PNAS

A Systematic Map of Methods for Assessing Societal Benefits of Earth Science Information

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Short Title: Assessing Societal Benefits of Earth Science Information

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Keywords: satellite, remote sensing, value of information, societal benefit

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Abstract

Remotely sensed Earth science information (ESI) has become increasingly central to addressing global challenges, yet its societal value, i.e., the difference ESI makes in real-world decisions and outcomes, is rarely quantified. In this study, we systematically map peer-reviewed literature that explicitly assesses the societal value of ESI across instrumental, intrinsic, and relational value types, and the diversity of approaches used to assess those values. Drawing from 13,823 publications across Scopus, Web of Science, and a curated library of ESI valuation studies, we identify 171 studies that applied ESI in a decision context and used a valuation method to compare outcomes with and without ESI. The majority of these studies employed decision analysis methods such as Value of Information and Cost-Benefit Analysis, focusing primarily on quantitative instrumental values (e.g., profit, crop yield, lives saved), particularly in agricultural contexts. Studies that applied preference elicitation methods including stated preference, surveys, interviews, and focus groups were able to capture qualitative benefits and relational values including quality of life improvements, empowerment, and procedural justice. By building on a solid foundation of methods and philosophy for valuation of ecosystem services and nature, we aim to expand our understanding of the societal benefits of ESI to help guide investment in future missions, enhance public support, and ensure that science and policy goals are well aligned.

Significance statement

Earth science information (ESI) from satellites and other remote sensing technologies is critical for managing climate, agriculture, disasters, and more. Yet the societal value of ESI, how it improves real-world decisions and outcomes, remains poorly understood. We systematically map studies that quantify this value, revealing how different methods capture diverse benefits, from economic efficiency and lives saved to empowerment and justice. Our findings demonstrate that a rich array of methods exists to assess societal benefits of ESI across many decision contexts, identifying benefits in terms of instrumental and relational values. This synthesis expands the evidence base for why ESI matters and how it can help guide future investments, promote public support, and align Earth science with societal goals.

Main Text

Introduction

In recent decades, remotely sensed information about the state of our planet has become increasingly vital for understanding and addressing global challenges such as climate change, water resource management, biodiversity conservation, sustainable development, and public health (4). Rapid technological progress has led to widespread availability of Earth science information (ESI), comprising global or regional datasets from remote sensing (e.g., satellite hyperspectral imagery, aerial drone photography, in-situ sensor networks) as well as models founded on such data (e.g., climate forecast models, famine early warning systems), at increasingly detailed and nearly continuous spatial and temporal coverage of the planet's surface (5). These advances in the availability and sophistication of ESI have accelerated its application across a wide range of decision contexts (6), supporting societal benefits as varied as impeding transmission of polio in Nigeria (7), protecting blue whales in the Eastern Pacific (8), improving targeting of cash transfers to poor villages in sub-Saharan Africa (9, 10), and empowering Indigenous communities to monitor deforestation (11). While the contribution of ESI to such societal benefits is undeniable, the magnitude of this contribution is rarely assessed. Yet if we don't understand the value of ESI, we risk underinvesting in information essential for protecting or enhancing our quality of life.

The gap in valuation of ESI is due in part to the separation of Earth system science from social and decision sciences, and further compounded by a lack of information-valuation frameworks that integrate different value types (e.g., instrumental vs. intrinsic). Understanding the breadth and magnitude of societal benefit of ESI, i.e., the value of practical application to socially desirable outcomes that goes beyond scientific merit (1), is important for guiding development of information that is actionable, meaningful, and credible for society's needs, thereby justifying investment in future missions, garnering public support, fostering ESI uptake, and ensuring that science and policy goals are well aligned.

Inclusive and pluralistic value systems have long been a topic of discussion in conservation science and sustainable development (e.g., (12–15)). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Values Assessment (16), a multi-year effort by scores of experts in diverse forms of valuation, identified three categories of value that reflect the ways in which nature and ecosystems are important for people: instrumental value as a means to satisfying specific human needs or interests, e.g., more revenue, higher crop yield, better health outcomes; intrinsic value independent of reference to people as valuers, e.g., the right of a whale to exist without regards to human preferences; and relational value deriving from meaningful and often reciprocal human relationships beyond means to an end, e.g., connection with a sacred landscape, a sense of responsibility toward one's community (17) (Table S1). While the IPBES framework focused on value types in the context of nature, we can expand these considerations to examine values related to our relationship with both natural and social systems as observed through ESI-informed decision outcomes. Failing to capture potential gains related to non-instrumental values will greatly underestimate the contribution of ESI to societal benefits.

The mechanism by which ESI, indeed any information, generates societal value is through its ability to improve decision making toward socially desirable outcomes. It does this by aiding in the scoping of decision contexts and assessing alternatives, thus reducing the likelihood of making decisions that result in undesireable outcomes. Note that this indicates that information, when put to use, by definition has instrumental value, and information can have intrinsic scientific value, whether used or not. But the focus of our study is not on the nature of information itself, but rather on the societal benefits that arise from the use of ESI in decision contexts, i.e., the value of the decision outcome, whether that is expressed in instrumental, relational, or intrinsic terms.

Economic frameworks to quantify the value of information typically calculate the difference in expected outcome of a decision made in a world with, versus without, the information (e.g., (18)). Such decision analysis methods have played a critical role in demonstrating ESI's potential to improve instrumental societal outcomes with instrumental values (i.e., means to an end, such as improved profits or crop yields) (19, 20). Value of information models based on decision analysis are well-suited to measuring socially desirable outcomes in terms of instrumental value, but these models are not sufficient to capture the ways in which ESI can contribute to intrinsic and relational values such as sustainability, justice, and human well-being (21). Other valuation methods can account for instrumental and non-instrumental values alike by eliciting individual and societal preferences for goods and services through quantitative, qualitative, and mixed-methods approaches (e.g., market price, stated/revealed preference, surveys, interviews, focus groups) (22). While these methods are commonly used for valuation of goods and services, they can also be leveraged to estimate the value of information in cases where they are used to account for the value of the differential outcome between a decision made with ESI relative to the decision made without.

In this study, we ask four questions: (1) To what degree have various valuation methods been used to evaluate the societal value of ESI? (2) Which types of value (instrumental, intrinsic, relational) do these methods capture, and how are these values articulated? (3) How is the application of various valuation methods distributed across sectors and decision contexts? And finally, (4) what opportunities exist to develop more inclusive, systematic, and interdisciplinary approaches to ESI valuation? Here we present a systematic map of the peer-reviewed literature to identify studies in which a valuation method was used to compare the result of a decision supported by ESI to the result supported by some alternate information source. Through this systematic map of the peer-reviewed literature across a wide range of disciplines, we clarify the current landscape of ESI valuation, identify methodological and disciplinary gaps, highlight emerging practices, and point toward a more pluralistic and actionable valuation framework. Understanding and improving the way we value information will promote investments in Earth observations that not only expand scientific understanding but also deliver equitable and measurable benefits across diverse communities and decision contexts.

Results

Screening Process

Application of the search string (see SI Methods and Fig. S1) to Scopus and Web of Science databases, combined with references from an existing curated library of ESI valuation literature (Societal Benefits Library, SBL) (not available online at time of publication), yielded 28,331 records. Pre-screening eliminated conference abstracts, spurious matches, duplicates, and incomplete records, narrowing the corpus to 13,823 unique citations (Fig. 1, Fig. S2). The unique citations were then screened according to the following criteria: 1) the study made substantive use of ESI; 2) ESI was applied in a decision context; 3) the predicted or realized outcome of an ESI-based decision was compared to that under an alternative information set; and 4) the difference in outcome was presented in terms of some societal benefit. Reviews were excluded as they do not present original data. After pre-screening, the full SBL and an additional 1,072 randomly-sampled documents were manually screened by the team and used as a training set to inform a machine-learning classifier model on the remaining 12,493 citations, resulting in 2,287 predicted “includes” and 10,206 predicted “excludes.” All predicted “includes” and a random sample of 200 predicted “excludes” then went through a title/abstract screening process. Of the 13,823 unique citations, 770 documents sufficiently met the title/abstract screening and were included in full text screening. Full text screening resulted in 170 documents that met all criteria (Fig. 1, Fig. S2), to which one more document was added based on prior knowledge of a coauthor (not shown in Fig. 1). All title/abstract screening was performed in the Colandr web-based machine-learning assisted screening app (23). Full text screening was performed using Zotero reference management software. The final list of 171 documents included in our study is listed in the supporting information (Table S3).

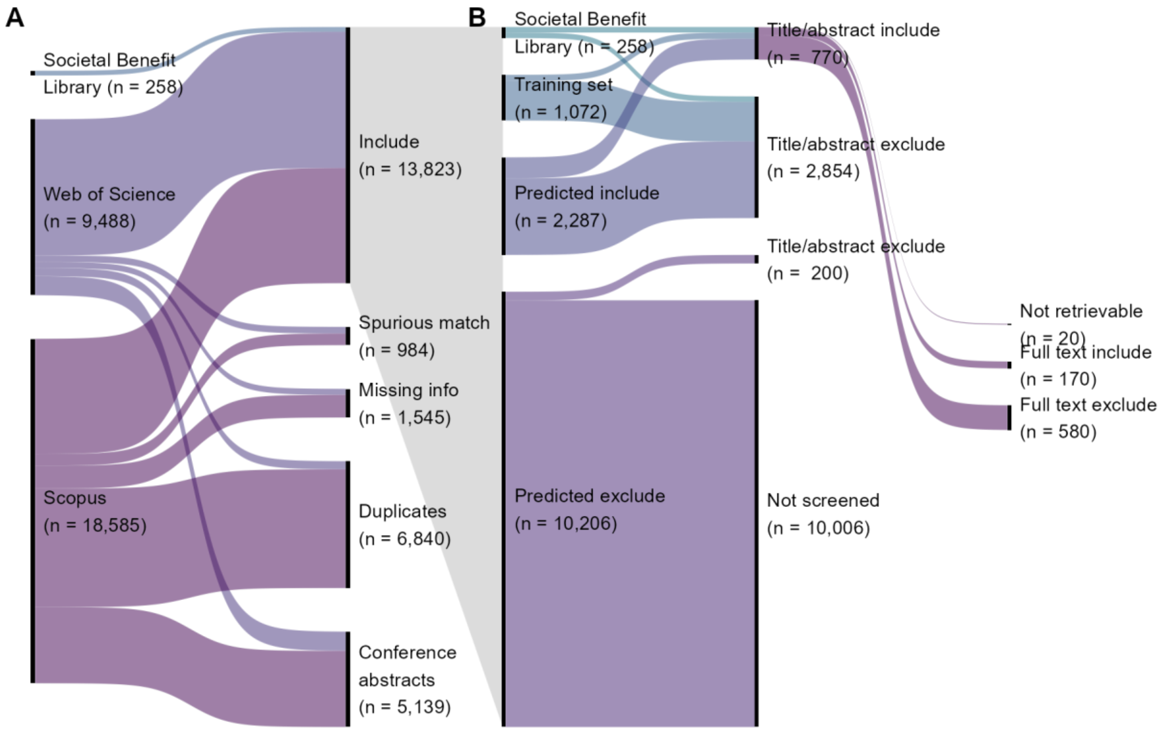

Figure 1. Citation retrieval, pre-screening, and screening results. A. Retrieval and pre-screening process and disposition of included and excluded records. Following pre-screening, n = 13,823 documents proceeded to title/abstract screening stage. B. Title/abstract screening and full text screening process and disposition of included and excluded documents. Following title/abstract and full text screening, n = 170 documents were included in our analysis. Based on expert knowledge, one additional document was added manually (not shown), resulting in a final corpus of n = 171 documents.

Valuation Methods

Nearly a third (56 studies) of the 171 included documents applied more than one information valuation method, with a total of 227 instances of valuation methods being observed (Fig. 2; see Table S2 for operational definitions used to categorize valuation methods). The most common approaches to assessing societal benefits of ESI in the literature were quantitative economic approaches grounded in decision analysis: Value of Information (VOI) framework (n = 82; 48% of papers) and Cost-Benefit Analysis (CBA) (n = 33; 19%) (Fig. 2). Applied qualitative or subjective methods were also frequently observed, including surveys of preference assessments (n = 26; 15%) and semi-structured or in-depth interviews (n = 23; 13%). Deliberative and consensus-based approaches were rare (n = 3 and 1 studies, respectively). Methods based on decision analysis (n = 144) were more frequently observed than methods based on preference elicitation (n = 80) (See Table S2 for categorization of methods as decision analysis vs. preference elicitation).

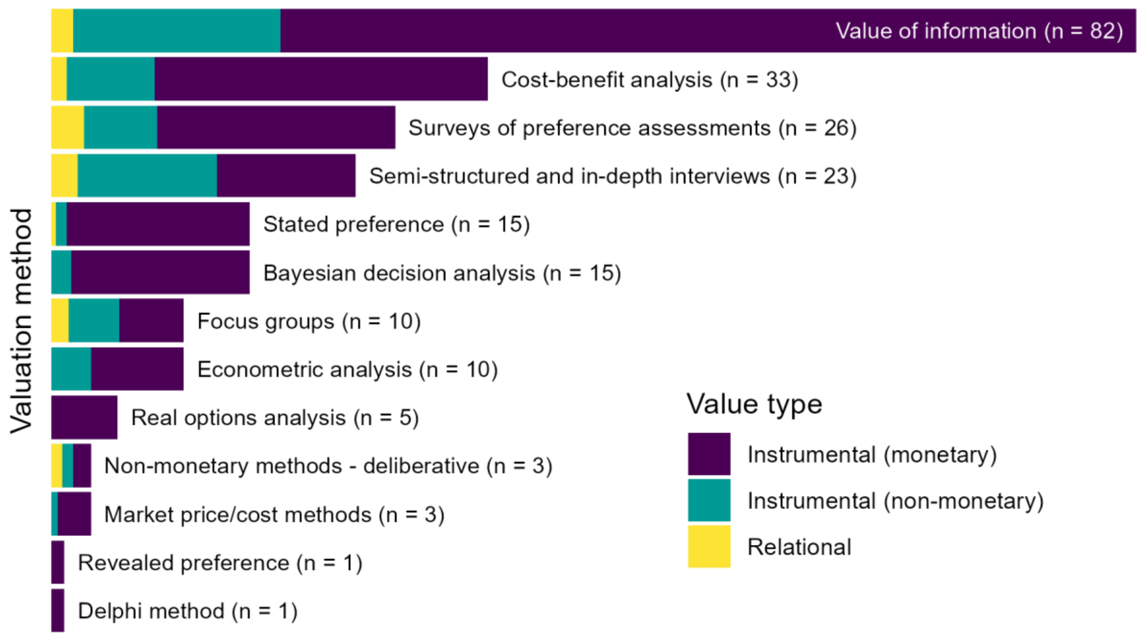

Figure 2. Number of valuation methods observed across included studies. Some studies applied multiple methods for valuation, thus the total number of observed methods (227) exceeds the total number of included studies (171). Color indicates value types assessed: instrumental, i.e., means to an end, including both monetary and non-monetary outcomes, and relational, i.e., deriving from meaningful and often reciprocal relationships among people, nature, and society (see Table S1).

Included studies most commonly measured societal benefits in terms of monetary instrumental value (e.g., improved profit) (n = 154) and/or non-monetary instrumental value (e.g., pollution reduction, lives saved) (n = 63), with many studies accounting for multiple instrumental metrics simultaneously (e.g., reduced crop pesticide application and the associated increase in profit; see Table S1 for definitions and examples). Studies that measured societal benefits in terms of relational value (e.g., connection with land, poverty alleviation, social justice, knowledge transfer among community, Table S1) were far less common in the literature (n = 17) and were more frequently assessed using qualitative preference elicitation methods, especially surveys, interviews, and focus groups. Studies rarely focused exclusively on outcomes associated with relational value, but typically examined relational value alongside instrumental value; for example, recreational fishing both as a pastime and as an economic activity (24). No papers in our study described decision outcomes in intrinsic terms such as the moral right of non-human species to exist in peace; one paper (8) examined potential for ESI to inform regulation to reduce fatal ship strikes of blue whales, but the authors focused on decision outcomes based on compliance with conservation policy, an instrumental goal.

Most studies in our corpus (n = 115) applied only a single method for valuing ESI. Studies that we identified as implementing multiple methods (n = 56) most commonly combined two decision analysis-based methods, particularly VOI with CBA (n = 12 of the 56 studies) (Fig. 3). For example, Fritz et al. (2) applied the counterfactual framework of VOI to estimate benefit, then modeled marginal cost based on CBA to construct their benefit chain model for valuing ESI from hypothetical satellite remote sensing data. Another common pairing combined preference elicitation methods of individual interviews and focus groups (n = 8). For example, Roberts et al. (25) used focus groups/workshops to qualitatively predict the value of weather forecast information for avoiding storm-related drownings in Lake Victoria, then after implementation of a severe weather warning system, followed with user interviews to quantify the realized benefits in lives saved. Of the remaining 36 multiple-method studies, 15 combined VOI with some other method (beyond CBA) and 16 combined surveys with some other method (beyond VOI). Paired decision analysis-based methods were more common (n = 22) than paired preference elicitation-based (n = 18), but 16 studies combined preference elicitation methods (mostly surveys) with decision analysis methods.

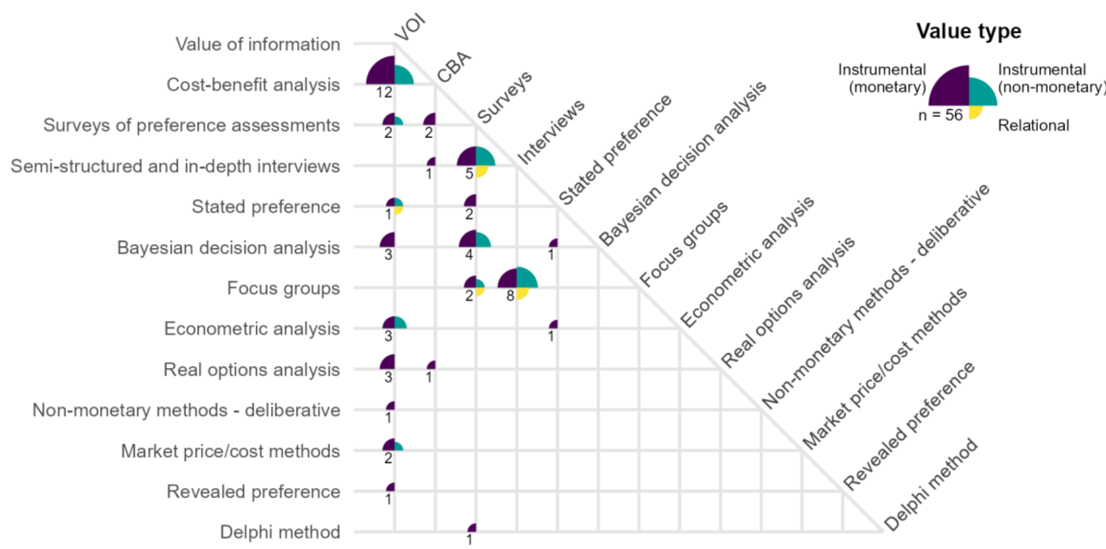

Figure 3. Number of papers applying multiple approaches to valuing ESI. The quadrants and colors at each intersection indicate which value types were examined; the size of the quadrants indicate proportion of papers that examined each value type. The number in the bottom left quadrant indicates the total number of papers that implemented the combination of methods. The majority of papers (115 out of 170) applied only a single method.

Societal Benefit Context Areas

For each of the 171 included studies, we categorized societal benefits into eight general decision context areas, based on existing classes from GEOSS Societal Benefit Areas and NASA Applied Sciences themes (REFS) (Fig. 4). Across the 171 included studies we observed societal benefits in 216 specific decision contexts (i.e., 45 studies examined societal benefits in more than one context). Studies largely focused on the societal benefits of ESI within agriculture contexts, including fisheries and forestry (n = 78, 46% of studies) (Fig. 4). A smaller but still substantial number of studies examined benefits in context of climate (n = 25, 15%), water resources (n = 23, 13%), and ecological conservation (n = 22, 13%). Societal benefits were least frequently examined in contexts of disaster response (n = 9, 5%), health and air quality (n = 8, 5%), and wildfires (n = 6, 4%). Some studies did not focus deeply on any particular context but rather broadly across various or undifferentiated contexts ("various," n = 27, 16%), for example, the value of an ocean observing network across many potential ocean uses (26) or the value of Landsat data that did not differentiate among user contexts (27). Two studies focused on ESI benefits in other areas ("other"):

one for monitoring pavement infrastructure (28), and one for assessing preferences for living and recreating in disturbed landscapes (29).

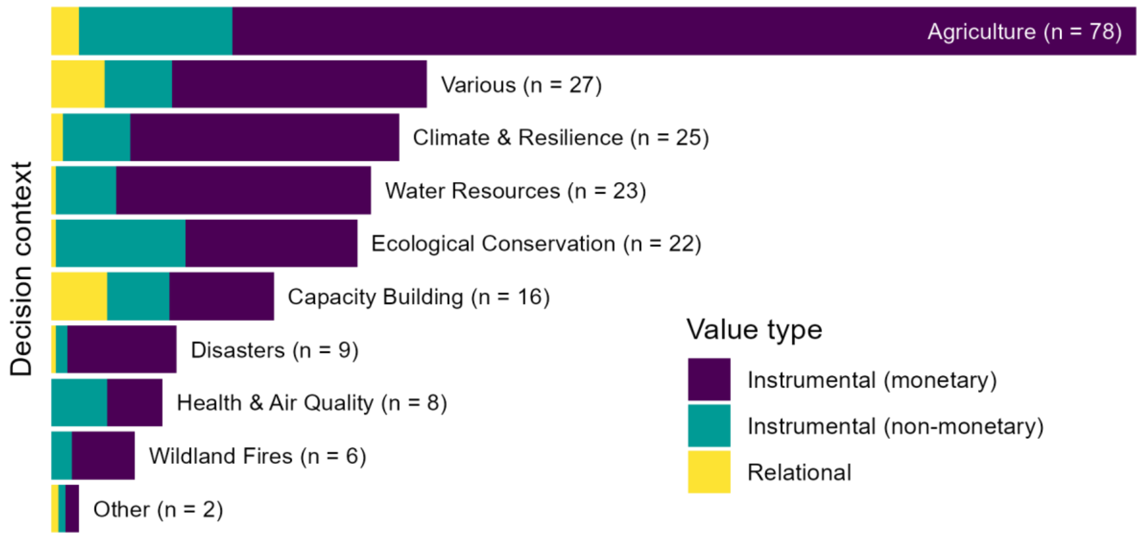

Figure 4. Number of studies investigating value of information in general decision context areas. Some studies examined more than one decision context, thus the total number of specific contexts (215) exceeds the total number of included studies (170). The label "various" indicates studies where decision contexts were broad or undifferentiated; "other" indicates studies where the societal benefit did not fit into any of these contexts. Color indicates value types assessed: instrumental, i.e., means to an end, including both monetary and non-monetary outcomes, and relational, i.e., deriving from meaningful and often reciprocal relationships among people, nature, and society (see Table S1).

Studies that valued ESI across multiple decision contexts (n = 45) most frequently examined agricultural impacts alongside water resources (n = 10), climate (n = 8), ecological conservation (n = 4), and capacity building (n = 4) (Fig. 5). Four studies examined capacity building across various contexts, involving training and supporting groups of stakeholders with diverse roles within their communities, e.g., participatory mapping projects in Nepal (30) and Tanzania (31).

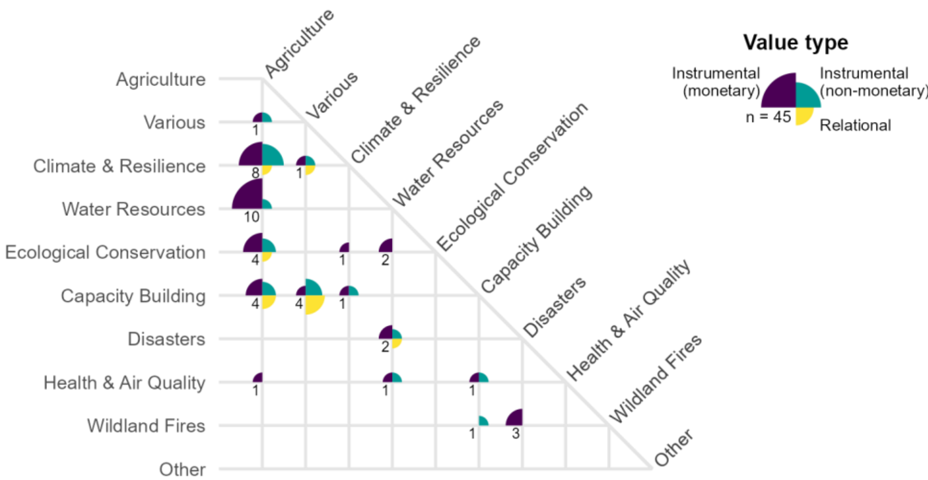

Figure 5. Number of papers valuing ESI in multiple contexts. The quadrants and colors at each intersection indicate which value types were examined; the size of the quadrants indicate how many papers examined that value type. The number in the bottom left quadrant indicates the total number of papers involving that pair of contexts.

Discussion

Despite a broad, inclusive search for research on diverse methods for valuing earth observation information, we found very few examples of evaluations of the societal benefits of ESI. Such a low inclusion rate (1.2%) is not unexpected, as our inclusion criteria are specific to methods of valuing information and data, but our search string was intentionally designed to be inclusive to maximize opportunities to find edge cases in the literature. The paucity of research directly addressing the value of ESI suggests a strong need to better understand how such information is being used to generate societal value, and to identify methods that can effectively assess this value.

The challenge of valuing information, as opposed to valuing goods or services, generally lies in identifying a relevant counterfactual information set as the basis of comparison. The counterfactual can be explicit, such as stated assumptions of outcomes without ESI built into a VOI analysis, or implicit, such as the mental counterfactual a respondent may generate for comparison in a survey or interview. Here we focused only on valuation methods where the resulting value was a function of ESI. In several of the publications we identified, multiple valuation methods were used in sequence to first identify the difference in outcome based on the inclusion of ESI, and then to translate that difference in outcome to some other metric, usually monetary. The first step is clearly dependent upon the availability of the ESI in question (access to ESI generates a difference in outcome); the second step may or may not be, depending on the assumptions of a given study. For example, Späti et al. (32) modeled the effect of variable-rate nitrogen application on crop yield for small-scale farmers based on several spatial resolutions of ESI data; they then valued the increased yield and reduced nitrogen, made possible through the improved resolution, into economic terms (Swiss francs) using market prices. However, the nitrogen and crop prices were treated as fixed, in other words independent of the ESI (a reasonable assumption for a small-scale farmer trading commodities within a global market), and thus this second valuation step was effectively a unit conversion, and not germane to our study. Conversely, Adams et al.

(33) modeled the benefits of an El Niño early warning system for agriculture across five Mexican states, accounting for alternative cropping decisions to optimize yield in the face of seasonal predictions, then translated the resulting crop yield into economic terms using modeled market prices. The difference in crop yield was again a result of access to ESI as in the previous example, but the market model accounted for changes in price due to ESI-driven changes in supply, and therefore this second valuation step was also considered relevant for our study.

Our systematic map shows that VOI methods have been the dominant approach to evaluating societal benefits derived from using ESI for decision support (Fig. 2). VOI is a well-established and intuitive method, and Macaulay (19) described a framework for applying VOI to ESI contexts that continues to influence recent research initiatives (e.g.,(34)). VOI methods are very well suited to situations where a reduction in uncertainty, based on an improved information set, can be expected to drive a clear and measurable improvement in decision outcomes. This is especially the case where costs of a mistake are high, where benefits can be expressed as objective quantities (typically in terms of instrumental value), and where the outcome is highly responsive to the set of actions that can be taken. For these reasons, VOI is particularly suited to agricultural contexts, where an improved seasonal forecast can inform farmers' decisions about crop choices and crop management to maximize yield and profit in the face of uncertainty; this is reflected in the high rates of VOI use in agricultural studies.

Our analysis revealed that CBA, a common method for estimating the net present value of a particular investment decision over an extended time frame, is the second most prevalent method for valuing ESI (Fig. 2). In an information context, this could be considered as the expected net benefit of investment in the infrastructure required to generate ESI, such as aerial drones or satellite instruments, and/or investment in technologies and labor to process ESI. In some identified studies, CBA and VOI were used in tandem (Fig. 3): the benefits of ESI are estimated using a VOI framework, while the costs of ESI are drawn from actual or projected budgets for producing the ESI. Use of CBA in valuation of ESI is most commonly observed in agriculture and conservation contexts, and like VOI, is focused primarily on instrumental value due to its traditionally monetary nature.

Valuation methods based on decision analysis (Table S2) necessarily focus on decision outcomes that can be quantified. However, many decision outcomes valued by individuals and society are impossible to objectively quantify and/or can be qualitatively valued across multiple, potentially incommensurable, value types. Preference elicitation methods (Table S2) can more readily account for qualitative and subjective benefits related to ESI-based decision outcomes in instrumental and non-instrumental terms, including relational value. For example, Altamirano et al. (29) surveyed people's preferences for visiting, living, admiring, and thriving across gradients of landscape disturbance, comparing perceptions of value based on eye-level photos to perceptions based on remote sensing photography. Colloredo-Mansfeld et al. (35), using participatory mapping and in-depth interviews, found that farmers given access to UAV photography perceived their land differently than before, improving relational value through a greater sense of scale and interconnectedness.

In addition to eliciting qualitative and subjective outcomes associated with ESI, preference elicitation methods are well suited to provide insights into the decision process itself, revealing relational values of stewardship, responsibility, and care within a community. For example, Eilola et al. (31) used interviews and focus groups to study how participatory mapping using ESI improved practitioners' perceptions of work quality, professional competence, participation, and spatial understanding. Gonzalez and Kroger (11) used focus groups and interviews to examine how training in and adoption of remote sensing data improved empowerment and agency of Indigenous people in protecting their land from illegal deforestation. Styers (36) surveyed her undergraduate students to gauge how the incorporation of satellite data into her courses improved student engagement, curiosity, collaborative skills, and learning outcomes. In these cases and others, access to and use of ESI improves saliency and legitimacy of decision making processes (37), providing value independent of outcome.

A few studies bridged the divide between decision-analytic methods and preference-elicitation methods (Fig. 3). For example, in several interrelated studies, Bouma et al. (38–41) applied Bayesian decision analysis to quantify societal benefits of ESI for managing water quality, but leveraged surveys of experts to elicit prior beliefs and expectations of accuracy of the ESI to parameterize the Bayesian analysis. Flipping that script, Luseno et al. (42) used a conceptual Bayesian framework to guide the design of surveys and interviews of pastoralists in Ethiopia and Kenya to understand their preferences around ESI-derived climate forecasts, including the pastoralists' prior beliefs based on traditional forecasting methods, trust in ESI forecast skill, and likelihood of using the ESI-based forecasts.

The scientific, political, and commercial structures governing ESI - especially whether datasets are publicly accessible or proprietary, freely available or commercial - in part determine who is likely to benefit from their societal value (43). Clearly, making ESI data freely available enhances the ability to generate societal benefits; for example, citations and downloads surged for Landsat data following the shift from a paid service to a free and open data policy in 2008, ultimately stimulating billions of dollars in scientific and societal benefits (6, 27). Alvarez León and Gleason (44) analyze how varying property rights can reinforce or challenge assumptions of scientific objectivity and ultimately users' ability to translate ESI into scientific and societal value. For example, recent data from the European Space Agency (ESA)'s SPOT (Satellite Pour l'Observation de la Terre) mission is commercially available, and users can request that the sensor can be directed to capture imagery of particular regions of commercial interest. As a result, historical SPOT data (through 2015), while freely available through various portals, are skewed toward scenes that were valuable to commercial users at the time of capture. In contrast, Landsat data of USGS are freely and openly available, and its fixed sensing path avoids bias based on commercial interests (44), although systematic gaps in archival georegional coverage may exist due to technical failures and inconsistent data sharing among cooperating nations (45).

Even freely and openly available satellite data come with barriers to technical expertise and capacity that pose significant hurdles to use for many practitioners (46), and poor integration with ground-based and local knowledge hampers development of machine learning algorithms to translate remote sensing imagery into actionable information (47–49). Capacity building can help local communities and Indigenous peoples access and incorporate ESI to co-produce knowledge across contexts including conservation (e.g., (50)), deforestation (e.g., (11)), marine resource management (e.g., (51, 52), and resilience to climate change (42, 53). Such collaborations can reduce power asymmetries and increase agency and self-governance of communities as they seek to address challenges facing indigenous landscapes and territories (11, 53); however, they can also create internal power divisions between tech adopters and non-adopters, potentially resulting in shifts in or loss of cultural values (11).

Positive societal benefits aided by use of ESI were the focus of most of the studies we identified, but a trade-off between information and privacy becomes increasingly relevant as advancements in the quality and quantity of remote sensing data accelerate the ability to identify and monitor objects and people on the ground. In general, remote sensing allows the observer to shift information asymmetry between the observer and the observed, in favor of the observer. Brennan and Macauley (54) describe several important use cases that determine whether the shift in information asymmetry is potentially beneficial or detrimental to society, based on whether the observer and the observed are state actors or private actors (corporations, groups, individuals) and whether the relationship between observer and observed is adversarial or cooperative. The ability of state actors to monitor and enforce compliance with conservation policy, emissions targets, and peace treaties certainly produces societal benefits by enabling cooperation (55); monitoring also holds promise for reducing international conflict (56), supporting human rights (57), and responding to genocide (58). To the extent that an open, transparent government whose laws and regulations reflect the will of the governed, these information asymmetries may actually promote societal benefits, e.g., reduced crime or pollution (54). However, the risks of abuse loom large, creating a clear tradeoff between the increasing capabilities of remote sensing technology and the privacy rights of the individual.

While most of the papers excluded from our target corpus either did not apply ESI data (e.g., spurious matches that were missed during our preliminary screening), or applied ESI data to calculate some other outcome (e.g., using land cover classification data to estimate ecosystem service value, but no further examination of the value of the ESI itself), two categories of excluded papers merit further consideration. These two categories of studies offer clear opportunities for those interested in evaluating the societal benefits of ESI.

First, a number of papers used cost-effectiveness analysis, a close relative of cost-benefit analysis, to demonstrate that an ESI data set could achieve equal or near-equal performance for a decision context but with less cost (e.g., reduced costs of labor or equipment relative to on-the-ground research) (e.g., (59)). We did not include these in our final corpus, reasoning that if the information itself is essentially identical between the ESI and non-ESI alternative, any outcome of a given decision would necessarily be identical, and therefore no additional marginal societal benefit would result from use of the ESI. We acknowledge that in resource-constrained settings, government or NGO cost savings in one area can closely translate into improved societal outcomes in another (e.g., lowering taxes on lower income people, or increasing budgets for social safety nets), but these indirect benefits were not explicitly examined in any of the papers we screened. While these excluded studies focused on a one-time analysis, reduced costs of labor and/or equipment imply the potential for increased frequency of measurement, which would prove valuable for certain types of decision contexts that involve rapidly changing phenomena, e.g., disaster response or wildfire management. We included several studies that explicitly valued the benefits of higher spatial resolution, though we encountered only one study (60) that explicitly accounted for the value of higher temporal resolution. This suggests an opportunity for future valuation studies, especially in light of trends toward increasingly fine temporal resolution of accessible satellite data.

Second, a larger subset of excluded papers compared the ability of ESI to accurately predict on-the-ground phenomena measured by some other means. For example, Marino (61) examined the potential for Sentinel-2 time series imagery to delineate subfields of sunflower crops and found that the image-based vegetation index provided a good proxy for ground-measured crop status; however, the implications for harvest decisions and resulting societal benefit were not explored. Similarly, Andrada et al. (62) demonstrated the efficacy of a drone-based lidar system for rapidly and accurately mapping potential wildfire fuel for forest management, but the authors did not quantify the societal benefit from this valuable scientific information. Such validation studies typically report accuracy scores, e.g., RMSE or AUC, and generally aim to demonstrate the adequacy or superiority of a particular ESI dataset or algorithm over the alternative approach. Importantly, while these studies presented results in terms of scientific value, they did not examine how the improved scientific knowledge would affect the decisions that generate societal benefits - though most included conceptual descriptions of potential decisions or societal value in their conclusions. With often minor additional information or simple economic modeling, many calibration/validation studies could readily translate the improved scientific accuracy of an ESI dataset relative into a hypothetical or realized decision that could be translated into calculable societal benefits.

Our wide-ranging search string resulted in a large corpus of studies identified as potential candidates for inclusion, but recent developments in machine learning (ML) have made such large screening processes much more feasible. We implemented two distinct ML algorithms in our screening process. First, for all title/abstract screening, we used the Colandr ML-assisted web-based screening tool (23) which uses machine learning and natural language processing to continually predict and sort citations in order of predicted relevance based on user screening decisions. Importantly, Colandr does not decide the disposition of a document - the user is intentionally involved throughout and ultimately makes the decision (23). Second, we generated a training set based on a subset of the full corpus and used this to train an ML algorithm to predict the inclusion/exclusion status of the remaining corpus, identifying nearly 80% of the corpus as likely "excludes." Because this ML process is recommending the disposition of documents, a low false negative rate (low chance of excluding a relevant document) is critical, though false positives are less problematic, as they are subject to additional human screening. Because our systematic map focused not on study questions or results (typically foregrounded in the title and abstract) but rather on methods (which are often described only vaguely if at all in the abstract), it was difficult to tune the ML model to reduce the false positive rate; however, for studies focused on top-line results typically described in the abstract, such ML methods would likely be far more discerning. Increasingly sophisticated ML algorithms and AI tools such as Elicit, OpenAI Deep Research, and SciSpace Deep Review will almost certainly accelerate rapid systematic evidence synthesis, though the threat of a flood of AI-generated fraudulent literature may drive an arms race in how such reviews are conducted (63).

While our literature search was broad, we restricted it to two databases of academic peer-reviewed literature (Scopus and Web of Science) and the Societal Benefits Library and did not systematically search grey literature sources. Of the 770 documents identified as candidates for full-text screening, 10 were not retrievable, and 20 more were excluded as not in English; while exclusion of non-English sources could potentially lead to bias, this subset is a tiny fraction of the retrieved papers (2.6%) so omitting these studies is unlikely to substantially affect our results. We note that many ESI applications may rely on highly derived, modeled, or processed data, such that remote-sensing terms (e.g., "satellite") or the name of the initial sensor (e.g., "Landsat") do not appear in the title, abstract, or keywords, which may limit the citations in our corpus; however, generalizing the search by excluding the ESI terms from the search string would have made the search impossibly large.

Conclusion

As technological advances increase the cost-effectiveness and capacity for acquisition, storage, and processing of satellite imagery and remote sensing data, ESI will further proliferate in decision support contexts. For example, Canada's WildfireSat constellation of mission-specific microsatellites, slated to launch in 2029, will image the entirety of Canada in near real time to inform wildfire management, potentially saving billions of dollars in avoided damages as wildfire regimes become increasingly extreme (64). Examining the societal benefits of Earth observation is important to justify existing and future investment (19), promote diffusion of use and applications (65), and identify gaps and priorities for future applications and missions (66, 67). Methods exist to evaluate ESI contributions across societal benefit areas and value types. However, even as the use of ESI data has grown to encompass a wide range of applications across the globe (65), published peer reviewed studies that attempt to qualitatively or quantitatively assess these contributions remain rare.

Our systematic map of the literature revealed a large subset of research that demonstrated the scientific value of particular ESI datasets and models but did not proceed to translate this scientific value into explicit societal value. A major impediment to the uptake of valuation methods as applied to ESI may lie in the gap between science and policy. This gap may be attributable in part to lack of in-house social science and policy knowledge to apply valuation methods, and in part to poor engagement between academics and user communities (68).

As technical capabilities of ESI instruments and machine learning models rapidly increase, opportunities to translate raw observations into actionable intelligence will multiply. Progress in measuring the instrumental, social, and relational value of ESI is essential to informing this work so that societies can mitigate risks and derive the greatest possible benefit. Here we have identified concrete examples of qualitative and quantitative valuation methods to measure societal benefits of ESI across a range of decision contexts and value types. By doing so, we hope to inspire other ESI researchers to explore the societal benefit of their own work and contribute to a greater network of valuation practitioners.

Methods

Our analysis of the literature consisted of five major phases (described in detail below): 1) developing a search string; 2) applying the search string to academic databases to acquire a set of citations; 3) screening citations by the title and abstract; 4) screening the full text of papers that passed the title and abstract screening stage using natural language processing and language models; and 5) coding the papers to identify ESI data source, valuation method, societal benefit area, and value type.

To develop a search string (see SI Methods), we focused on three key domains: 1) application of ESI, 2) a decision context or analysis framework in which the ESI is applied, and 3) an expected or observed change in societal benefits based on decision outcome due to use of ESI. The research team collected (via Google Scholar searches) and solicited (via professional networks) a preliminary set of 72 candidate documents, which were screened based on these three domains. Of these 72 candidate documents, 14 were identified as a benchmark set that the research team felt exemplified valuation of ESI. From this benchmark set, we developed a preliminary search string combining the three domains: ESI (e.g., “remote sensing”, “satellite”, “Sentinel”, “Landsat”), decision context (e.g., “management”, “policy”, “cost-benefit”, “contingent valuation”), and societal benefit (e.g., “value”, “benefit”, or “utility” combined with terms such as “societal”, “cultural”, “environmental”, “ecosystem service”, or terms related to GEOSS societal benefit areas). The preliminary set of terms was used to collect citations (title, abstract, authors, metadata) from Web of Science (n = 1,158). We applied the functionality of the litsearchr package in R (69) to this preliminary citation set, using text mining and keyword co-occurrence networks to identify additional terms to increase the inclusion of our search string. The final search string (see SI Methods) was used to collect citations from Web of Science (January 26, 2024, n = 9,488) and Scopus (February 4, 2024, n = 18,585), including all 14 benchmark papers. In addition to these two citation sets we included a curated set of citations from the USGS Joint Societal Benefits of Earth Observation Digital Library (!!!REF USGS 2024) (SBL, n = 258). See Fig. S2 for PRISMA flow diagram.

The results of the search (Web of Science and Scopus) were then cleaned. Citations noted as conference abstracts or proceedings (n = 1,030 and n = 4,109 respectively) were dropped. Then, citations with missing title, author, abstract, or digital object identifier (DOI) field (n = 319 and n = 1,226 respectively) were dropped. After resolving minor differences among titles, author names, and DOI fields, 6,840 duplicate citations were removed from the combined citation set. The resulting set of 14,807 distinct citations were subjected to a preliminary screening to remove known spurious matches (n = 984), leaving n = 13,823 citations for screening and analysis (Fig. 1).

Screening was performed in two stages, the first to label a training set to train a supervised learning classification model, and the second to apply the classification model to predict relevant papers within the larger corpus (Fig. 2). In the first stage, the citations from the SBL and a random sample of ~1000 citations from the Web of Science/Scopus corpus were subjected to title/abstract screening, and then full-text screening on the title/abstract “include” papers, based on a set of inclusion criteria (See SI Methods for screening criteria). All title/abstract screening was performed using the Colandr web-based screening application (23), which uses machine learning and natural language processing to continually predict and sort citations in order of predicted relevance based on user screening decisions. As a user screens documents and codes them as “include” or “exclude,” Colandr develops a predictive model and iteratively sorts the remaining unscreened documents, presenting the user with the most likely relevant documents early. As fewer and fewer relevant documents are identified, and the inclusion rate approaches zero, the user can opt to establish an early-stopping rule as the remainder of the corpus is deemed increasingly irrelevant. For this initial stage, we did not set an early-stopping rule, and simply screened all citations.

The resulting set from the first stage was then used to train a classification model based on the XLNet generalized autoregressive pretraining algorithm, which considers all permutations of dependencies between sets of words in the citation titles and abstracts to “understand” the context (70), to classify citations in the remainder of the corpus as either “include” or “exclude”. The predicted “include” citations were then title/abstract screened (using Colandr) and those that passed were then screened based on the full text. The include/exclude classification model showed a low false negative rate (1.2%, sensitivity 92.3%) on the training data, but to ensure this held true of the larger document set, a random sample of 1000 predicted “excludes” was uploaded to Colandr. After screening 200 of these documents and finding no relevant matches to our screening criteria despite Colandr’s ability to prioritize relevant articles, this screening phase was stopped early. While the classifier’s false positive rate was higher (27.1%, specificity 71.2%), these false positives were subject to title/abstract screening so were not a concern. Of the 13,823 unique citations retrieved from Scopus, Web of Science, and the SBL, our screening process resulted in only n = 170 documents that met all screening criteria for inclusion (see SI Methods) in our corpus, for an inclusion rate of 1.2%. One additional reference was added post-screening, at the recommendation of one of the coauthors, for a final corpus of n = 171 documents.

Documents included in the final corpus were manually coded based on reading the full text to identify valuation methods and value types according to Tables S1 and S2. All analysis and figures were generated using R statistical software version 4.4.1 (71) and the tidyverse metapackage version 2.0.0 (72). All code and data are freely available at https://github.com/convei-wwf/sp1_systematic_map and in a persistent repository at the Knowledge Network for Biocomplexity (KNB DOI TBD).

Author Contributions

Conceptualization: CCO, MBS, RCK, SC, AE, GLG, RKG, CLM, MCM, GS, PB, YK, SP, ADR, RPS, ET, JZ, BSH Methodology: CCO, MBS, SC, RPS, BSH Software: CCO, RPS Validation: CCO, MBS, SC, RKG, MCM Formal analysis: CCO Investigation: CCO Data Curation: CCO, RPS Writing - Original Draft: CCO Writing - Review & Editing: CCO, MBS, RCK, SC, AE, GLG, RKG, CLM, MCM, GS, PB, YK, SP, ADR, RPS, ET, JZ, BSH Visualization: CCO Supervision: RCK, BSH Project administration: MBS, RCK, BSH Funding acquisition: RCK, GLG, RKG, SP, ADR, RPS, BSH

Acknowledgments

This work was supported in part by the National Aeronautics and Space Administration (NASA) (Grant 80NSSC23K0914). It may not necessarily express the views of the funder. This work contributes to the Global Land Programme science plan (https://glp.earth). We thank the National Center for Ecological Analysis and Synthesis (https://nceas.ucsb.edu) for computational support.

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Supporting Information for: A Systematic Map of Methods for Assessing Societal Benefits of Earth Science Information

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List of Supporting Materials

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Value domains

Table S1. This table is based on 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.

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	Reduced polio transmission and reduced health cost due to improved targeting of populations (Borowitz et al. 2023); increased consumer surplus of crops due to improved weather forecasts (Cooke and Golub 2020); avoided losses from improved wildfire suppression (Herr et al. 2020)
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	Inceased agency of Indigenous communities for monitoring and enforcing illegal deforestation (Gonzalez et al. 2023); sense of community and quality of life through common understanding of decision contexts (Sawyer et al. 2022)

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Valuation methods

Table S2. Valuation methods with potential application to valuing Earth science information. Preference elicitation methods are defined in Arias-Arevalo (2018) and adapted to apply to Earth science information.

Category	Method	Description	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.	Brathwaite and Saleh 2013, Bouma et al. 2011, Luseno et al. 2003
	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.	Forney et al. 2012, Herr et al. 2020, Macauley 2006, Oddo and Bolten 2019,
	Cost-benefit analysis	Compares expected/realized value of outcome with new information to the cost of obtaining that information. Flows of benefits and costs over time are expressed on a common basis in terms of their net present value. Benefits can be *avoided costs* e.g., use of ESI helps avoid loss of crop profits	Li et al. 2017, Morretta et al. 2023, Vuolo et al. 2015
	Real options analysis	Real options value based on the right, but not obligation, to act in the future based on resolution of uncertain outcomes.	Cooke and Golub 2020, Fuss et al. 2006
	Econometric analysis	Information is explicitly 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	Bridges et al. 2018, Diana and Farida 2021
Preference elicitation: Monetary valuation methods (quantitative)	Market price-based methods	Uses prices of ESI traded in markets (e.g., commercial satellite imagery) as a proxy for its monetary value	Harris et al. 2000, Hautala et al. 2008
	Market cost-based methods	Estimate the costs that are averted due to the ESI application. The production function estimates the degree to which ESI contributes to the delivery of a marketed good	Stroming et al. 2020
	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	Jabbour et al. 2020, Kim et al. 2022
	Revealed preference (travel cost; hedonic pricing)	Travel cost method analyses individual choices in markets related to ESI. Travel cost methods use the costs of travel to a natural area as a measure of the value of recreation. Hedonic pricing method reveals the monetary value of ESI mainly through house prices	Newbold et al. 2022
	Benefit transfer	Estimates the monetary value of ESI by transferring a measure estimated in a similar context	none found
Preference elicitation: 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)	none found
	Deliberative economic valuation	Combines stated preference valuation methods with elements of deliberative processes	none found
Preference elicitation: 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	Amegnaglo et al. 2022, Diana and Ibrahim 2020, Safar et al. 2022
	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	Altamirano et al. 2020, Colloredo et al. 2020

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Category	Method	Description	Examples in included corpus
	Time use surveys	Captures individuals' willingness to give up time (WTT) for activities that promote ESI production/maintenance	none found
	Psychometric surveys	Elicits data on individual attitudes, views, reported behaviour, motivations and values towards ESI	none found
Preference elicitation: 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	Taramelli et al. 2020
NA	Q Methodology	Analyses subjectivity (i.e. attitudes, shared perceptions and worldviews) through individual ranking of statements. Common worldviews are elucidated through factor analysis	none found
Preference elicitation: 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	Boyd et al. 2022, Bruno Soares 2017, Luseno et al. 2003
	Participatory observation	The researcher gets involved with people in their natural environment. Aimed at analysing people's cultural behaviours and interactions	none found
	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	none found
	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	none found
	Focus groups	An externally-guided group discussion about a topic. Aimed at discovering different positions and to explore how participants interact in discussion	Eilola et al. 2023, Roberts et al. 2022, Sciavon et al. 2023
Preference elicitation: Non-monetary valuation methods - deliberative	Citizen juries	Groups of representative citizens – randomly chosen - act as jurors to consider issues of public importance	none found
	Deliberative focus groups	Similar to focus groups, but may have more than one reunion, and have an emphasis on consensus and collective decision	none found
	Participant action research	People work collaboratively with researchers in knowledge co-production. Aimed at finding solutions to problems of common interest	Seelan et al. 2003, Seielstad et al. 2002
	Participatory rural appraisal; rapid rural appraisal	Promotes local knowledge and enables local people to make their own appraisals, analysis and plans	Parajuli et al. 2020
	Participatory scenario planning	A tool for analysing future prospects of change in ESI and its trade-offs. Involves the participatory identification of storylines, drivers of change, uncertainties and scenario outcomes	none found
	Mediated modelling	Combines dynamic system modelling with stakeholder participation, aimed at creating a shared model of alternative outcomes	none found
	Deliberative mapping	Stakeholders create a map via consensus, indicating valuable ES and landscape futures	none found

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Included papers

Table S3. Corpus of papers included in analysis.

Reference	ESI source	Valuation method(s)	Decision context	Value type(s)
R. M. Adams, et al., The benefits to Mexican agriculture of an El Niño-southern oscillation (ENSO) early warning system. Agricultural and Forest Meteorology 115, 183–194 (2003).	ENSO early warning system (hypothetical)	Value of information; Bayesian decision analysis	Agriculture	Instrumental (monetary)
R. M. Adams, et al., Value of Improved Long-Range Weather Information. Contemporary Economic Policy 13, 10–19 (1995).	ENSO early warning system (hypothetical)	Value of information; Bayesian decision analysis	Agriculture	Instrumental (monetary)
A. Altamirano, et al., Landscape disturbance gradients: The importance of the type of scene when evaluating landscape preferences and perceptions. Land (2020).	aerial images	Surveys of preference assessments	Other	Instrumental (non-monetary); Relational
C. J. Amegnaglo, K. A. Anaman, A. Mensah-Bonsu, E. E. Onumah, F. Amoussouga Gero, Contingent valuation study of the benefits of seasonal climate forecasts for maize farmers in the Republic of Benin, West Africa. Climate Services 6, 1–11 (2017).	Seasonal forecasts (hypothetical)	Stated preference; Surveys of preference assessments	Agriculture	Instrumental (monetary)
R. A. Asiyanbola, An evaluation of public servant awareness and use of gis/remote sensing in africa-nigeria. South African Journal Of Geomatics (2018).	remote sensing (hypothetical)	Surveys of preference assessments	Capacity Building	Instrumental (monetary)
H. Awada, et al., Assessing the performance of a large-scale irrigation system by estimations of actual evapotranspiration obtained by landsat satellite images resampled with cubic convolution. International Journal Of Applied Earth Observation And Geoinformation (2019).	Landsat	Value of information	Agriculture; Water Resources	Instrumental (monetary)
B. A. Babcock, The Value of Weather Information in Market Equilibrium. American J Agri Economics 72, 63–72 (1990).	seasonal forecast (hypothetical)	Value of information; Bayesian decision analysis	Agriculture	Instrumental (monetary)
J. Bacenetti, et al., May smart technologies reduce the environmental impact of nitrogen fertilization? A case study for paddy rice. Science Of The Total Environment (2020).	Sentinel	Value of information	Agriculture; Climate & Resilience	Instrumental (monetary); Instrumental (non-monetary)
J. F. Bard, A. Watkins, Improved rangeland management with an earth resource survey system. Technological Forecasting And Social Change (1983).	Earth Resource Survey system	Value of information; Cost-benefit analysis	Agriculture	Instrumental (monetary); Instrumental (non-monetary)
J. Berenter, I. Morrison, J. M. Mueller, Valuing User Preferences for Geospatial Fire Monitoring in Guatemala. Sustainability 13, 12077 (2021).	SIGMA-I	Stated preference	Wildland Fires	Instrumental (monetary)
E. Bergseng, H. O. Ørka, E. Næsset, T. Gobakken, Assessing forest inventory information obtained from different inventory approaches and remote sensing data sources. Annals Of Forest Science (2015).	airborne laser scanning	Value of information	Agriculture	Instrumental (monetary)
R. Bernknopf, Agricultural case studies for measuring the value of information of earth observation and other geospatial information for decisions. Geovalue: The Socioeconomic Value Of Geospatial Information (2017).	Landsat;MODIS;AWiFS;GRACE	Value of information; Econometric analysis	Agriculture; Water Resources	Instrumental (monetary)
R. L. Bernknopf, W. M. Forney, R. P. Raunikar, S. K. Mishra, Estimating the benefits of land imagery in environmental applications: a case study in nonpoint source pollution of groundwater. The Value Of Information: Methodological Frontiers And New Applications In Environment And Health (2012).	MRLI (Landsat)	Value of information	Water Resources; Agriculture	Instrumental (monetary)

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Reference	ESI source	Valuation method(s)	Decision context	Value type(s)
R. Bernknopf, et al., The Value of Remotely Sensed Information: The Case of a GRACE-Enhanced Drought Severity Index. Weather, Climate, and Society 10, 187–203 (2018).	GRACE	Bayesian decision analysis	Climate & Resilience	Instrumental (monetary)
R. Bernknopf, D. S. Brookshire, P. T. Ganderton, "The Role Of Geoscience Information In Reducing Catastrophic Loss Using A Web-Based Economics Experiment" (2003).	Simulated	Stated preference	Disasters	Instrumental (monetary)
R. L. Bernknopf, D. S. Brookshire, M. McKee, D. R. Soller, Estimating the Social Value of Geologic Map Information: A Regulatory Application. Journal of Environmental Economics and Management 32, 204–218 (1997).	geologic map	Bayesian decision analysis	Various	Instrumental (monetary)
R. Bernknopf, C. Shapiro, Economic Assessment of the Use Value of Geospatial Information. IJGI 4, 1142–1165 (2015).	MRLI (Landsat)	Value of information	Agriculture; Water Resources	Instrumental (monetary)
R. Bernknopf, A. Steinkruger, Y. Kuwayama, "Earth Observations Can Enable Cost-Effective Conservation of Eastern North Pacific Blue Whales: A Value of Information Analysis" (Resources for the Future, 2021).	Remotely sensed data and information	Value of information	Ecological Conservation	Instrumental (monetary); Instrumental (non-monetary)
P. Bettinger, et al., Stakeholder perceptions on the need for updated tree species distribution maps. Forests (2021).	remote sensing	Surveys of preference assessments	Agriculture	Instrumental (monetary)
I. Bobojonov, A. Aw-Hassan, R. Sommer, Index-based insurance for climate risk management and rural development in syria. Climate And Development (2014).	MODIS	Econometric analysis	Agriculture; Climate & Resilience	Instrumental (monetary)
M. Borowitz, J. Zhou, K. Azelton, I.-Y. Nassar, Examining the value of satellite data in halting transmission of polio in Nigeria: A socioeconomic analysis. Data & Policy 5, e16 (2023).	DigitalGlobe	Value of information	Health & Air Quality; Capacity Building	Instrumental (monetary); Instrumental (non-monetary)
S.-A. Boukabara, R. N. Hoffman, Optimizing observing systems using aspen: An analysis tool to assess the benefit and cost effectiveness of observations to earth system applications. Bulletin Of The American Meteorological Society (2022).	various	Cost-benefit analysis	Various	Instrumental (monetary)
J. A. Bouma, O. J. Kuik, H. J. van der Woerd, A. G. Dekker, The value of Earth Observation for marine water quality management in Remote Sensing of Environment, (2009), pp. 1–4.	EO data	Bayesian decision analysis; Surveys of preference assessments	Agriculture; Ecological Conservation	Instrumental (monetary)
J. A. Bouma, H. J. van der Woerd, O. J. Kuik, Assessing the value of information for water quality management in the North Sea. Journal of Environmental Management 90, 1280–1288 (2009).	Global Earth Observation (hypothetical)	Bayesian decision analysis; Surveys of preference assessments	Ecological Conservation; Agriculture	Instrumental (monetary); Instrumental (non-monetary)
J. A. Bouma, O. Kuik, A. G. Dekker, Assessing the value of Earth Observation for managing coral reefs: An example from the Great Barrier Reef. Science of The Total Environment 409, 4497–4503 (2011).	Ocean color satellite data (hypothetical)	Bayesian decision analysis; Surveys of preference assessments	Ecological Conservation	Instrumental (monetary); Instrumental (non-monetary)
J. Bouma, O. Kuik, A. Dekker, The Value of Earth Observation for Managing the Great Barrier Reef. (2009).	Ocean color satellite data (hypothetical)	Bayesian decision analysis; Surveys of preference assessments	Ecological Conservation	Instrumental (monetary); Instrumental (non-monetary)
A. Bounfour, E. Lambin, How valuable is remotely sensed information? The case of tropical deforestation modelling. Space Policy (1999).	Landsat	Cost-benefit analysis	Ecological Conservation	Instrumental (monetary)
D. S. Boyd, et al., Citizen science for earth observation (citzens4eo): Understanding current use in the uk. International Journal Of Remote Sensing (2022).	Maxar WorldView imagery	Semi-structured and in-depth interviews; Surveys of preference assessments	Various; Capacity Building	Instrumental (monetary); Instrumental (non-monetary); Relational

Reference	ESI source	Valuation method(s)	Decision context	Value type(s)
J. Brathwaite, J. H. Saleh, Bayesian framework for assessing the value of scientific space systems: Value of information approach with application to earth science spacecraft. Acta Astronautica 84, 24–35 (2013).	Hypothetical hurricane forecast	Bayesian decision analysis	Climate & Resilience	Instrumental (monetary)
D. J. Bridges, et al., Accuracy and impact of spatial aids based upon satellite enumeration to improve indoor residual spraying spatial coverage. Malaria Journal (2018).	Satellite imagery	Econometric analysis	Health & Air Quality	Instrumental (non-monetary)
M. Bruno Soares, Assessing the usability and potential value of seasonal climate forecasts in land management decisions in the southwest UK: challenges and reflections. Adv. Sci. Res. 14, 175–180 (2017).	seasonal climate forecast	Focus groups; Semi-structured and in-depth interviews	Agriculture	Instrumental (monetary)
A. Burgin, Compliance with european union environmental law: An analysis of digitalization effects on institutional capacities. Environmental Policy And Governance (2020).	Copernicus;satellite;digitalization	Semi-structured and in-depth interviews	Capacity Building	Instrumental (monetary)
V. E. Cabrera, D. Letson, G. Podestá, The value of climate information when farm programs matter. Agricultural Systems 93, 25–42 (2007).	ENSO forecasts	Value of information	Agriculture	Instrumental (monetary)
A. Chamuah, R. Singh, Securing sustainability in indian agriculture through civilian uav: a responsible innovation perspective. Sn Applied Sciences (2020).	UAV	Semi-structured and in-depth interviews	Agriculture	Instrumental (monetary); Instrumental (non-monetary); Relational
C.-C. Chen, B. McCarl, H. Hill, Agricultural Value of ENSO Information under Alternative Phase Definition. Climatic Change 54, 305–325 (2002).	ENSO forecasts	Value of information	Agriculture; Climate & Resilience	Instrumental (monetary)
B. R. Christensen, Use of UAV or remotely piloted aircraft and forward-looking infrared in forest, rural and wildland fire management: evaluation using simple economic analysis. N.Z. j. of For. Sci. 45, 16 (2015).	UAV	Surveys of preference assessments; Cost-benefit analysis	Disasters; Wildland Fires	Instrumental (monetary)
F. Collard, C. Haritchabalet, Valuing satellite systems to support fishing in a dynamic competitive model. Applied Economics (2012).	hypothetical satellite system to detect fish	Value of information	Agriculture	Instrumental (monetary)
M. Colloredo-Mansfeld, F. J. Laso, J. Arce-Nazario, Drone-based participatory mapping: Examining local agricultural knowledge in the galapagos. Drones (2020).	UAV	Semi-structured and in-depth interviews; Surveys of preference assessments	Agriculture; Ecological Conservation	Instrumental (monetary); Instrumental (non-monetary); Relational
R. Cooke, et al., Using the social cost of carbon to value earth observing systems. Climate Policy (2017).	CLARREO	Value of information; Real options analysis	Climate & Resilience	Instrumental (monetary)
R. Cooke, A. Golub, Market-based methods for monetizing uncertainty reduction. Environ Syst Decis 40, 3–13 (2020).	SMAP	Real options analysis; Value of information	Agriculture	Instrumental (monetary)
R. Cooke, B. A. Wielicki, D. F. Young, M. G. Mlynczak, Value of information for climate observing systems. Environ Syst Decis 34, 98–109 (2014).	CLARREO	Value of information	Climate & Resilience	Instrumental (monetary)
C. J. Costello, R. M. Adams, S. Polasky, The Value of El Niño Forecasts in the Management of Salmon: A Stochastic Dynamic Assessment. American J Agri Economics 80, 765–777 (1998).	ENSO forecasts	Value of information	Agriculture; Ecological Conservation	Instrumental (monetary)
L. Cristini, et al., Cost and value of multidisciplinary fixed-point ocean observatories. Marine Policy 71, 138–146 (2016).	FixO3 ocean observatory network	Cost-benefit analysis	Climate & Resilience; Ecological Conservation	Instrumental (monetary)
F. Destandau, A. P. Diop, An analysis of the value of additional information provided by a water quality measurement network. Journal of Water Resource and Protection 8, 767 (2016).	Water quality monitoring networks	Bayesian decision analysis	Water Resources; Ecological Conservation	Instrumental (monetary)

Reference	ESI source	Valuation method(s)	Decision context	Value type(s)
F. Destandau, Y. Zaiter, Spatio-temporal design for a water quality monitoring network maximizing the economic value of information to optimize the detection of accidental pollution. Water Resources and Economics 32, 100156 (2020).	Water quality monitoring networks	Value of information	Water Resources; Ecological Conservation	Instrumental (monetary)
G. Di Lallo, P. Mundhenk, M. Marchetti, M. Köhl, Understanding measurement reporting and verification systems for redd+ as an investment for generating carbon benefits. Forests (2017).	Satellite imagery;lidar	Cost-benefit analysis; Value of information	Agriculture; Climate & Resilience	Instrumental (monetary); Instrumental (non-monetary)
I. Diafas, P. Panagos, L. Montanarella, Willingness to Pay for Soil Information Derived by Digital Maps: A Choice Experiment Approach. Vadose Zone Journal 12, 1–8 (2013).	airborne hyper-spectral among other ground-based systems	Stated preference	Agriculture; Water Resources	Instrumental (monetary)
S. R. Diana, F. Farida, Applying bag of words approach to determine remote sensing technology acceptance among smallholder plantations. Arab Gulf Journal Of Scientific Research (2023).	Remote sensing	Focus groups; Semi-structured and in-depth interviews	Agriculture	Instrumental (monetary); Instrumental (non-monetary)
S. R. Diana, F. Farida, Economic Potential of Oil Palm Plantation Using Remote Sensing-Based Technology in Indonesia. ajtm 14, 19–34 (2021).	SPOT	Econometric analysis	Agriculture	Instrumental (monetary)
S. R. Diana, I. M. Ibrahim, Intangible economic benefit of remote sensing data in Indonesia. IJRBS 9, 150–159 (2020).	remote sensing	Surveys of preference assessments; Semi-structured and in-depth interviews	Agriculture	Instrumental (monetary); Instrumental (non-monetary)
E. Diez, B. S. McIntosh, Organisational drivers for, constraints on and impacts of decision and information support tool use in desertification policy and management. Environmental Modelling & Software (2011).	NA	Semi-structured and in-depth interviews	Agriculture	Instrumental (monetary); Instrumental (non-monetary)
H. M. I. Ebaid, S. S. Ismail, Lake nasser evaporation reduction study. Journal Of Advanced Research (2010).	remote sensing and GIS	Value of information	Water Resources	Instrumental (non-monetary)
S. Eilola, N. Kayhko, N. Fagerholm, Lessons learned from participatory land use planning with high-resolution remote sensing images in tanzania: Practitioners' and participants' perspectives. Land Use Policy (2021).	satellite imagery; aerial imagery	Semi-structured and in-depth interviews; Focus groups	Various; Capacity Building	Instrumental (non-monetary); Relational
Y. S. Eom, J. H. Hong, Measuring the economic benefits of an environmental monitoring satellite project: The value of information approach. Space Policy 29, 203–209 (2013).	GEMS	Stated preference	Health & Air Quality	Instrumental (monetary); Instrumental (non-monetary)
J. R. B. Fisher, E. A. Acosta, P. J. Dennedy-Frank, T. Kroeger, T. M. Boucher, Impact of satellite imagery spatial resolution on land use classification accuracy and modeled water quality. Remote Sensing In Ecology And Conservation (2018).	Digital Globe;Landsat	Cost-benefit analysis	Water Resources	Instrumental (monetary)
P. D. Fisher, M. Abuzar, M. A. Rab, F. Best, S. Chandra, Advances in precision agriculture in south-eastern australia. I. A regression methodology to simulate spatial variation in cereal yields using farmers' historical paddock yields and normalised difference vegetation index. Crop & Pasture Science (2009).	Landsat;SPOT	Value of information	Agriculture	Instrumental (monetary)
J. K. Fletcher, et al., Tropical africa's first testbed for high-impact weather forecasting and nowcasting. Bulletin Of The American Meteorological Society (2023).	African Science for Weather Information and Forecasting Techniques	Surveys of preference assessments	Climate & Resilience; Capacity Building	Instrumental (monetary); Instrumental (non-monetary)
J. Florens, C. Foucher, Pollution monitoring: Optimal design of inspection - an economic analysis of the use of satellite information to deter oil pollution. Journal Of Environmental Economics And Management (1999).	Satellite imagery	Cost-benefit analysis	Ecological Conservation	Instrumental (monetary); Instrumental (non-monetary)

Reference	ESI source	Valuation method(s)	Decision context	Value type(s)
W. M. Forney, R. Raunikar, S. Mishra, R. Bernknopf, An economic value of remote-sensing information: Application to agricultural production and maintaining ground waterquality in 2012 Socio-Economic Benefits Workshop: Defining, Measuring, and Communicating the Socio-Economic Benefits of Geospatial Information, (IEEE, 2012), pp. 1–6.	MRLI (Landsat)	Value of information	Water Resources; Agriculture	Instrumental (monetary)
C. Fraccaroli, et al., Climate data for the european forestry sector: From end-user needs to opportunities for climate resilience. Climate Services (2021).	Copernicus Climate Change Services (C3S)	Semi-structured and in-depth interviews	Agriculture; Climate & Resilience	Instrumental (non-monetary)
J. Francis, M. Disney, S. Law, Monitoring canopy quality and improving equitable outcomes of urban tree planting using lidar and machine learning. Urban Forestry & Urban Greening (2023).	lidar	Value of information	Agriculture; Climate & Resilience	Instrumental (non-monetary); Relational
S. Fritz, R. J. Scholes, M. Obersteiner, J. Bouma, B. Reyers, A Conceptual Framework for Assessing the Benefits of a Global Earth Observation System of Systems. IEEE Systems Journal 2, 338–348 (2008).	NA	Value of information; Cost-benefit analysis	Various	Instrumental (monetary); Instrumental (non-monetary)
S. Fuss, J. Szolgayova, M. Obersteiner, A real options approach to satellite mission planning. Space Policy (2008).	Satellite imagery	Real options analysis	Disasters	Instrumental (monetary)
M. Glantz, The value of a Long-Range weather Forecast for the west African sahel. 58 (1977).	hypothetical long-range weather forecast system	Surveys of preference assessments; Value of information	Agriculture	Instrumental (monetary); Instrumental (non-monetary)
N. C. Gonzalez, M. Kroger, The adoption of earth-observation technologies for deforestation monitoring by indigenous people: Evidence from the amazon. Globalizations (2023).	forest monitoring technology (satellite, drone)	Focus groups; Semi-structured and in-depth interviews	Agriculture; Capacity Building	Instrumental (non-monetary); Relational
N. E. Graham, K. P. Georgakakos, C. Vargas, M. Echevers, Simulating the value of El Niño forecasts for the Panama Canal. Advances in Water Resources 29, 1665–1677 (2006).	NINO3 SST ENSO forecast	Value of information	Water Resources	Instrumental (monetary)
A. Haara, A. Kangas, S. Tuominen, Economic losses caused by tree species proportions and site type errors in forest management planning. Silva Fennica (2019).	aerial imagery; satellite imagery; airborne laser scanning	Value of information	Agriculture	Instrumental (monetary)
D. L. Halsing, K. Theissen, R. Bernknopf, A cost-benefit analysis of The National Map. Circular (2004).	National Map	Cost-benefit analysis	Various	Instrumental (monetary)
J. W. Hansen, A. Mishra, K. P. C. Rao, M. Indeje, R. K. Ngugi, Potential value of GCM-based seasonal rainfall forecasts for maize management in semi-arid Kenya. Agricultural Systems 101, 80–90 (2009).	GCM precipitation forecast	Value of information	Agriculture	Instrumental (monetary)
R. Harris, N. Olby, Pricing policy and legal issues: 6th and 7th EOPOLE workshops. Space Policy 16, 287–290 (2000).	various	Market price/cost methods	Various	Instrumental (monetary)
J. Haskins, et al., Uav to inform restoration: a case study from a california tidal marsh. Frontiers In Environmental Science (2021).	UAV	Cost-benefit analysis	Ecological Conservation	Instrumental (monetary); Instrumental (non-monetary)
R. Hautala, et al., 'Benefits of meteorological services in South Eastern Europe' (VTT Technical Research Centre of Finland, 2008).	meteorological and hydrological services	Value of information; Market price/cost methods	Various	Instrumental (monetary)
G. C. Hays, et al., Translating marine animal tracking data into conservation policy and management. Trends In Ecology & Evolution (2019).	marine animal tracking data	Semi-structured and in-depth interviews	Ecological Conservation	Instrumental (non-monetary)

Reference	ESI source	Valuation method(s)	Decision context	Value type(s)
L. Heldt, P. Beske-Janssen, Solutions from space? A dynamic capabilities perspective on the growing use of satellite technology for managing sustainability in multi-tier supply chains. International Journal Of Production Economics (2023).	satellite forest monitoring	Semi-structured and in-depth interviews	Agriculture	Instrumental (non-monetary)
V. Herr, et al., A method for estimating the socioeconomic impact of Earth observations in wildland fire suppression decisions. Int. J. Wildland Fire 29, 282 (2020).	MODIS	Value of information	Disasters; Wildland Fires	Instrumental (monetary)
M. Holopainen, M. Talvitie, Effect of data acquisition accuracy on timing of stand harvests and expected net present value. Silva Fennica (2006).	NA	Value of information; Cost-benefit analysis	Agriculture	Instrumental (monetary)
J. Honey-Roses, J. Lopez-Garcia, E. Rendon-Salinas, A. Peralta-Higuera, C. Galindo-Leal, To pay or not to pay? Monitoring performance and enforcing conditionality when paying for forest conservation in mexico. Environmental Conservation (2009).	aerial imagery	Value of information	Ecological Conservation	Instrumental (monetary); Instrumental (non-monetary)
M. Isik, D. Hudson, K. Coble, The value of site-specific information and the environment: Technology adoption and pesticide use under uncertainty. Journal Of Environmental Management (2005).	remote sensing	Cost-benefit analysis; Real options analysis	Agriculture	Instrumental (monetary)
C. Jabbour, A. Hoayek, P. Maurel, H. Rey-Valette, J.-M. Salles, How much would you pay for a satellite image?: Lessons learned from french spatial-data infrastructure. Ieee Geoscience And Remote Sensing Magazine (2020).	GEOSUD	Stated preference	Various	Instrumental (monetary)
C. Jabbour, A. Hoayek, J.-M. Salles, Formalizing a two-step decision-making process in land use: Evidence from controlling forest clearcutting using spatial information. Land (2023).	GEOSUD	Bayesian decision analysis; Stated preference	Agriculture	Instrumental (monetary)
K. Jantke, C. Schleupner, U. A. Schneider, Benefits of earth observation data for conservation planning in the case of european wetland biodiversity. Environmental Conservation (2013).	NA	Cost-benefit analysis	Ecological Conservation	Instrumental (monetary); Instrumental (non-monetary)
D. Jin, P. Hoagland, The value of harmful algal bloom predictions to the nearshore commercial shellfish fishery in the Gulf of Maine. Harmful Algae 7, 772–781 (2008).	HAB predictions (not necessarily EO based)	Value of information	Agriculture	Instrumental (monetary)
J. W. Jones, J. W. Hansen, F. S. Royce, C. D. Messina, Potential benefits of climate forecasting to agriculture. Agriculture, Ecosystems & Environment 82, 169–184 (2000).	ENSO forecasts	Value of information	Agriculture	Instrumental (monetary)
M. J. Kaiser, A. G. Pulsipher, The potential value of improved ocean observation systems in the Gulf of Mexico. Marine Policy 28, 469–489 (2004).	Ocean observing network	Value of information	Various	Instrumental (monetary)
A. Kangas, T. Gobakken, S. Puliti, M. Hauglin, E. Naesset, Value of airborne laser scanning and digital aerial photogrammetry data in forest decision making. Silva Fennica (2018).	airborne laser scanning; digital aerial photogrammetry	Value of information	Agriculture	Instrumental (monetary)
T. Keenan, et al., The sydney 2000 world weather research programme forecast demonstration project. Bulletin Of The American Meteorological Society (2003).	Nine different observationally based nowcasting systems	Surveys of preference assessments	Climate & Resilience	Instrumental (monetary)
P. L. Kenkel, P. E. Norris, Agricultural Producers' Willingness to Pay for Real-Time Mesoscale Weather Information. Journal of Agricultural and Resource Economics 20, 356–372 (1995).	Mesonet weather network	Stated preference	Agriculture	Instrumental (monetary)

Reference	ESI source	Valuation method(s)	Decision context	Value type(s)
N. Khabarov, E. Moltchanova, M. Obersteiner, Valuing Weather Observation Systems For Forest Fire Management. IEEE Systems Journal 2, 349–357 (2008).	Aerial observation data	Value of information	Disasters; Wildland Fires	Instrumental (monetary)
J.-H. Kim, H. Lim, J. Shin, S.-H. Yoo, Evaluating the public value of improving early detection accuracy of cumulonimbus using a geostationary satellite in south korea. Space Policy (2022).	Cheollian Satellite 2A called Geo-Kompsat-2A	Stated preference	Climate & Resilience	Instrumental (monetary)
H. Kite-Powell, The Value of Ocean Surface Wind Information for Maritime Commerce. mar technol soc j 45, 75–84 (2011).	Various instrument systems	Value of information	Climate & Resilience	Instrumental (monetary)
A. Koppa, et al., A Scalable Earth Observations-Based Decision Support System for Hydropower Planning in Africa. J American Water Resour Assoc 57, 711–736 (2021).	Earth Observing System derived P and ET datasets	Value of information	Water Resources	Instrumental (non-monetary)
S. V. Kumar, K. W. Harrison, C. D. Peters-Lidard, J. A. Santanello, D. Kirschbaum, Assessing the impact of l-band observations on drought and flood risk estimation: a decision-theoretic approach in an osse environment. Journal Of Hydrometeorology (2014).	Simulations based on SMAP Radiometer	Value of information	Agriculture; Water Resources	Instrumental (monetary)
A. L'Astorina, I. Tomasoni, A. Basoni, P. Carrara, Beyond the dissemination of earth observation research: Stakeholders' and users' involvement in project co-design. Journal Of Science Communication (2015).	remote sensing	Econometric analysis	Agriculture	Instrumental (monetary)
J. A. Larson, et al., Factors affecting farmer adoption of remotely sensed imagery for precision management in cotton production. Precision Agriculture (2008).	Earth observation technologies	Semi-structured and in-depth interviews	Agriculture; Capacity Building	Instrumental (monetary)
C. Lauer, J. Conran, J. Adkins, Estimating the Societal Benefits of Satellite Instruments: Application to a Break-even Analysis of the GeoXO Hyperspectral IR Sounder. Frontiers in Environmental Science 9 (2021).	GeoXO Hyperspectral Sounder	Value of information; Surveys of preference assessments	Climate & Resilience	Instrumental (monetary)
J. K. Lazo, L. Chestnut, Economic Value of Current and Improved Weather Forecasts in the U.S. Household Sector. (2002).	NWS weather forecast	Stated preference; Value of information	Climate & Resilience; Various	Instrumental (monetary); Instrumental (non-monetary); Relational
D. Letson, et al., Value of perfect ENSO phase predictions for agriculture: evaluating the impact of land tenure and decision objectives. Climatic Change 97, 145–170 (2009).	ENSO forecasts	Value of information	Agriculture	Instrumental (monetary)
M. Li, A. Faghri, A. Ozden, Y. Yue, Economic feasibility study for pavement monitoring using synthetic aperture radar-based satellite remote sensing cost-benefit analysis. Transportation Research Record (2017).	SAR	Cost-benefit analysis	Other	Instrumental (monetary)
S.-Y. Liao, C.-C. Chen, S.-H. Hsu, Estimating the value of El Niño Southern Oscillation information in a regional water market with implications for water management. Journal of Hydrology 394, 347–356 (2010).	ENSO forecasts	Value of information; Econometric analysis	Water Resources	Instrumental (monetary); Instrumental (non-monetary)
S. H. Lim, Y. Ge, J. M. Jacobs, X. Jia, Measuring the economic benefits of advanced technology use for river flood forecasting. Journal Of Flood Risk Management (2022).	satellite SWE observations	Stated preference; Econometric analysis	Agriculture	Instrumental (monetary)
C. Linés, A. Iglesias, L. Garrote, V. Sotés, M. Werner, Do users benefit from additional information in support of operational drought management decisions in the Ebro basin? Hydrol. Earth Syst. Sci. 22, 5901–5917 (2018).	General remote sensing	Value of information; Real options analysis	Agriculture; Water Resources	Instrumental (monetary)
J. Loomis, S. Koontz, H. Miller, L. Richardson, Valuing Geospatial Information: Using the Contingent Valuation Method to Estimate the Economic Benefits of	Landsat	Stated preference	Various	Instrumental (monetary)

Reference	ESI source	Valuation method(s)	Decision context	Value type(s)
Landsat Satellite Imagery. Photogrammetric Engineering & Remote Sensing 81, 647–656 (2015).				
W. K. Luseno, J. G. McPeak, C. B. Barrett, P. D. Little, G. Gebru, Assessing the Value of Climate Forecast Information for Pastoralists: Evidence from Southern Ethiopia and Northern Kenya. World Development 31, 1477–1494 (2003).	climate forecasts	Semi-structured and in-depth interviews; Surveys of preference assessments	Agriculture	Instrumental (monetary); Instrumental (non-monetary)
M. K. Macauley, The value of information: Measuring the contribution of space-derived earth science data to resource management. Space Policy 22, 274–282 (2006).	hypothetical	Value of information	Various	Instrumental (monetary)
B. Maxwell, E. Luschei, Justification for site-specific weed management based on ecology and economics. Weed Science (2005).	remote sensing precipitation data	Value of information	Agriculture	Instrumental (monetary)
I. McCallum, et al., Banda Aceh-The Value of Earth Observation Data in Disaster Recovery and Reconstruction: A Case Study. (2008).	earth observation data	Surveys of preference assessments; Cost-benefit analysis	Disasters; Water Resources	Instrumental (monetary)
B. M. Miller, The Not-So-Marginal Value of Weather Warning Systems. Weather, Climate, and Society 10, 89–101 (2018).	weather warning system	Econometric analysis	Climate & Resilience	Instrumental (monetary); Instrumental (non-monetary)
H. M. Miller, L. A. Richardson, S. R. Koontz, J. Loomis, L. Koontz, "Users, uses, and value of Landsat satellite imagery: results from the 2012 survey of users" (U.S. Geological Survey, 2013).	Landsat	Surveys of preference assessments; Stated preference	Various	Instrumental (monetary)
A. Millner, Getting the Most out of Ensemble Forecasts: A Valuation Model Based on User–Forecast Interactions. Journal of Applied Meteorology and Climatology 47, 2561–2571 (2008).	hypothetical weather forecast	Bayesian decision analysis	Climate & Resilience	Instrumental (monetary)
J. Moellmann, M. Buchholz, O. Musshoff, Comparing the hedging effectiveness of weather derivatives based on remotely sensed vegetation health indices and meteorological indices. Weather Climate And Society (2018).	AVHRR	Econometric analysis	Agriculture	Instrumental (monetary)
E. B. Molder, S. F. Schenkein, A. E. McConnell, K. K. Benedict, C. L. Straub, Landsat Data Ecosystem Case Study: Actor Perceptions of the Use and Value of Landsat. Frontiers in Environmental Science 9 (2022).	Landsat	Semi-structured and in-depth interviews	Various	Instrumental (monetary); Instrumental (non-monetary)
E. Moltchanova, N. Khabarov, M. Obersteiner, D. Ehrlich, M. Moula, The value of rapid damage assessment for efficient earthquake response. Safety Science (2011).	hypothetical earthquake rapid response based on earth observation	Value of information; Cost-benefit analysis	Disasters	Instrumental (monetary); Instrumental (non-monetary)
J. Morgenroth, R. Visser, Uptake and barriers to the use of geospatial technologies in forest management. New Zealand Journal Of Forestry Science (2013).	aerial photography, lidar, radar	Surveys of preference assessments	Agriculture	Instrumental (monetary)
V. Morretta, M. Florio, M. Landoni, The social value of earth observation: a new evaluation framework for public high-tech infrastructures. Structural Change And Economic Dynamics (2023).	hypothetical	Cost-benefit analysis	Various	Instrumental (monetary); Instrumental (non-monetary); Relational
V. Morretta, D. Vurchio, S. Carrazza, The socio-economic value of scientific publications: The case of Earth Observation satellites. Technological Forecasting and Social Change 180, 121730 (2022).	Cosmo Skymed	Cost-benefit analysis	Various	Instrumental (monetary); Relational
J. Musinsky, et al., Conservation impacts of a near real-time forest monitoring and alert system for the tropics. Remote Sensing In Ecology And Conservation (2018).	MODIS, VIIRS active fire data	Surveys of preference assessments; Semi-	Agriculture; Various	Instrumental (monetary); Instrumental (non-monetary)

PNAS

Reference	ESI source	Valuation method(s)	Decision context	Value type(s)
		structured and in-depth interviews		
S. C. Newbold, S. Lindley, S. Albeke, J. Viers, R. Johnston, 'Valuing Satellite Data for Harmful Algal Bloom Early Warning Systems' (Resources for the Future, 2022).	HAB warning system based on satellite imagery	Value of information; Revealed preference	Water Resources	Instrumental (monetary)
N. Nikolic, et al., Site- and time-specific early weed control is able to reduce herbicide use in maize - a case study. Italian Journal Of Agronomy (2021).	UAV	Value of information	Agriculture	Instrumental (monetary)
L. Noordermeer, T. Gobakken, E. Naesset, O. M. Bollandsas, Economic utility of 3d remote sensing data for estimation of site index in nordic commercial forest inventories: a comparison of airborne laser scanning, digital aerial photogrammetry and conventional practices. Scandinavian Journal Of Forest Research (2021).	Airborne laser scanning and digital aerial photogrammetry	Value of information; Cost-benefit analysis	Agriculture	Instrumental (monetary)
F. Nutini, et al., Supporting operational site-specific fertilization in rice cropping systems with infield smartphone measurements and sentinel-2 observations. Precision Agriculture (2021).	Sentinel	Value of information	Agriculture	Instrumental (monetary)
K. O'Dell, et al., Public health benefits from improved identification of severe air pollution events with geostationary satellite data. (2023).	GEOSS	Value of information; Cost-benefit analysis	Various	Instrumental (monetary)
M. Obersteiner, F. Rydzak, S. Fritz, I. McCallum, Valuing the potential impacts of geoss: a systems dynamics approach. The Value Of Information: Methodological Frontiers And New Applications In Environment And Health (2012).	MODIS	Value of information	Disasters	Instrumental (monetary)
P. C. Oddo, J. D. Bolten, The Value of Near Real-Time Earth Observations for Improved Flood Disaster Response. Frontiers in Environmental Science 7 (2019).	GOES;VIIRS;	Value of information	Health & Air Quality	Instrumental (monetary); Instrumental (non-monetary)
R. Opitz, et al., Practicing critical zone observation in agricultural landscapes: Communities, technology, environment and archaeology. Land (2023).	various	Semi-structured and in-depth interviews; Focus groups	Agriculture; Capacity Building	Instrumental (monetary)
B. P. Parajuli, et al., An open data and citizen science approach to building resilience to natural hazards in a data-scarce remote mountainous part of nepal. Sustainability (2020).	Satellite imagery	Non-monetary methods - deliberative	Various; Capacity Building	Instrumental (non-monetary); Relational
S.-Y. Park, S.-H. Yoo, The public value of improving a weather forecasting system in Korea: a choice experiment study. Applied Economics 50, 1644–1658 (2018).	weather forecast	Stated preference	Climate & Resilience	Instrumental (monetary)
F. Pearlman, R. Bernknopf, M. A. Stewart, J. S. Pearlman, Impacts of geospatial information for decision making. Advances In Natural And Technological Hazards Research (2014).	MRLI (Landsat); PRISM	Value of information; Cost-benefit analysis	Health & Air Quality; Agriculture	Instrumental (monetary)
E. H. Petersen, R. W. Fraser, An assessment of the value of seasonal forecasting technology for Western Australian farmers. Agricultural Systems 70, 259–274 (2001).	climate forecasts	Value of information	Agriculture	Instrumental (monetary)
S. Quiroga, et al., The economic value of drought information for water management under climate change: a case study in the Ebro basin. Nat. Hazards Earth Syst. Sci. 11, 643–657 (2011).	drought forecast	Value of information	Agriculture	Instrumental (monetary)
A. Rango, Operational applications of satellite snow cover observations. Jawra Journal Of The American Water Resources Association (1980).	Landsat, VHRR	Cost-benefit analysis	Water Resources	Instrumental (monetary)

Reference	ESI source	Valuation method(s)	Decision context	Value type(s)
R. D. Roberts, et al., Taking the highway to save lives on lake victoria. Bulletin Of The American Meteorological Society (2022).	weather warning system	Focus groups; Semi-structured and in-depth interviews	Climate & Resilience	Instrumental (monetary); Instrumental (non-monetary)
K. S. Rollins, J. Shaykewich, Using willingness-to-pay to assess the economic value of weather forecasts for multiple commercial sectors. Meteorological Applications 10, 31–38 (2003).	weather forecast	Stated preference	Climate & Resilience	Instrumental (monetary)
K. W. Ross, M. E. Brown, J. P. Verdin, L. W. Underwood, Review of fews net biophysical monitoring requirements. Environmental Research Letters (2009).	FEWS NET	Surveys of preference assessments	Agriculture; Climate & Resilience	Instrumental (monetary)
T. F. Rotheli, Applied welfare economics with bounded rationality: Public policies toward remote sensing. International Advances In Economic Research (2005).	hypothetical crop health	Cost-benefit analysis	Agriculture	Instrumental (monetary)
M. Rouget, Measuring conservation value at fine and broad scales: Implications for a diverse and fragmented region, the agulhas plain. Biological Conservation (2003).	remote sensing at different scales	Value of information	Ecological Conservation	Instrumental (monetary); Instrumental (non-monetary)
F. Rydzak, M. Obersteiner, F. Kraxner, Impact of Global Earth Observation - Systemic view across GEOSS societal benefit areas. International Journal of Spatial Data Infrastructures Research 216–243 (2010).	GEOSS	Value of information	Various	Instrumental (monetary); Instrumental (non-monetary)
V. Šafář, et al., The role of remote sensing in agriculture and future vision. Agris On-Line Papers In Economics And Informatics (2022).	Copernicus	Surveys of preference assessments; Focus groups	Agriculture	Instrumental (monetary)
V. G. Sales, E. Strobl, R. J. R. Elliott, Cloud cover and its impact on brazil's deforestation satellite monitoring program: Evidence from the cerrado biome of the brazilian legal amazon. Applied Geography (2022).	multispectral remote radar	Value of information	Climate & Resilience; Agriculture	Instrumental (monetary); Instrumental (non-monetary)
P. G. Sassone, The economics of atmosphere monitoring systems: Theory and applications. Climatic Change (1982).	atmosphere monitoring systems	Value of information	Health & Air Quality	Instrumental (monetary)
G. Sawyer, E. Mamais, D. Papadakis, The Six Dimensions of Value Associated to the use of Copernicus Sentinel Data: Key Findings From the Sentinel Benefits Study. Frontiers in Environmental Science 10 (2022).	Sentinel	Value of information	Various	Instrumental (monetary); Instrumental (non-monetary); Relational
E. Schiavon, et al., Maximizing societal benefit across multiple hyperspectral earth observation missions: a user needs approach. Journal Of Geophysical Research-Biogeosciences (2023).	NA	Focus groups; Semi-structured and in-depth interviews	Various	Instrumental (monetary); Instrumental (non-monetary)
C. Schweik, C. Thomas, Using remote sensing to evaluate environmental institutional designs: a habitat conservation planning example. Social Science Quarterly (2002).	LandSat	Cost-benefit analysis	Ecological Conservation	Instrumental (non-monetary)
S. Seelan, S. Laguette, G. Casady, G. Seielstad, Remote sensing applications for precision agriculture: a learning community approach. Remote Sensing Of Environment (2003).	AVHRR, MODIS, ETM+, IKONOS, digital aerial camera	Non-monetary methods - deliberative	Agriculture; Capacity Building	Instrumental (monetary); Instrumental (non-monetary); Relational
G. A. Seielstad, et al., Applications of remote sensing to precision agriculture with dual economic and environmental benefits. Proceedings Of Spie-The International Society For Optical Engineering (2002).	AVHRR; ETM+; IKONOS; ADAR5500; MODIS	Value of information; Non-monetary methods - deliberative	Agriculture	Instrumental (monetary)
J. C. Selgrath, C. Roelfsema, S. E. Gergel, A. C. J. Vincent, Mapping for coral reef conservation: Comparing the value of participatory and remote sensing approaches. Ecosphere (2016).	Digital Globe Worldview 2	Value of information; Cost-benefit analysis	Ecological Conservation	Instrumental (non-monetary)

Reference	ESI source	Valuation method(s)	Decision context	Value type(s)
V. Sharda, P. Srivastava, Value of ENSO-Forecasted Drought Information for the Management of Water Resources of Small to Mid-Size Communities. Transactions of the ASABE (American Society of Agricultural and Biological Engineers) 59, 1733–1744 (2016).	ENSO forecasts	Value of information	Water Resources	Instrumental (monetary); Instrumental (non-monetary)
K. Smith, R. Berry, L. E. Clarke, Exploring the potential of google earth as a communication and engagement tool in collaborative natural flood management planning. Geographical Journal (2020).	Google Earth	Focus groups; Surveys of preference assessments	Disasters; Water Resources	Instrumental (monetary); Instrumental (non-monetary); Relational
I. S. Smythe, J. E. Blumenstock, Geographic microtargeting of social assistance with high-resolution poverty maps. Proc. Natl. Acad. Sci. U.S.A. 119, e2120025119 (2022).	satellite imagery	Value of information	Capacity Building	Instrumental (monetary); Relational
A. R. Solow, et al., The Value of Improved ENSO Prediction to U.S. Agriculture. Climatic Change 39: 47–60 (1998).	ENSO forecasts	Bayesian decision analysis	Agriculture	Instrumental (monetary)
M. Sozzi, et al., Economic comparison of satellite, plane and uav-acquired ndvi images for site-specific nitrogen application: Observations from italy. Agronomy-Basel (2021).	Satellite imagery, aerial imagery, UAV	Value of information; Cost-benefit analysis	Agriculture	Instrumental (monetary)
K. Spaeti, R. Huber, R. Finger, Benefits of increasing information accuracy in variable rate technologies. Ecological Economics (2021).	satellite imagery, drone imagery	Value of information; Cost-benefit analysis	Agriculture	Instrumental (monetary)
J. H. Stel, B. F. Mannix, A benefit-cost analysis of a regional global ocean observing system: Seawatch Europe. Marine Policy 20, 357–376 (1996).	Seawatch system	Cost-benefit analysis	Various	Instrumental (monetary)
S. Stroming, M. Robertson, B. Mabee, Y. Kuwayama, B. Schaeffer, Quantifying the Human Health Benefits of Using Satellite Information to Detect Cyanobacterial Harmful Algal Blooms and Manage Recreational Advisories in U.S. Lakes. Geohealth 4, e2020GH000254 (2020).	Sentinel-3	Value of information; Market price/cost methods	Water Resources; Health & Air Quality	Instrumental (monetary); Instrumental (non-monetary)
D. M. Styers, Using big data to engage undergraduate students in authentic science. Journal Of Geoscience Education (2018).	MODIS; Landsat	Surveys of preference assessments	Various; Capacity Building	Relational
D. M. Sullivan, A. Krupnick, Using Satellite Data to Fill the Gaps in the US Air Pollution Monitoring Network. (2019).	various satellite	Value of information; Econometric analysis	Health & Air Quality	Instrumental (non-monetary)
Y. Tang, et al., Grid-scale agricultural land and water management: a remote-sensing-based multiobjective approach. Journal Of Cleaner Production (2020).	MODIS	Value of information	Agriculture; Water Resources	Instrumental (monetary); Instrumental (non-monetary)
T. Tanhuanpaa, et al., Input data resolution affects the conservation prioritization outcome of spatially sparse biodiversity features. Ambio (2023).	Simulated data at various resolutions	Value of information	Ecological Conservation	Instrumental (non-monetary)
A. Taramelli, et al., An interaction methodology to collect and assess user-driven requirements to define potential opportunities of future hyperspectral imaging sentinel mission. Remote Sensing (2020).	Sentinel	Surveys of preference assessments; Delphi method	Various	Instrumental (monetary)
A. Tassa, S. Willekens, A. Lahcen, L. Laurich, C. Mathieu, On-Going European Space Agency Activities on Measuring the Benefits of Earth Observations to Society: Challenges, Achievements and Next Steps. Frontiers in Environmental Science 10 (2022).	ESA missions	Value of information	Various	Instrumental (monetary)
W. Toombs, et al., Use and benefits of nasa's recover for post-fire decision support. International Journal Of Wildland Fire (2018).	RECOVER post-fire decision support system	Semi-structured and in-depth interviews	Wildland Fires	Instrumental (monetary); Instrumental (non-monetary)

Reference	ESI source	Valuation method(s)	Decision context	Value type(s)
S. N. Trigg, D. P. Roy, A focus group study of factors that promote and constrain the use of satellite-derived fire products by resource managers in southern africa. Journal Of Environmental Management (2007).	MODIS	Focus groups; Semi-structured and in-depth interviews	Wildland Fires; Capacity Building	Instrumental (non-monetary)
K. R. Varshney, et al., Targeting villages for rural development using satellite image analysis. Big Data (2015).	satellite imagery	Cost-benefit analysis	Capacity Building	Instrumental (monetary); Instrumental (non-monetary); Relational
F. Vuolo, L. Essl, C. Atzberger, Costs and benefits of satellite-based tools for irrigation management. Frontiers In Environmental Science (2015).	Landsat; DEIMOS	Cost-benefit analysis; Semi-structured and in-depth interviews	Agriculture; Water Resources	Instrumental (monetary)
H. Wang, et al., Drone-based harvest data prediction can reduce on-farm food loss and improve farmer income. Plant Phenomics (2023).	drone	Value of information	Agriculture	Instrumental (monetary); Instrumental (non-monetary)
K. F. Wellman, M. Hartley, Potential Benefits of Coastal Ocean Observing Systems to Alaskan Commercial Fisheries. Coastal Management 36, 193–207 (2008).	Alaska Ocean Observing System	Value of information	Agriculture	Instrumental (monetary); Instrumental (non-monetary)
K. Wieand, A Bayesian Methodology for Estimating the Impacts of Improved Coastal Ocean Information on the Marine Recreational Fishing Industry. Coastal Management 36, 208–223 (2008).	Integrated Ocean Observation System	Bayesian decision analysis	Agriculture	Instrumental (monetary)
S. Wikberg, et al., Cost-effectiveness of conservation strategies implemented in boreal forests: The area selection process. Biological Conservation (2009).	satellite imagery	Cost-benefit analysis; Value of information	Ecological Conservation	Instrumental (monetary)
D. S. Wilks, A skill score based on economic value for probability forecasts. Meteorological Applications 8, 209–219 (2001).	hypothetical weather forecast	Value of information	Climate & Resilience	Instrumental (monetary)
C. Yeh, et al., Using publicly available satellite imagery and deep learning to understand economic well-being in africa. Nature Communications (2020).	Landsat; night light data	Value of information	Capacity Building	Instrumental (monetary)
D. R. Zeh, et al., Is acoustic tracking appropriate for air-breathing marine animals? Dugongs as a case study. Journal Of Experimental Marine Biology And Ecology (2015).	satellite and acoustic telemetry	Cost-benefit analysis	Ecological Conservation	Instrumental (monetary); Instrumental (non-monetary)
J. R. Ziolkowska, Economic value of environmental and weather information for agricultural decisions - A case study for Oklahoma Mesonet. Agriculture, Ecosystems & Environment 265, 503–512 (2018).	Mesonet weather network	Value of information	Agriculture	Instrumental (monetary)

Methods

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.

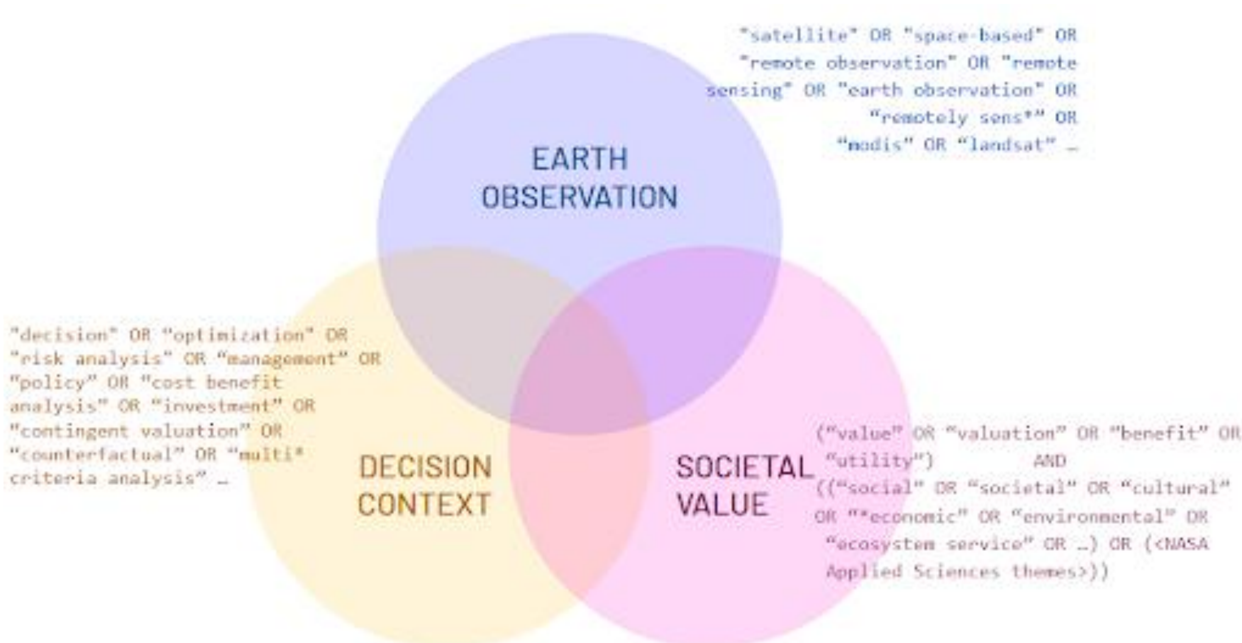

Figure S1. Conceptual diagram of search string.

Terms in italics are from the exploratory search on October 25, 2023; terms in bold were added following the use of the `litsearchr` R package functionality (69); terms in bold italics were added following discussion at the American Geophysical Union conference in December 2024. The final Web of Science search was performed using these search strings on January 26, 2024; the final Scopus search was performed using these search strings on February 4, 2024.

- 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

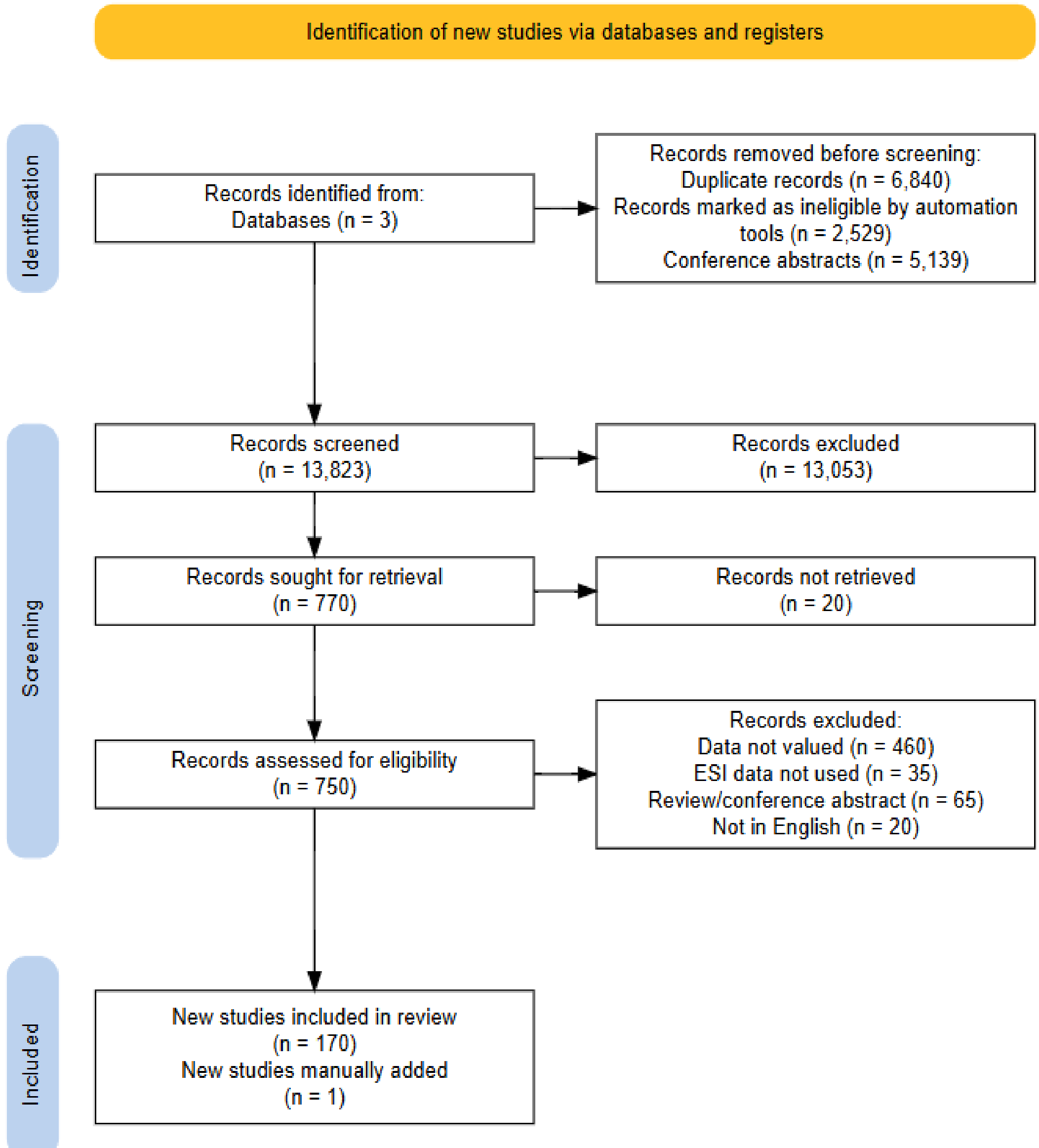

Figure S2. PRISMA flow diagram. Created using https://estech.shinyapps.io/prisma_flowdiagram/

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 - i.e., the ESI measurement did not generate value.
- 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, i.e., scientific merit. However, the resulting information is not used to inform a management decision that would translate to some societal benefit.