Supporting Information for: Surveying the landscape of approaches to assessing societal benefits of Earth science information

Casey C. O’Hara^1\\*^, Samantha Cheng2, Mabel Baez-Schon2, Rebecca Chaplin-Kramer2, Alejandra Echeverri3, Gillian Galford4,5, Rachelle K. Gould4,5, Cristina Mancilla1, Maura Muldoon4,5, Gerald Singh6, Priscilla Baltezar7 Yusuke Kuwayama8, Stephen Polasky9, Amanda D. Rodewald10, Elizabeth Tennant11, Jiaying Zhao12, Benjamin S. Halpern - 1,13

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# Value domains

This table is inspired by the work of Himes et al. (2024) on valuation of nature, and adapted to account for potential value derived from Earth science information. In nearly all cases, the value of ESI is based on the degree to which the expected outcome of a decision is improved by incorporating ESI into the decision. Where applicable, we have broadened ecosystems, biodiversity, and ecosystem services to include social and natural features and outcomes that are improved by incorporation of ESI into decision making processes.

Table S1: This table is inspired by the work of Himes et al. (XXX) on valuation of nature, and adapted to account for potential value derived from Earth science information. In nearly all cases, the value of ESI is based on the degree to which the expected outcome of a decision is improved by incorporating ESI into the decision. Where applicable, we have broadened ecosystems, biodiversity, and ecosystem services to include social and natural features and outcomes that are improved by incorporation of ESI into decision making processes.

| Value Domain | Core Meaning | Salient Articulation | Examples in included corpus |
| --- | --- | --- | --- |
| Instrumental | Values of entities or processes  important as means to achieve human ends or satisfy human preferences (in principle replaceable, albeit not always in practice) | Means to an end (mostly intended as usefulness for humans, utility, or benefits, sometimes also for other-than-human beings); Leading to satisfaction of needs, preferences, interests, and desires; Nature’s value as a resource, for ecosystem services, as an asset, capital, or property | Increased crop yield and profit based on improved seasonal forecasts |
| Intrinsic | Values of entities expressed independently of any reference to people as valuers (including values associated with entities worth protecting as ends in and of themselves) | Defined negatively as noninstrumental value; Value of something that is an end in itself, has agency; Objective value or value independent of being valued or recognized by (human) valuer—inherent properties of something; Regardless of importance or usefulness to humans; Inherent moral value of natural beings (right to exist) | Not observed in literature |
| Relational | Values of meaningful and often reciprocal human relationships—beyond means to an end—with nature (often specified as a particular landscape, place, species, forest, etc.) or society, and among people through nature or society | Values of or deriving from desirable, meaningful, just and reciprocal relationships with “nature” or between people through nature; Values relative to or deriving from relationships that are constituent parts of identity (cultural, individual or collective); Values relative to or deriving from relationships that are constituent elements for living a “good life”; Values associated with sense of place, including interconnection of cultural and sacred landscapes; Values associated with care for or about specific landscapes, places, human and other-than-humans; Value of nature as a point of connection among people, binding communities together and supporting social networks, such as in traditional markets | NA |

# Valuation methods

Decision analysis methods from XXX. Preference elicitation methods are taken from Arias-Arevalo (20XX) and adapted to apply to Earth science information.

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| Category | Method | Description | Notes/indicators | Examples in included corpus |
| --- | --- | --- | --- | --- |
| Decision analysis (quantitative) | Bayesian Decision Analysis | Information is used to update a decision-maker’s prior beliefs about potential outcomes, generally to reduce uncertainty and/or variance in expected outcome.  Accounts for decision-maker’s prior beliefs about the quality of information. | Explicit comparison to counterfactual, often in the form of a payoff matrix.  Decisionmaker/stakeholder subjective beliefs about probabilities of outcomes and quality of information are explicitly accounted for. | Brathwaite and Saleh 2013, Bouma et al. 2011, Luseno et al. 2003 |
| NA | Value of Information | Subset of Bayesian Decision Analysis. Compares expected/realized value of outcome with ESI vs counterfactual. Decision-maker’s prior beliefs not addressed. | Explicit comparison to counterfactual, often in the form of a payoff matrix.  Decisionmaker/stakeholder subjective beliefs about probabilities of outcomes and quality of information are not accounted for. | Macauley 2006 |
| NA | Cost-benefit analysis | Compares expected/realized value of outcome with new information to the cost of obtaining that information (implicit counterfactual is outcome with existing information, or other source new info/cost of new info).  Flows of benefits and costs over time are expressed on a common basis in terms of their net present value. | Expected benefit minus cost of acquiring information to improve decision context.  Counterfactual is often implicit (i.e., business as usual - don’t invest in new information).  Flows of benefits and costs over time are expressed on a common basis in terms of net present value. | Li et a. 2017, Vuolo et al. 2015 |
| NA | NA | For our purposes, the cost must be related to the cost of obtaining information, not the costs of implementing a program/decision. Benefits can be *avoided costs* e.g., use of ESI helps avoid loss of crop profits | NA | NA |
| NA | Real options analysis | Real options value based on the right, but not obligation, to act in the future based on resolution of uncertain outcomes. | Difference in value is determined by the difference in expected outcome between acting now with high uncertainty, or maintaining the option to wait for uncertainty to be resolved before acting. | Cooke and Golub 2020, Fuss et al. 2006 |
| NA | Econometric analysis | Information is included in econometric analysis as an independent/predictor variable; its effect on outcome variable (monetary or other benefit) is used to determine value of information | Explicit inclusion of information state(s) in econometric analysis as categorical or continuous variable. | Bridges et al. 2018, Diana and Farida 2021 |
| Monetary valuation methods (quantitative) | Market price-based methods | Uses prices of ES traded in markets (e.g., water, timber) as a proxy for its monetary value | Purchase of commercial ESI e.g., commercial satellite data, market price sets floor for expected value to buyer, as it is at or below buyer’s willingness to pay.. | NA |
| NA | Market cost-based methods | Estimate the costs that are averted due to the ES functioning: costs of replacing an ES (e.g. waste treatment) or mitigating environmental damage (e.g. natural hazard mitigation by forests). The production function estimates how much an ES contributes to the delivery of a marketed good | Market cost generally applied to replacement of lost ecosystem services or avoided damages; information used to avoid damage or loss of ES would indicate a decision analysis method. | NA |
| NA | Stated preference (contingent valuation; choice modeling) | Constructs hypothetical markets and asks about willingness to pay (WTP) to obtain a specified ESI, or willingness to accept (WTA) giving it up. Choice modelling infers WTP through trade-offs incurred when choosing between alternatives with different levels of ESI and costs | Questionnaire/survey asking about monetary preferences/willness to pay - i.e., a simulated market price. | NA |
| NA | NA | NA | Respondent selects sets of price/quality at which they would purchase ESI. | NA |
| NA | Revealed preference (travel cost; hedonic pricing) | Travel cost method analyses individual choices in markets related to ES. Travel cost methods use the costs of travel to a natural area as a measure of the value of recreation | Observations of participant behavior are used to deduce willingness to pay, based on cost of that behavior. | NA |
| NA | NA | Hedonic pricing method reveals the monetary value of ES (e.g. green areas) mainly through house prices | NA | NA |
| NA | Benefit transfer | Estimates the monetary value of an ES by transferring a measure estimated in a similar context | Value of ESI estimated for one context is applied to a new context, based on contextual similarities. | NA |
| Monetary valuation methods - Mixed (quantitative and qualitative) | Economic field experiments | Experiments developed in naturally-occurring settings aimed at analysing behaviour and decision making (e.g. choices influenced by reciprocity, norms, altruism and uncertainty) | NA | NA |
| NA | Deliberative economic valuation | Combines stated preference valuation methods with elements of deliberative processes | NA | NA |
| Non-monetary valuation methods (quantitative) | Surveys of preference assessments | Surveys aiming to rank or rate preferences for ESI. Used to analyse perceptions, knowledge and values of ESI demand/use | NA | NA |
| NA | Photo-elicitation surveys | Visual elements (e.g. photographs, pictures) are included in surveys to assess individuals’ perception of ESI values and preferences towards landscape views | NA | NA |
| NA | Time use surveys | Captures individuals’ willingness to give up time (WTT) for activities that promote ES maintenance | NA | NA |
| NA | Psychometric surveys | Elicits data on individual attitudes, views, reported behaviour, motivations and values towards ESI | NA | NA |
| Non-monetary valuation methods - mixed (qualitative and quantitative) | Delphi Method | Uses expert opinion to reach an agreed conclusion. It may involve quantitative and qualitative assessments | NA | NA |
| NA | Q Methodology | Analyses subjectivity (i.e. attitudes, shared perceptions and worldviews) through individual ranking of statements. Common worldviews are elucidated through factor analysis | NA | NA |
| Non-monetary valuation methods (qualitative) | Semi-structured and in-depth interviews | In-depth interviews capture how people value or understand something. In a semi-structured interview, the researcher orients the conversation to specific topics | NA | NA |
| NA | Participatory observation | The researcher gets involved with people in their natural environment. Aimed at analysing people’s cultural behaviours and interactions | NA | NA |
| NA | Participant diaries | Participants are asked to make regular records or narrative descriptions of personal experiences. Aimed at exploring thoughts, feelings and understandings of a topic of interest to the research | NA | NA |
| NA | Photo-voice | Stakeholders take their own photographs of different features of ecosystems and landscapes (e.g. ES). Useful to integrate the perceptions of marginalised social groups | NA | NA |
| NA | Focus groups | An externally-guided group discussion about a topic. Aimed at discovering different positions and to explore how participants interact in discussion | NA | NA |
| Non-monetary valuation methods - deliberative | Citizen juries | Groups of representative citizens – randomly chosen - act as jurors to consider issues of public importance | NA | NA |
| NA | Deliberative focus groups | Similar to focus groups, but may have more than one reunion, and have an emphasis on consensus and collective decision | NA | NA |
| NA | Participant action research | People work collaboratively with researchers in knowledge co-production. Aimed at finding solutions to problems of common interest | NA | NA |
| NA | Participatory rural appraisal; rapid rural appraisal | Promotes local knowledge and enables local people to make their own appraisals, analysis and plans | NA | NA |
| NA | Participatory scenario planning | A tool for analysing future prospects of change in ES and its trade-offs. Involves the participatory identification of storylines, drivers of change, uncertainties and scenario outcomes | NA | NA |
| NA | Mediated modelling | Combines dynamic system modelling with stakeholder participation, aimed at creating a shared model of alternative outcomes | NA | NA |
| NA | Deliberative mapping | Stakeholders create a map via consensus, indicating valuable ES and landscape futures | NA | NA |

# Methods details

## Search string

Consolidated search term (January 26 2024) included several broad topics: Earth science information; a decision context or value analysis; and some notion of societal benefit. Each of these broad topics was encoded as a collection of related terms joined by OR logic to maximize inclusivity within the topic; then the three topics were joined using AND logic to identify papers at the intersection of the three broad topics.

* Earth science information terms:
  + (*“satellite” OR “space-based” OR “remote observation” OR “remote sensing” OR “earth observation”* OR \_\_“remotely sens\*” OR “MODIS” OR “Landsat”\_\_ OR ***“GRACE” OR “SRTM” OR “Sentinel” OR “VIIRS” OR “TERRA” OR “CLARREO”***)
* Decision context terms:
  + (*“decision” OR “optimization” OR “risk analysis” OR “management” OR “policy”* OR **“cost benefit analysis” OR “benefit cost analysis” OR “investment” OR “contingent valuation” OR “counterfactual”** OR ***“value chain analysis” OR “multi\* criteria analysis” OR “multi\* criteria decision analysis” OR “planning” OR “governance” OR “prioritization” OR “impact assessment” OR “impact evaluation” OR “willingness to pay”***)
* Societal benefit terms:
  + (*“value\*” OR “valuation” OR “benefit\*”* OR **“utility”**) AND (*“social” OR “societal” OR “cultural” OR “\*economic”* OR **“environmental” OR “ecosystem service” OR “sustainable development” OR “protected area” OR “heritage site” OR “non use value” OR “capacity building” OR “disaster” OR “water resource\*” OR “climate resilience” OR “air quality” OR “conservation” OR “wildland fire\*” OR “wildfire”** OR ***“empower\*” OR “power structure\*” OR “justice” OR “equit\*” OR “financial” OR “monetary” OR “health” OR “well-being” OR “livelihood” OR “community-\*” OR “inspiration\*” OR “educat\*” OR “arts” OR “familial” OR “spiritual” OR “religious”***)

## Screening process

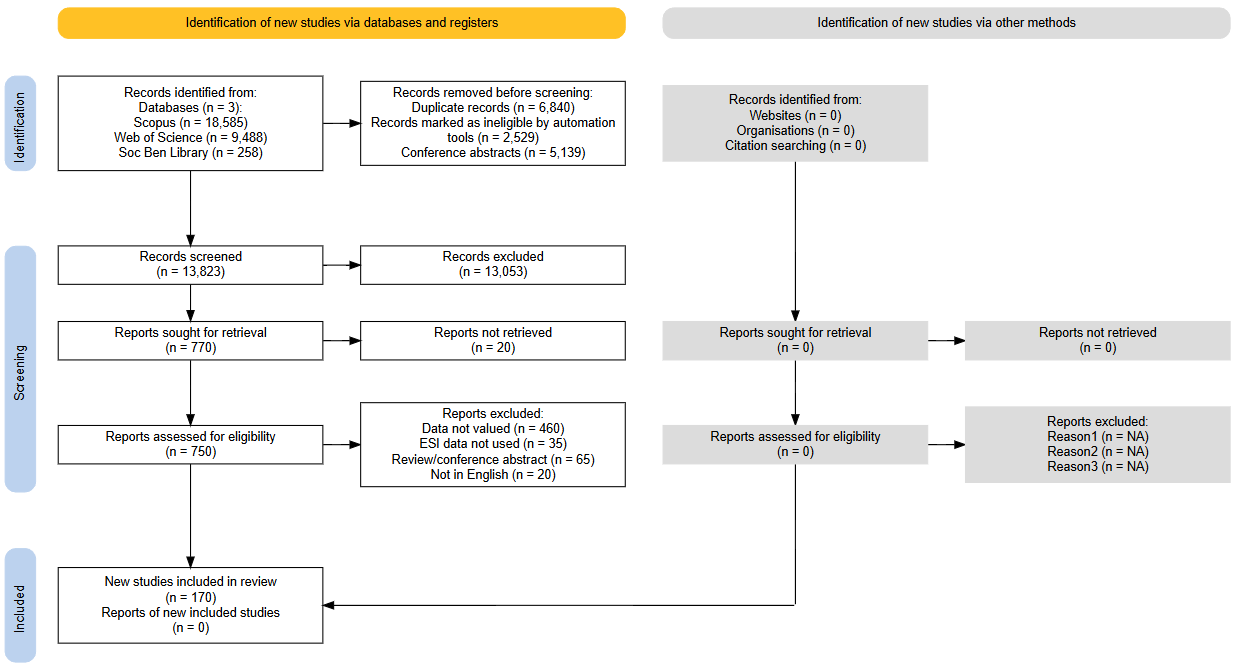


Fig. SXXX. PRISMA flow diagram. Created using https://estech.shinyapps.io/prisma\_flowdiagram/

## Preliminary screening of spurious matches

An early examination of search results showed that many of the ESI-focused terms resulted in spurious matches, since many of those terms on their own have alternate meanings unrelated to ESI. For example, “satellite” is used to describe sub-nodes in networks such as libraries or medical clinics; in medical research, “sentinel” (relating to the ESA’s Copernicus mission) can refer to lymph nodes and cells observed for early detection of cancers; and “terra” (relating to one of two satellites equipped with MODIS sensors) can be paired with “preta” to describe the carbon-rich black soil found in indigenous regions of the Amazon. To eliminate some of the most common instances of these spurious matches, we identified a set of terms to be excluded using regular expressions for flexibility; if these terms were removed from titles/abstracts and no other terms in the title or abstract matched other ESI-related terms, then that document would be excluded from further consideration.

* “Satellite” terms:
  + ‘satellite’ plus any of: ‘account’, ‘office’, ‘laborator(y|ies)’, ‘campus’, ‘([a-z]+.)?clinic’, ‘([a-z]+.)?hospital’, ‘([a-z]+.)?cent(er|re)’, ‘lesion’, ‘nodule’, ‘mass’, ‘h(a)?emodialysis’
* “Sentinel” terms (relating to the Sentinel satellites of ESA’s Copernicus programme):
  + ‘sentinel’ plus any of: ‘study’, ‘(lymph.)?node’, ‘site’, ‘([a-z]+.)?surveillance’, ‘species’, ‘behavior’, ‘catalyst’, ‘event’
* “Grace” terms (relating to NASA/JPL Gravity Recovery and Climate Experiment mission):
  + ‘grace.period’
* “Terra” terms (relating to NASA’s Terra MODIS satellite):
  + ‘Terra’ plus one of: ‘preta’, ‘nova’, ‘firme’, ‘nullius’
* Health terms that frequently showed up in spurious matches:
  + Any of ‘cancer’, ‘cardiac’, ‘cardio’

## Screening criteria

Exclusion criteria used in the citation screening (title + abstract) and full text phases: ESI data are not used: No relation to Earth science information. For example, spurious matches related to health care remote observation. Related to satellites but not related to information about Earth’s systems. For example, documents relating to space weather, solar or lunar information, or communications/navigation satellites. Data are not valued ESI data are used to determine some scientific finding, but the scientific finding is not used to inform a specific societal decision or otherwise valued. For example, ESI data used to estimate changes in ecosystem service value over time, but the resulting ecosystem service value is not used to inform any management decisions within the paper. Valued data is not ESI Valuation methods are used in the paper, but applied to data or information other than the ESI. For example, a study that applies a new classification algorithm to the same underlying data; in this case, the additional value is attributable to the algorithm rather than the underlying data. Review/opinion Document is a review or opinion piece and does not provide new analysis or new frameworks for valuation. Conference abstract/proceedings Document is a conference abstract or proceeding describing presentations rather than published work Validation/calibration A special case of “Data is not valued” - ESI data are used to generate scientific information, and this information is compared to some reference to demonstrate scientific value; however, this scientific value is not then translated into societal benefit. For example, NDVI data is used to estimate land cover, and this result is compared to some alternate information source and shown to be an adequate or even superior proxy. However, the resulting information is not used to inform a management decision that would result in some societal benefit.