follows:

$$wet\_sed = g(slope, precip, till, crop, soil) \qquad (9)$$

where wet_sed is level of wetland sediment and slope, precip, till, crop and soil are, respectively, slope of the field, precipitation levels, tillage practices, crop grown and soil type.[11] Inherent in this relationship is the "intermediate product" of soil erosion. It is likely that the effect of these explanatory variables is stochastic and so a measure of variability or uncertainty for the functional parameters (e.g., standard error) would need to be provided along with the mean or expected values of the parameters.

The proposed areas of research are then placed within the framework of the biophysical system. As noted at the beginning of this section, two alternative areas of research are considered; the relationship between agricultural practices and water attributes (i.e., sediment and/or chemical levels), or the relationship between those attributes and aquatic population ES. Implicit here is the assumption that some knowledge is already available for these two relationships, represented by the green checkered and blue (downward) diagonally striped arrows, respectively. The research being considered would result in improved information in both cases. Given that the research has not yet occurred, this is problematic for the prioritisation analysis. As discussed in the previous section, current knowledge is used as the starting point for these estimates; information from current literature as well as expert opinion. Similar to other parameters associated with the wetland example, these estimates likely have a significant degree of uncertainty associated with them,

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[11] The explanatory variables included here are defined for illustrative purposes and are not intended to represent an exhaustive list of factors affecting sediment levels.

which would need to be quantified in some way. The way in which the improved knowledge is modeled within this empirical framework is outlined in the discussion below.

Given all of this information, a net benefit function is formulated that takes into account the value of benefits (and costs) of ES production, along with the potential effects of the BMPs under consideration (if adopted). The result is a net benefit function for each BMP. These net benefit functions are then used in a Monte Carlo simulation procedure. Given the distributional information for the stochastic parameters, draws are repeatedly made from the distributions and used to simulate net benefits for each BMP "action". The action (BMP) that generates the greatest expected net benefit is "optimal" and the associated net benefit represents the value of current information.

The potential value of research activities to improve knowledge concerning the relationship between agricultural production practices and water quality (i.e., agricultural chemical concentrations in wetland water) is determined next. A draw is made from the distribution(s) associated with this relationship. Substituting the value(s) from that draw into the net benefit functions, a Monte Carlo procedure is then carried out to simulate the performance of the alternative BMP actions over multiple draws from the other stochastic parameter distributions in the system. The action with the greatest resulting expected net benefit is identified as "best" for that research state of nature. This process is repeated iteratively for subsequent draws from the research relationship parameter distributions. The expected value of the maximum expected net benefits, calculated over these iterations, minus the value of current information determined earlier, represents the expected value of information generated by this line of research.

The same process is followed, this time for the value of information generated by research activities to improve knowledge regarding the relationship between water quality attributes an aquatic population ES. The research that generates the greater expected value of information, net of expected research costs, will be the "higher priority" area of environmental research.

As noted earlier in the paper, the process outlined here implicitly makes a specific assumption regarding the way in which knowledge is improved by the potential research activities. Rather than assuming that the degree of uncertainty associated with the relevant relationships is reduced (e.g., reduction in standard error associated with functional parameters), use of this approach implies that the uncertainty is resolved prior to decisions being made about relevant actions (i.e., adoption of BMPs) such that the (partial) information available to decision makers is "perfect".

While not explicitly discussed here, it is possible to use this empirical framework to model an intermediate case of research generating updated but still "imperfect" information. The same process is followed as outlined in this paper, with the second stage Monte Carlo analysis being done using a priori (i.e., hypothesised) updated parameters resulting from the potential research activities; that is, updated imperfect information is used instead of perfect information. In this way, the process becomes more explicitly Bayesian as prior probabilities are replaced with projected posterior probabilities. The challenge, which is beyond the scope of this discussion, is to obtain credible estimates for the posterior probabilities.

Concluding Comments

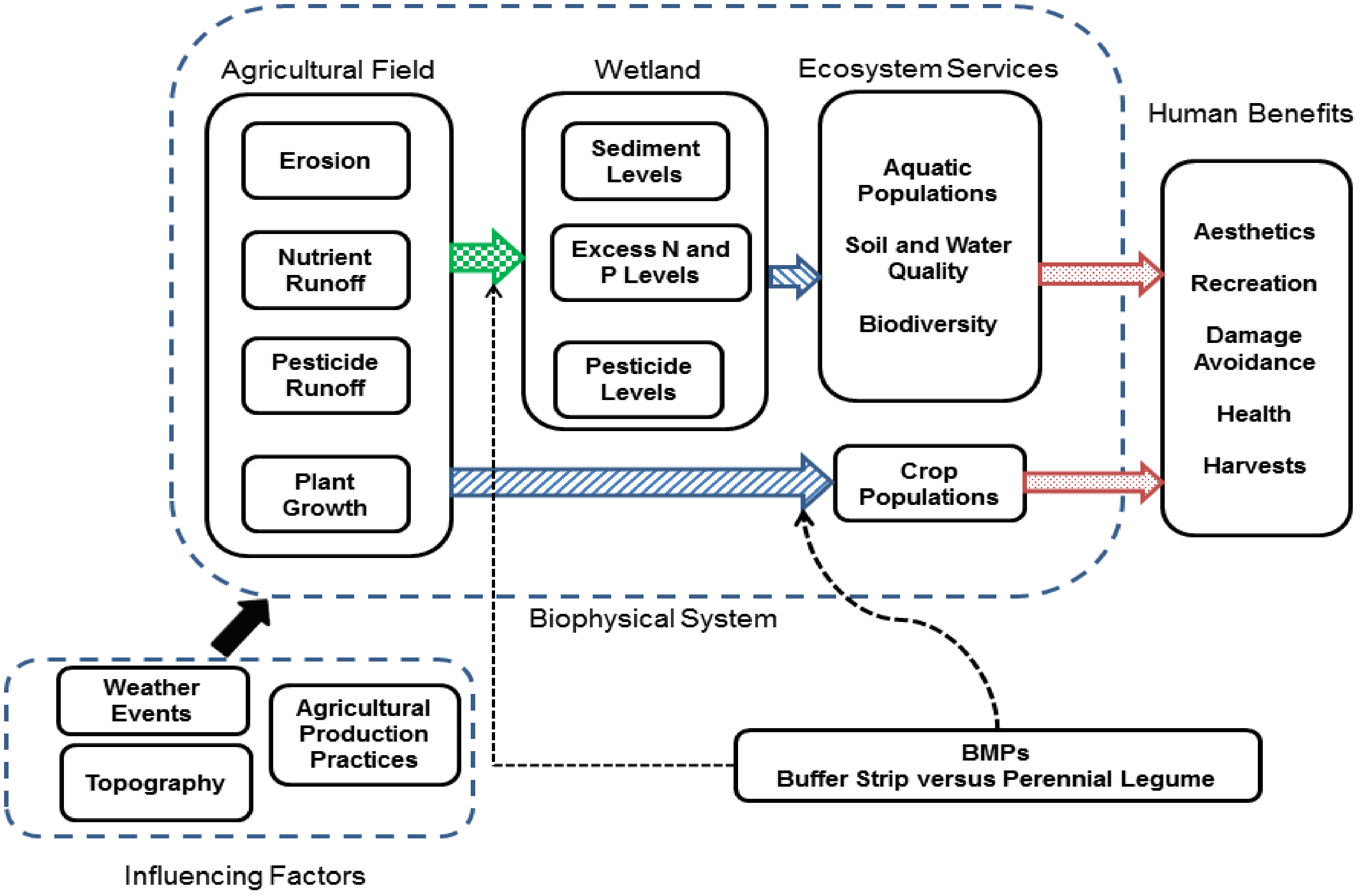
This paper addresses the issue of prioritisation of environmental research activities. Environmental research plays an important role in contributing information that ultimately informs public policy and environmental management. Given the significance placed by society on environmental quality combined with the limited nature of resources available to fund research, being able to prioritise environmental research is essential. The discussion in this paper outlines a rigorous economic framework within which empirical analysis of research prioritisation may be conducted. In particular, an expected value of partial perfect information (EVPPI) structure is proposed as being appropriate for use in this area. A discussion of empirical methods and a hypothetical example are provided to highlight information needs and challenges as well as to suggest quantitative approaches that are appropriate for use given this proposed structure.

There are different types of activities that can be characterised as environmental research. These include discovery (e.g., identifying new relationships, threats, opportunities), knowledge (e.g., quantifying links between human actions and environmental consequences), decision support, technology development and/or human behaviour. Prioritisation approaches based on value of information concepts (i.e., such as EVPPI) are well suited for use in evaluating some of these areas of research. In particular, these approaches are likely appropriate for use in situations where environmental "decision variables" can be identified that have economic values associated with them. This is illustrated through the hypothetical example discussed earlier (i.e., BMP land use decisions generating changes in ecosystem services with market or non-market economic values).

There are limitations associated with the use of the EVPPI approach. It does assume that research has a particular impact on the probability distributions for uncertain parameters. As well, the use of the this approach requires a significant amount of information and would be time consuming if there are a wide range of potential research directions to be considered. Finally, it may not be appropriate or even feasible to use an EVPPI approach for all types of environmental research prioritisation questions. For example, some types of basic environmental research activities are sufficiently removed from direct effects on ecosystem services that identifying decision variables and relevant economic values is problematic. Given the heterogeneous nature of environmental research, a range of analytical approaches may be needed.

Despite these issues, the discourse provided in this paper should be of value to practitioners interested in pursuing empirical analysis regarding prioritising environmental research efforts. Quantifying the value of research in economic terms and evaluating the impact of research in a way that is consistent with economic principles and concepts should form the basis for prioritisation analyses.

Figure 1: Illustration of Biophysical System and Associated Ecosystem Services and Benefits – Agricultural Field with Associated Wetlands



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Appendix: Expected Value of Sample Information (EVSI)

As noted at the end of the theoretical model discussion, an alternative approach may be used in valuing potential research. This method, referred to as the Expected Value of Sample Information (EVSI), is consistent with EVPPI in terms of concepts and (often) empirical methods. The main distinguishing characteristic of EVSI analysis is that it provides a mechanism to estimate the effect of updated (rather than perfect) probability information for parameters hypothesised to be affected by proposed research. The use of EVSI for this purpose is more explicitly Bayesian than is EVPPI.

Consider the same (generic) research project that was used to develop and discuss the theoretical model for EVPPI. There are N potential actions (n=1,2,…,n), with environmental net benefit for the n^th^ action (NB) being defined as in (2). Vectors of influencing factors $\theta=(\theta^R,\theta^O)$ (stochastic) and α (deterministic) are also defined as before. Based on currently available information, the problem may be considered as choosing the best action in order to maximize the net benefits to society:

$$\max_n E_\theta[NB(n,\theta,\alpha)]$$

or

$$V_{current} = \max_n \iint NB(n,\theta,\alpha)f(\theta^O)d\,\theta^O f(\theta^R)d\theta^R \qquad \text{(A.1)}$$

$$V_{current} = E_\theta[NB(n^*,\theta,\alpha)]$$

This is exactly the same specification as (4), with n^* being the optimal action given current information and $V_{current}$ being the level of expected net benefits associated with that action.

Using an EVSI approach, the level of expected net benefits given that the research project is undertaken is stated as follows:

$$E_{\theta^R} \max_n E_{\theta^O|\theta^R} NB(n,\theta^O,(\theta^R|D),\alpha) \qquad \text{(A.2)}$$

where all notation is defined as before and $(\theta^R|D)$ represents the values of the stochastic parameters affected by research, given a sample D from the prior distribution of θ^R. The density function $f(\theta^R|D)$ is the posterior distribution for θ^R, given the updated information from D. The maximization problem contained within (A.2) is equivalent to the problem specified earlier in the paper for EVPPI (i.e., equation 6) and (A.2) may then be restated as:

$$V_{PPI} = \int NB^*(n^*, \theta, \alpha) f(\theta^R | D) d\theta^R \qquad \text{(A.3)}$$

This represents the expected net benefit, given availability of sample information generated by research (V_{PPI}) and is used in a similar fashion to the value obtained earlier from the EVPPI analysis.