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On-Going European Space Agency Activities on Measuring the Benefits of Earth Observations to Society: Challenges, Achievements and Next Steps

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Understanding the Earth system and its physical and societal processes is crucial for helping humankind develop in a sustainable way, and for designing effective policies across a wide range of applications that include mitigating the effects of climate change, the sustainable management of natural resources, food security and public health. Earth observation (EO) satellites provide regular and accurate observations of the entire planet that can greatly support improvements in such understanding. The European Space Agency (ESA) is committed to supporting international efforts to decipher the processes and phenomena that regulate life on Earth, by building world class EO space missions and making data available to scientists and citizens across the world. How successful is ESA in this endeavour? Given the variable and dynamic nature of EO data use, it is difficult to answer the question through established figures. Yet, it is crucial that ESA be able to discriminate and assess the benefits brought by the use of its EO missions, in order to demonstrate its achievements, to keep improving its systems, to better design and plan future missions, and to promote further uptake. In this article, after recalling its commitments in support of Earth system sciences, ESA's attempts to conduct valuations of the impact of its own space missions are described. In particular, the challenges encountered in measuring such impacts and the solutions pursued by the Agency to improve its assessment capabilities are detailed, together with the open issues and the current lines of work.

Keywords: satellite Earth Observations, socio-economic impacts, impacts assessment, indicators, Value of Information

INTRODUCTION

A better understanding of the complexities of the Earth and about its changing climate is essential for international efforts and decision-makers to address challenging environmental and societal issues. It is, therefore, no surprise that the need for authoritative information is growing at an ever-increasing rate. Earth observations (EO) satellites provide a wealth of data which can be used to answer important Earth-science questions, to reveal interactions between the atmosphere, biosphere, hydrosphere, cryosphere and the Earth's interior, and to forecast the weather, and so the data support decision-making in a number of everyday applications.

ESA is Europe's gateway to space, mandated to shape the development of Europe's space capabilities and to ensure that its investments in space deliver benefits to the citizens of Europe and the world. The Agency has long-standing activities in Earth observation, which develop along the following three main programmatic lines (see ESA, 2021a):

The Earth Explorer missions, that are designed to improve our understanding of Earth using cutting-edge space technologies and, in many cases, pave the way for future operational EO missions. Importantly, they address scientific questions that help predict the effects of climate change and have a direct bearing on societal issues that humankind is likely to face in the coming decades. Examples of these missions are Cryosat, the Gravity Field and Steady-State Ocean Circulation Explorer, the Soil Moisture and Ocean Salinity mission, the Atmospheric Dynamics Mission Aeolus-1 (ESA, 2021b), and others.

The Copernicus Sentinel missions, that are developed specifically for the European Union's Copernicus programme—the largest environmental monitoring programme in the world (European Commission, 2021a). Each Sentinel mission carries state-of-the-art technology to deliver a stream of complementary imagery and data tailored to the needs of Copernicus. By providing a set of key information services for a wide range of practical applications, the programme is making a step change in the way we manage the environment, understand and tackle the effects of climate change and safeguard everyday lives (see e.g. EEA, 2020; von Schukmann et al., 2021; Copernicus Climate Change Service, 2020).

The meteorological missions, that respond to the requirements of the meteorological community, aimed at allowing people to make informed decisions, whether it be harvesting a crop before it rains, gritting the roads to prevent accidents, routing aircraft and marine traffic to avoid adverse conditions or simply plan everyday activities. Thanks to the cooperation between ESA and EUMETSAT, Europe has a fleet of meteorological satellites, in both geostationary and polar orbits, to provide essential information for weather forecasts. Information from these satellites is also used to understand climate change.

In addition to building and operating satellite missions, ESA works hard to ensure that its data are optimally exploited to maximize the benefits for science and society. For instance, ESA has been instrumental in setting up a number of initiatives related to the use of EO to support climate change studies or to protect citizens. The Climate Change Initiative (climate.esa.int), aimed at generating long-term datasets on key indicators of climate change, and the International Charter 'Space and Major Disasters' (disastercharter.org), which provides rapid access to satellite data to help disaster management authorities in the event of natural disasters, are just two concrete examples in this respect. Through its "science for society" activities and its accelerators, ESA forges new scientific discoveries and pioneers new services, stimulating downstream industrial and economic growth (see eo4society.esa.int and https://vision.esa.int/category/ambition/accelerate-the-use-of-space/).

It is worth highlighting that, in order to maximize opportunities and benefits, most EO data are now provided under a free and open access policy. The logic for this choice—which was not a self-evident one in the conceptual phase of public operational EO—had arisen as part of an evolving understanding on the key role of the public sector in creating goods to allow new commercial markets to form and grow around publicly provided services. Open data, as a public good, offer incredible opportunities for exploitation: it stimulates research and innovation and leads to the promotion of education at every level. The free accessibility tears down the barriers that hinder proper cross-fertilization in research and market entry for entrepreneurship. Behind open and free data also lies the key for better governance, as it contributes to better informed public decision-making and transparency. As a matter of fact, the considerable and diverse forms of public value generated by Earth observation-related information and knowledge are largely the result of the deliberate choice to have a full, free and open data policy in public programmes (see, for instance, Wulder et al., 2012; Harris and Baumann, 2015; NEXTSPACE, 2019). This is coupled with an increased focus on data exploitation: increasingly, wide and diverse user communities have been gaining a central position in the definition of the user needs and efforts are made by most space agencies to maximise user uptake in all layers of society (see e.g., European Commission, 2016). From a technical point of view, this results in stronger integration of technology-push and demand-pull approaches, with continued efforts to deliver quality-proof and reliable data streams, pre-process ever larger data sets and translate them into easily exploitable information up to embedding EO-based solutions into collaborative digital solutions aimed at tackling urgent societal needs, such as climate change mitigation measures and adaptation. In this context, the EU's Destination Earth initiative (European Commission, 2021b) is expected to trigger further improvements in modelling and predictive capacities to be able to e.g. help anticipate and plan measures in case of events having potentially major socio-economic impacts such as extreme weather and natural disasters. The initiative will provide a platform supporting digital modelling of the Earth's physical resources but also of related phenomena on a global scale. Data-intensive "digital twins" of the Earth will integrate continuous observations, modelling and high-performance simulations to enable predictions across many intertwined domains and bringing together also social and economic models with the aim of supporting the delineation of potential overarching "what-if?" scenarios. Notwithstanding the future adoption of Destination Earth as a policy-making tool and its consequential impacts on society, the role of EO data lakes at its core will certainly prove a key development for the use of EO data.

As the main procurement and implementation public agency for the European space programmes, ESA is responsible for steering the European space industrial and scientific communities in responding to critical societal needs and maximising benefits to Europe's society and economy[1]. In short, whilst each space programme has its own specific objective, designing innovative space solutions that can address Earth system science and societal challenges and

[1]See ESA Convention.

deliver value for society is at the core of practically all ESA's Earth Observations Programmes. In this context, the ability to assess the societal and economic impacts of its own activities is identified as key for the Agency, to evaluate its ability to fulfil its mandates. This rationale has matured and significantly evolved over time: the Agency has gone from demonstrating the benefits generated from past ESA programmes (ex-post) towards the analysis of new programmes proposed to Ministerial representatives (ex-ante). The latter have the objective of introducing the socio-economic perspective as early as possible in the activity design process, with the strategic objective of informing decision-makers about the potential benefits of the proposed programmes. As an example, a currently on-going economic analysis is investigating a set of potential new space activities based on their socio-economic benefit potential. This could imply that, in the future, socio-economic impact assessments could be introduced much earlier in the mission definition phase to assess different options i.e., instead of estimating the expected socio-economic impact from an already defined future mission, the socio-economic impacts could concur to drive its definition.

In contrast with this increased need, however, the studies and methodologies analysed so far consistently seem to fall short of providing a complete overview of all the value underpinned by space activities, particularly regarding a sector fertile for societal applications such as Earth Observation. So how can benefits studies be enhanced to meet ESA needs? We present in this article a wide-ranging overview of different approaches being explored by the Agency to widen its notion of value. We start from describing how ESA currently carries on studies about the impact of its own space missions (in **Section 2**) and then we explain the encountered challenges and the solutions being explored to address these challenges (**Section 3**). Conclusions in **Section 4** provide a summary of the currently identified open issues, areas of interest and planned lines of action. By providing a user perspective and highlighting the identified shortcomings, we hope to support improvements in value assessments and stimulate further research in the field.

ON-GOING ESA ACTIVITIES TO MEASURE THE BENEFITS OF ITS EARTH OBSERVATION SATELLITES TO SOCIETY

Background and Rationale of ESA Socio-economic Assessment Framework

Committed to provide evidence and transparency about its effectiveness to secure returns on Member States' investments, ESA has been studying the socio-economic benefits of its activities and programmes since the 1990s.

At that time, space programmes worldwide were benefitting from a rather continuous increase of public investments and in 2020 the European space budget (including national programmes for upstream and downstream activities and Member States' contributions to ESA, EUMETSAT, and the EU) was €11.5 billion[3], posting a 9% growth especially following the success of ESA's Ministerial Conference in 2019 (Space19+). However, it is worth highlighting that global public space expenditures had suffered from a significant slowdown after the 2007–2008 global financial crisis and almost 8 years had been needed to return to the pre-crisis growth path (see e.g., Euroconsult, 2020a). The economic shock increased constraints on overall public budgets and grew the need to justify government spending in space activities, demonstrating return on investment and the sector's contribution to economic growth and addressing of critical social issues. This has renewed efforts for ESA to engage into regular structured assessments.

Since 2012, ESA has started preparing regular reports on the space economy to support the preparation of ESA Council Meetings at Ministerial Level. These reports include key figures on the space economy, national analyses of the socio-economic impact of space activities from ESA Member States and the results of the socio-economic impact assessments of ESA programmes across all ESA activities (including e.g. navigation, telecommunications, space exploration and human spaceflight). They follow the European Commission's best practices (European Commission, 2021) as well as the definition of the Space Economy developed by the Organisation for Economic Co-operation and Development (OECD), which comprises the space industry's core activities in space manufacturing and in satellite operations but also other consumer activities that have been derived over the years from governmental research and developments. Crucially, it also includes all public and private factors involved in developing, providing and using space-related outputs, space-derived products and services and the scientific knowledge arisen from space research (see OECD, 2012).

Throughout the years, ESA has sought to adopt increasingly robust and standardised methodologies, investigating their applicability from the economic theory to measure the socio-economic benefits generated by public-funded space activities. With the aim to obtain ever more robust and consistent measures of the impact of its space Programmes, ESA cooperates with national space agencies but also with international partners and communities such as the OECD Space Forum, which investigates the economic and innovation dimensions of the whole space sector within the larger economy and society. The space economy reports build on available information from relevant trusted sources and pertinent organisations (e.g., PwC, 2019a; Euroconsult, 2020b; EARSC, 2020) but also on dedicated ESA-procured assessments, where appropriate and needed. Since 2014, more than a dozen independent studies have been conducted covering different ESA activities (see ESA, 2021c). Among these, a recent example for EO is an ex-ante socio-economic impact assessment which was carried out in 2019 in support of the proposal for ESA's envelope programme for innovative Earth Observations (also known as FutureEO) (see PwC, 2019b). ESA studies are based on stakeholders

TABLE 1 | Examples of ESA's socio-economic indicators used in socio-economic impact studies of ESA space programmes.

Impact category	Impact indicator	Description	Relevant stakeholders across the space value chain	Examples of studies which assessed the indicator[a]
Economic	Additional sales	Sales from additional business (recurring units, excl. ESA contract value) enabled by the project implementation	Upstream space industry; Downstream space segment; Non-space verticals	Euroconsult for ESA (2019) Socio-economic impact assessment of selected ESA Telecommunication Partnership Projects
	Gross Value-Added (GVA)	Contribution to GDP from the investment (ESA contract value) and additional sales	The entire economy	PwC for ESA (2019) Socio-Economic Impact Assessment of Access to Space in Europe: an Ex-Post Analysis of the Ariane 5 and Vega Programmes
	Government revenues	Contribution to taxes from the investment (ESA contract value) and additional sales	The entire economy	PwC for ESA (2019) Socio-Economic Impact Assessment of Access to Space in Europe: an Ex-Post Analysis of the Ariane 5 and Vega Programmes
	Jobs supported by the project	Full Time Equivalent (FTE) or man-year maintained or enabled by the project implementation	Upstream space industry; Downstream space segment; Non-space verticals	PwC for ESA (2019) Assessment of the socioeconomic impact of the ESA participation to the International Space Station (ISS) Programme
Strategic	Market share	Measure of industry competitiveness—increased share of an entity's sales in a specific market	Upstream space industry; Downstream space segment; Non-space verticals	Euroconsult for ESA (2019) Socio-economic impact assessment of selected ESA Telecommunication Partnership Projects
	Cost competitiveness	Measure of industry competitiveness –improved product cost/quality ratio	Upstream space industry; Downstream space segment; Non-space verticals	Know.Space for ESA (2021a) Socio-economic benefits from Future Aircraft Composite Firewall - Using space-grade materials to enhance next generation aircraft
Technological	In Orbit Demonstration/ In Orbit Validation (iod, iov)	In-orbit demonstration or validation enabled by the project	Upstream space industry	Euroconsult for ESA (2019) Socio-economic impact assessment of selected ESA Telecommunication Partnership Projects
	Technological advancement	Technology readiness level (TRL) increase enabled by the project	Upstream space industry	Euroconsult for ESA (2019) Socio-economic impact assessment of selected ESA Telecommunication Partnership Projects
	Technology transfers	Technology transfers for (spin-in) or from (spin-off) the project execution	Upstream space industry; non-space verticals	Know.Space for ESA (2021b) Socio-economic benefits from Space technology for energy providers through automated complex system coordination
	Increased efficiency	Improvement of internal processes and operations enabled by the project	Upstream space industry; Downstream space segment; Non-space verticals	EARSC for ESA (2021c) Copernicus Sentinels' Products Economic Value: A case Study of Winter Navigation in the Baltic
	Intellectual property	Proxy measure of innovation—e.g. patent filing	Upstream space industry; Downstream space segment; Non-space verticals	Euroconsult for ESA (2019) Socio-economic impact assessment of selected ESA Telecommunication Partnership Projects
Societal	Societal value creation	Key social issues (e.g. UN SDGs) on which the project has a positive contribution	Upstream space industry; Downstream space segment; Non-space verticals; End-users	Euroconsult for ESA (2019) Socio-economic impact assessment of ESA's activities on secure satcom for safety and security
	Environmental value creation	Key environmental issues (e.g. European Green Deal) on which the project has a positive contribution	Upstream space industry; Downstream space segment; Non-space verticals; End-users	Know.Space for ESA (2021a) Socio-economic benefits from ESA Technology Transfers - From waste to resource
	Scientific knowledge production	Number and profile of publications, citations, scientific community width, scientific breakthrough…	Upstream space industry; Downstream space segment; Non-space verticals; End-users	PwC for ESA (2019) Socio-economic impact assessment of ESA's Science Programme

[a] *Executive summaries of the studies are publicly available on ESA Space Economy website restricted area https://space-economy.esa.int/restricted-area (free registration).*

consultations (e.g., how many new FTEs the project supported) or on well-known methodologies from the economic theory (e.g., Cost Benefit Analysis, Input-Output modelling, Multi Criteria Analysis) but limitedly to the approaches and indicators that are considered as the most robust and appropriate for the programme/s under evaluation. Typically, they provide in-depth information on various economic parameters that provide an essential perspective on the general state of the market and on the returns on investments for Member States, based on economic outputs and GDP contributions, such as the status, trends and evolution of the upstream manufacturing industry and of the data market, revenues from so-called Value-Added Services (VAS), levels of employment as well as contribution to Member States' GDP (in terms of Gross Value-Added). However, the scope of the studies is generally framed depending on the needs (and resources) of the specific programme under investigation and this means that they often are not meant to assess indicators across the entire value chain but rather focus on a specific part of it. As an example, in a 2019 study of selected ESA artes telecommunication partnership projects, the additional sales generated by the satcom missions were assessed only for the prime manufacturers and for a selection of primary subcontractors (in terms of recurring sales of the hardware or software developed specifically under the ESA programme) and for the satcom operator (in terms of generated satcom service revenues). Additional sales potentially generated further down the value chain, from e.g. the use of the developed satcom service in non-space user verticals or any additional sales which could have arisen from technology transfers, were knowingly neglected. These limitations are generally well known and recognized, as they serve the specific cost/benefits trade-off of the study itself.

In order to widen its oversight of relevant suitable methodologies and indicators that can be leveraged and tailored to fit the needs of the specific studies at stake, ESA is increasingly screening the available knowledge. And, with the aim to improve its understanding about the reliability and robustness of the available methodologies, it is increasingly reaching out to the practitioners and the academic community. Starting with a critical review of the literature and of all former studies, it has adopted an empirical approach to identify an encompassing set of socio-economic indicators that could be relevant for all ESA activities and span across different segments of the space value chain (e.g., upstream and downstream space sectors, non-space verticals[2] and end-users). Efforts have also been made to review and consolidate a relevant taxonomy which is generated from economic theory through a comprehensive literature review of socio-economic analyses as well as vocabulary specificities from the space sector at large (e.g., Technology Readiness Level advancements, In Orbit Demonstration and Validation). Leveraging on this taxonomy, a socio-economic indicators framework is being generated, a preliminary example of which is provided in **Table 1**. The Table provides a general framework intended to support ESA's assessment activities across all its programmes which has been progressively enriched via an empirical approach, alongside the generation of increasingly complete socio-economic assessments. It is anticipated that, being developed across very different types of activities within different Directorates, the framework provides benefit from some degree of fertilization across the various programmes, with methodological advances in one area propagated to other areas as applicable.

It is worth highlighting that the framework includes diverse indicators but that very often only a subset of them is considered as relevant for the assessment, depending on the specific nature, scope and objectives of the space activity being addressed. For example, indicators such as the Gross Value-Added or the contribution to GDP are not deemed appropriate (too small to be significant) to assess the benefits of small-size missions, while the number of peer-reviewed scientific publications might not be relevant to demonstrate the value of a new satcom solution. Specifically for EO, even though a vast set of the indicators is recognized as potentially relevant, a tailoring may be applied depending on the specific nature of the satellite mission/s at stake. As an example, the FutureEO study (PwC, 2019b) included a wide range of indicators: next to economic ones (e.g., contribution to GDP in terms of Gross-Value Added generated, government revenues in terms of taxes, employment supported in both the space and non-space sectors but also estimates of innovation spill-overs), others were included to show trends in scientific exploitation (annual academic publication rates) as well as in the growth of the users community (e.g., monthly traffic on ESA's data access platforms, attendance to ESA EO events). Notably, societal impacts were also highlighted through example use cases of innovative technologies in support of e.g., crop monitoring, water management, international development aid or coastal management.

As the set of socio-economic impact assessments of ESA programmes has been developed and its results presented, it has been clearly identified that they currently fail to capture the full extent of the value brought by space activities to society. For instance, it was increasingly evident that various parameters traditionally used by the EO community to collectively look at its own achievements were not captured in the current assessments (e.g., scientific outputs, value of EO data for decision-makers in the decision-making processes, contribution to global environmental goals). Thus, ESA has been working, along with its Member States and reference partners such as the OECD, to further investigate the applicability of new and complementary approaches. In particular, ESA is progressively consolidating the socio-economic indicator framework and reviewing its applicability as it enlarges the scope of its analyses, aiming

[2]Non-space vertical segments are economic sectors which make use of space data and or services, such as aviation, agriculture, energy, but also insurance, tourism or disaster response.

at extending further the understanding and robustness of its valuation, especially for the non-monetary benefits that space programmes bring to society, with new approaches being tested to capture aspects that are not yet part of its space mission valuation protocols.

Recent efforts, therefore, tend to increasingly extend the analysis by considering additional relevant parameters, as we will explain in the following chapters.

Valuing ESA's Earth Observation as Support to Knowledge and Innovation

Innovation and technological and scientific pursuit are key endeavours for a thriving society and, in a context of immense economic constraints and critical social issues, the demonstration of the value of EO data in support of science and technological breakthrough is considered of primary importance. But the ability to estimate knowledge benefits is a recognised challenge for research and technological agencies all over the world when trying to justify public investments (see e.g., Mazzuccato, 2013; Florio, 2019).

As already discussed, EO data provide fundamental contributions to improvements in understanding about Earth System Science, particularly with respect to climate change. But designing, building and operating EO satellites can also represent, by itself, an innovation endeavour and result in improvements in human capital in terms of e.g., skills and experience acquired, competitive advantages for the contracted firms (that learn from technological collaboration with major space agencies), technological transfers from space to other industrial sectors. In perspective, benefits from Research and Development (R&D) lie in the potential of growing into new or improved operational technologies, contributing to the creation of new services and new markets with consequential economic and societal growth. But these impacts frequently materialize after long-lead times and have to be balanced against (sometimes substantial) risks. This makes their assessment very challenging but, at the same time, all the more compelling.

Traditionally, the most common indicators used to measure benefits derived from science and innovation are the number of patents filed upon deployed solutions and the (weighted) number of academic publications stemming from the design of new systems or from the use of the data (see e.g., OECD, 2016). ESA maintains a patent portfolio for technological transfers and regularly looks at the number of scientific publications that make reference to its own missions. In this respect, thousands of peer-reviewed scientific publications have been tracked, with more than 5,000 related to the EO scientific missions and a rate of publication that has more than tripled in the last years (PwC, 2019b). However, these only provide a partial view and additional elements should be considered. For example, assimilating outer space probes to public research infrastructures the likes of large particle accelerators and genomics platforms, Florio (2019) takes into account aspects such as benefits to the work of scientists and students; knowledge spillovers for firms; benefits to users of information technology and science-based innovation; welfare effects on the general public and even willingness of taxpayers to fund scientific knowledge creation.

R&D in space is at the core of ESA's purpose, so the Agency is actively exploring improvements in this respect. As an example, the FutureEO study which has been mentioned (PwC 2019a) included an attempt to measure knowledge spillover impacts (including spillovers from both manufacturing and data and processing activities with ESA). These were not captured in the GDP impact calculations (which instead focused on transactional impacts derived from the initial public spending) and were taken to represent innovation and knowledge creation externalities derived from the past development of previous ESA EO R&D programmes (i.e., Earth Observation Envelope Programmes EOEP4 and EOEP5). In order to estimate these impacts, PwC consulted 93 entities previously contracted by ESA (collectively accounting for about EUR 516.4 M of ESA procurements between 2013 and 2018) to observe that 88% considered that they have generated spillovers thanks to their participation in the EOEP programmes. Some of these entities were able to provide the associated monetary estimations, on the basis of which PwC postulated total spillover benefits in the range of EUR 794.9 to 1,089.1 M, with associated weighted spillover multipliers ranging between 1.63 and 2.24. As recognized by the Authors, the calculation was certainly approximate and it was intended only to provide a "minimal estimation of a very complex phenomenon (i.e., innovation and knowledge development) to demonstrate its existence rather than over estimating it". Even so, the resulting figures were comparable to the GDP transactional ones, highlighting that the phenomenon is not negligible and would deserve to be taken into account for the evaluation of R&D intensive programmes such as the space ones.

Valuing ESA's Earth Observation as Support to Decision Making

EO is well established as an effective tool to support decision-making across many different applications and at different levels (see e.g., Onoda and Young, 2016; Kruse et al., 2019; PwC 2019a; Hanan et al., 2020). From this perspective, EO missions have value insofar as they provide information which is useful for taking decisions. This notion is generally framed as the Value of Information or VOI theory: this was originally developed in the late 1960s to support public policy evaluation in the areas of health, environment and climate change, to appreciate the value of public goods, and was then transposed to the valuation of EO data (see e.g., Macauley, 2006) and used to assess the value of several past or future projects in Earth Observation and Earth Science (see e.g., Kruse et al., 2019). VOI analysis, leveraging on Bayesian decision theory and the theory of the economics of information, essentially addresses the decisions taken under uncertainty with, and without, information. Decisions taken relying on alternative types of data (e.g., often, ground-based measurements) represent the so-called "counterfactual", against which an improvement is measured (and value attributed). Depending on the degree of the uncertainty and on what is at stake, decision makers may be willing to pay for information, either additional or improved, as long as the expected benefit exceeds the cost of the information. The technique, therefore, includes conceptualizing a decision problem, developing a decision model, identifying the relevant parameters, conducting a probabilistic analysis and estimating the subsequent value of information (as opposed to the *counterfactual*) to derive the expected net benefit for the decision maker. All these steps are extremely sensitive to the specific case under analysis. In particular, the counterfactual is not always available or only partially fitting as in some cases space-based solutions allow for improvements in the public services that cannot be easily monetized and compared. Moreover, one must consider that the EO-derived information is rarely based on EO data only but is frequently intertwined with other types of data and this implies that the value of the EO data must be disentangled from the VOI in order to attribute to the data its correct share. Again, such attribution cannot be determined a-priori and requires a precise knowledge of the specific process. To address this challenge, real-life examples offer the advantage of being intimately related to the use benefits in a way that no general fit-for-all assessment can credibly attempt. However, this reliability cannot be easily extrapolated and a large number of case analyses and on-the-field investigations would be ideally required, covering at least core influential applications. Indeed, micro-diffusion models have been used even to assess the end-user benefits of large Programmes such as Copernicus (PwC, 2019a). Ultimately, approaches based on concrete use cases could contribute solid foundations for meta-analyses and provide useful information to feed economic models in a "bottom up" perspective (see e.g., Tassa, 2019).

The "use cases" also offer the additional advantage of providing a convincing tool for communication and user uptake purposes, as shown by the experience of the Sentinels Benefits Study (Sawyer and Papadakis, 2020). This also explains why "use case collections" have become increasingly popular to showcase the Copernicus Programme (European Commission, 2021a). Through dedicated procurements within the EU Copernicus Programme, ESA has also embraced the collection and analysis of use cases, with particular regards to cases of use from scientific users (e.g., Copernicus Sentinels Success Stories) and from public authorities (see NEREUS, European Space Agency and European Commission, 2018).

Use case analyses are fundamental to deepen the understanding of the benefits and can be extremely effective to showcase the value of the data in specific contexts, but they lack the amplitude and the global perspective that represents a key asset brought by Earth Observations.

Valuing ESA's Earth Observation as Contribution to Established Global Indicator Frameworks

An effective way to illustrate the global value of EO data is through its contribution to established frameworks of indicators underpinning international treaties and cooperation efforts, like those established through the UN Conferences of the Parties.

EO data are recognized as a vital source of information when tracking progress with respect to global environmental commitments. Often, this contribution is framed through well-defined and internationally agreed bio-geophysical indicator schemes, against which the relevance of ESA's EO data can be exposed in a straightforward way. One example in this respect comes from the set of geophysical parameters defined as "essential" to support international climate research, for which it has been estimated that EO missions contribute to about 60% of the 54 Essential Climate Variables (ECVs) defined by the Global Climate Observing System (GCOS, 2021). In addition to providing own data sources, ESA's CCI specifically produces data records of 21 ECVs over the whole world, stretching back more than 30 years, based on its full satellite archive. These contribute to a rapidly expanding body of scientific knowledge and provide significant input to the studies of the International Panel on Climate Change (see IPCC, 2021). Alongside ECVs, a set of Essential Biodiversity Variables (or EBVs) has emerged to provide a first level of abstraction between low-level primary observations and high-level indicators of biodiversity (Pereira et al., 2013). Although the framework, and especially its links with respect to remotely sensed parameters, is still under consolidation (see Skidmore et al., 2021), this represents another benchmark to be considered when assessing the contribution of ESA's EO data to global environmental efforts.

Through supporting environmental protection and contributing to the advancement of Earth and Environmental Sciences—particularly in support of resilience and adaptation to climate change - EO can also be seen as relevant to a surprisingly broad range of efforts to ensure human well-being and societal progress around the world. In this sense, EO contributes to the United Nation's 2030 Agenda for Sustainable Development and helps to address the UN's Sustainable Development Goals (SDGs) and 169 of the associated specific targets. The UN, in fact, explicitly recognizes the role of EO in supporting the achievement of the SDGs (UNOOSA, 2018), and over half of the SDGs are recognized to be affected positively by EO (with almost 40% of the associated specific targets directly benefitting from the use of navigation and Copernicus services) either through permanent monitoring of the evolution of the indicators or through active contribution to their accomplishment (e.g., using EO data to optimize agricultural practices, thereby contributing to the achievement of the second SDG on zero hunger).

Obviously, the more abstract the target indicators, the more complex the assessment of the EO contribution, which might require a deeper analysis. In order to unambiguously assess the suitability of EO-derived data for measuring the SDG indicators, Andries et al. (2019) developed a Maturity Matrix Framework that took into account multiple dimensions such as:

1) Uncertainty (i.e., the level of bias and the possibility of estimating said bias),
2) Directness (i.e., the level of direct measure of the indicator by EO data),
3) Completeness (i.e., the level of support of EO data to an indicator),
4) Requirement for non-EO information (i.e., the level of non-EO information needed to complete the contribution of EO data to an indicator),

5) Practicability (i.e., the extent to which the approach of using EO data is integrated by end-users for decision-making), and
6) Cost-Effectiveness (i.e., the extent to which EO data is the most cost-efficient and advantageous approach to measure the indicator).

Even through this more critical scrutiny, EO data (mostly free Copernicus and Landsat data) are confirmed to be largely and effectively contributing to a substantial number of SDGs and their indicators.

AREAS FOR IMPROVEMENT AND FUTURE PERSPECTIVES

Throughout the years, ESA has been evaluating the suitability of different standards and practices through the definition and the procurement of different studies. The continued efforts to pursue methodological robustness lead to the understanding that current socio-economic impact analyses do not sufficiently capture the benefits for humanity and that a more holistic approach is needed.

The Agency is, therefore, progressively widening its notion of value, by exploring possible ways to include non-economic aspects in a way that is sufficiently robust and structured and widely acceptable to its decision makers. Possible areas for improvements are described below, expanding on the current lines of action identified in the previous section.

Understandably, due to its R&D vocation, the ability to demonstrate the benefits derived from investments in research and development is considered a key area for improvement for ESA. As introduced in Sub-**Section 2.2**, expert advice has been leveraged to perform some preliminary assessments of the economic value of the (accrued and potential) knowledge externalities derived from some specific ESA R&D programmes. This certainly highlights the importance of the phenomenon but is not sufficient. To secure improvements in this direction, the ability to expose the links between benefits accrued in the past and their enabling R&D activities, is perceived as crucial. After all, the key convincing argument of the FutureEO Programme proposal was that it can pave the way to future operational programmes like Copernicus. The argument implicitly rested on past track records, and on the wide recognition that, without the legacy from the previous missions (such as Envisat and Cryosat) and ESA's preparatory actions (such as the GMES Service Elements), the Copernicus programme would not have been possible, at least not in its current shape (PWC, 2019b). However, such legacy tributes are not systematically tracked in ESA, and heritage attribution is substantially linked to occasional experience which might be fading relatively quickly. As an example, if Envisat's (and SPOT's and Landsat's) legacies are well recognized for the Copernicus Sentinel satellites, that of the GMES Service Elements (as precursors of the Copernicus Services) is much less so. Such knowledge is embedded in the personal memories of the people who participated but, with time, the message might be fading and, with this, the opportunity to reflect upon the substantial factors and conditions that led to a major European achievement. Possible developments for ESA in this area could then be to improve its tracking capabilities through e.g., the retrospective analyses of past achievements and legacies, at least for breakthrough developments. Such analyses could also improve the awareness and understanding of the factors contributing to major achievements (or failures), providing concrete elements to inform forward-looking perspectives.

A second line of action concerns the assessment of the benefits accrued through the use of EO data to support decision-making in (semi) operational applications. Progress in this area is pursued in many directions. For instance, ESA is seeking to widen the applicability of the VOI theoretical approach: so far, this has only been applied in a relatively limited number of Sentinel data use cases but, following requests from Member States, the applicability is being tested within ex-ante studies in support of Programme Proposals for the Ministerial Council meetings. A pilot activity has just been started to study the VOI for two ESA Earth Explorers missions: the currently flying Aeolus-1 (ESA, 2021b) and the upcoming Aeolus-2, which is to be proposed at the next ESA Council at Ministerial level in 2022. As part of the project, VOI will be used to measure the Willingness to Pay (WTP) of European decision-makers, based on how new or improved information derived from Aeolus has changed (or is supposed to change) their prior knowledge about uncertainties, and the decision which he or she would make if the uncertainty were reduced or resolved ahead of time. In addition, the estimated WTP value of the mission will have to be attributed by disentangling its relative contribution to the weather forecasts within the European Centre for Medium-Range Weather Forecasts numerical weather prediction model (see also ECMWF, 2021) which will also serve as the basis for the counterfactual. As described previously, this technique is particularly challenging because it crucially requires the availability and cooperation of the data users, so the availability and acquisition of detailed decision-maker data represents the most challenging step of the analysis. The study, to be completed in 2022, is expected to bring to the ESA Member States ministries a complementary perspective beyond the industrial economic multiplier and the technological and scientific effects. Results from this experience will not only provide inputs for the ESA Ministers, but will also be critical for ESA to understand the potential challenges of applying VOI to assess the potential of new EO missions in a more systematic way for its future programmes.

The valuation of EO-derived information is also to be improved through an expanded notion of value. Since EO applications support public decision-making related to disparate sectors such as urban planning, smart mobility, water and air quality monitoring, consideration must be taken also into parameters related to overall societal improvements including in terms of e.g., life quality, well-being, social progress and even the happiness of world populations. Such impacts are obviously complex to measure: they often rely on subjective factors and cannot always be quantified. Yet clearer appreciation of value to citizens is becoming increasingly relevant, the more so in the wake of a triple health, economic and climate crisis. ESA explores possible ways to include non-economic aspects in a way that is sufficiently robust and structured and widely acceptable to its decision-makers and is making efforts to widen the number of non-economic indicators, including those that cannot be measured in quantitative ways. One way to build knowledge around these is through the analysis of benefits already accrued, at least for mature use cases of interest and for strategically relevant areas of application. In this respect, Sawyer et al. (2022) propose to make systematic use of five additional dimensions other than economic (i.e., environmental, regulatory/policy, innovation, scientific and societal) when analysing use cases. The different dimensions of value are certainly straightforward to acknowledge, although the emphasis can be variable depending on the programme being addressed. For instance, for a public programme such as Copernicus, regulatory benefits are of primary interest: the assessment about how far EO data potentially and actually contribute to support environmental policy making across ESA Member States and in Europe is a key measure of the overall programme's success. The information about how the data are being used for policy making in Europe is a necessary input but is fragmented and incomplete and even if numerous collections are published, they are heterogeneous in scope and depth (see e.g., NEREUS, European Space Agency and European Commission, 2018; Kucera et al., 2020). Environmental benefits are perhaps even harder to assess, with complexity being enhanced by the lack of input data but also of suitable models extending over much longer temporal perspectives. Social benefits assessments, on the other hand, would possibly require large scale surveys that have so far only been pursued at ESA to a limited extent. In this respect, ESA has also been testing alternative approaches based on distinctive theories of *public value*. Using the Schwartz framework of *human values* (Schwartz et al., 2012), a study has been carried out which surveyed two samples of informed citizens. Findings from the study revealed a comprehensive contribution of ESA to the public sphere (Baldesi et al., 2020).

A third line of action is to look at progressively expanding the spectrum of indicators and frameworks against which the impact of EO data can be benchmarked. In doing this, wide ranging and general notions of value can be leveraged that are related to the Agency's mandate at large, even though the actual choice of the indicators of interest for each specific programme will depend on its specific objectives as specified in the programme proposal or in the requirements documents. Whenever an established set of policy indicators is already available and recognized as relevant for a given EO mission, the contribution can be singled out in a similar vein as it is done with respect to the ECVs or the SDGs (see **Section 2.4**). A critical review is carried out in ESA to identify existing frameworks which represent relevant objectives for EO. An example in this respect is the UN System of Environmental Economic Accounting (SEEA) which was set in March 2021 by the United Nations Statistical Commission to bring together economic and environmental information in an internationally agreed set of standard concepts, definitions and accounting rules to produce internationally comparable statistics (United Nations, 2021). This new international statistical framework is regarded to potentially bring a paradigm shift in the appreciation and valuation of natural resources, allowing countries worldwide to use a common set of rules and methods to track changes in ecosystem assets (e.g. ecosystem extent and conditions) and related flow of services (i.e. ecosystem services), thereby linking ecosystem information to economic and development activities. In a similar vein at European level, the European Mapping and Assessment of Ecosystems and their Services (MAES) framework can be considered. This is used to measure change in ecosystems over the entire EU territory and to inform all related policies, helping Member States and stakeholders to carry out national ecosystem assessments through both an agreed analytical framework and indicators (Maes et al., 2020). As of today, EO and Copernicus data already contribute to monitoring an important share of MAES indicators, across its various assessed thematic ecosystems, thus confirming the increasing use of such data by the European Commission within the EU's conspicuous legislative corpus (e.g., Kucera et al., 2020). The contribution of Copernicus Sentinel data within the MAES (including through the Copernicus Services) will be analyzed as yet another measure of their support to European policies.

All the above described the possible lines of actions that are being pursued in the short to medium term. Consolidated findings from all these practical experiences will be progressively taken into account for further updates of the ESA socio-economic indicators framework and the set of methodologies to be used for ESA's forthcoming institutional impact assessments. But it is also worth reflecting on more far-sighted considerations on the impact and role of EO.

When it comes to the planet and human development, the need for more holistic approaches seems to be increasingly recognized at global level. In particular, it is becoming increasingly established and visible that humanity's current way of conducting economic activities has a major responsibility for degrading the environment and that it does not necessarily ensure a balanced and fair development for humanity as a whole. The latter is evidenced by the ever growing social inequality in both developing and developed societies (UNOOSA, 2018). Consequently, new models are being explored aimed at internalising many of the "external costs" (e.g., societal or environmental) which are not accounted for in the monetary measures of progress (i.e., GDP-related indicators) (Stiglitz, 2020). Of particular concern, the notion is being raised that humanity might be hitting environmental tipping points that, if exceeded, can cause important changes in the ecosystems and create chain reactions that will further trigger snowballing natural disasters (Lenton et al., 2019). This paradigm shift has led to an evolution within economic theory towards the establishment of approaches that put a much stronger focus on the notion of sustainable and inclusive economic growth—placing those concepts at the centre or starting point of economic development, rather than treating them as considerations on the side. Insofar as bio-geophysical models of the Earth can be coupled with socio-economic modelling, a continuing shift towards more holistic frameworks can be anticipated.

A recent promising concept in this respect is the so-called "doughnut" model (Raworth, 2017). This is a visual framework

TABLE 2 | Relevance of EO data and information for assessing the parameters of the Doughnut economics model (authors' assessment).

Ecological ceilings	
Boundary	**EO contributions (examples)**
Climate change	EO monitors both the causes and effects of climate change and will soon support compliance of climate policies, in terms of. • Causes: e.g. GHG/deforestation monitoring and the monitoring of feed-back loops within the Earth system that could cause climate change to accelerate. • Effects on: e.g. sea ice, ice sheets, ocean salinity, ocean colour, sea surface temperature, aerosols, ozone, sea level, sea state, water vapour, clouds, soil moisture, land surface temperature, biomass, land cover, fire, lakes, glaciers, snow, permafrost (36 of the 54 Essential Climate Variables defined by the WMO benefit from space observations). •Compliance: first global stocktake of the Paris Agreement in 2023
Ocean acidification	• Sea salinity measurements, which play a key role in ocean acidification
Chemical pollution	• Oil spills, atmospheric chemical pollution (see air pollution), acid rain effects, impact assessment of industrial accidents
Nitrous and phosphorus loading	• Surface runoff and wind erosion monitoring (key drivers of eutrophication in surface waters), algae bloom monitoring
Freshwater withdrawals	• Sub-ground water table assessments using gravity measurements, above ground evolution of freshwater reserves within lakes, glaciers and snow
Land conversion	• optical, radar and hyperspectral measurements to monitor at local, regional and global scales
Biodiversity loss	• optical, radar and hyperspectral measurements to monitor at local, regional and global scales
Air pollution	• Nitrogen dioxide, sulphur dioxide, formaldehyde, carbon monoxide measurements
Ozone layer depletion	• The ozone layer and its evolution are monitored by EO satellites since several decades
Social Foundations	
Boundary	**EO contributions (examples)**
Water	• Assess local and regional evolution of water reservoirs, monitoring soil moisture
Food	• Monitoring of crops, prediction of agricultural yields
Health	• EO data is used in epidemiological models, air pollution monitoring
Energy	• Assessing green energy potential and biomass reserves
Education	• EO images/results contribute to raise awareness amongst children and adults on global issues affecting humankind
Income and work	• Limited potential for EO contributions
Peace and justice	• Monitoring the impacts of war and large-scale conflict, potential for assessing aspects of environmental justice
Political voice	• Limited potential for EO contributions
Social equity	• Limited potential for EO contributions
Gender equality	• Limited potential for EO contributions
Housing	• Mapping of informal housing in developing regions and of parameters that determine housing quality (building age, thermal insulation etc.)
Networks	• Limited potential for EO contributions

for sustainable development that takes into account both social and planetary boundaries. The framework is particularly effective to show that the core challenge for humanity consists in finding a way to meet humanity's needs without collectively over-pressuring Earth's life supporting systems nor falling short on internationally agreed social standards. The "Doughnut" model is at the crossroads between Earth and Environmental Sciences, Environmental economics and Well-being economics. It fixes minimal social standard thresholds as well as an environmental ceiling consisting of science-based definition of planetary boundaries. In the words of its co-creator Prof. Raworth, the doughnut consists in identifying the "*environmentally safe and socially just space in which humanity can thrive*" between these social and environmental boundaries. Complementing Earth and environmental sciences on monitoring Earth systems and climate change, EO data can help to keep track of the environmental tipping points and could therefore contribute to monitoring achievements through such an economic model. ESA is currently investigating the possible linkages with such a holistic model and is identifying possible EO-based indicators in this framework. A preliminary analysis is summarised in **Table 2**. In particular, the table shows that for the planetary boundaries (the ecological ceiling), EO data is key to enabling monitoring capabilities and to tracking progress over time both at local, regional and global scales.

CONCLUSION

ESA Earth Observation activities benefit the environment and society in multiple ways. By pushing the technological frontiers of manufacturing and data processing, they steer knowledge and innovation. With their precious data, they support decision-making at different levels and help advance our understanding of core Earth system processes. By providing information about the state of Earth's life-support systems, including freshwater, oceans, land, biodiversity, atmosphere, and climate, they can greatly support humanity to improve sustainability on the planet. ESA undertakes to measure and expose these benefits in a reliable way.

For more than 20 years, ESA has been assessing the impact of its own activities. Since 2012, it has been regularly collecting information for its Member States in dedicated space economy reports, that span across the many diverse activities of the Agency (from human spaceflight to telecommunications, from R&D activities to Technology Transfers). The reports build on dedicated and cross-cutting studies, that are guided by a streamlined set of socio-economic indicators that provide the Agency's internal framework. Since the assessment of socio-economic value of space missions remains relatively recent, the focus so far has been strongly on testing approaches and initiating pilot studies fitting ESA's requirements for different space missions and programmes, striving to increase the methodological robustness of the studies it procures. Approaches are diverse in nature and scope and the choice of the most appropriate methodology often depends on the specific space mission or programme at stake.

Although the space sector lacks its own set of data in official statistics (a fact which hampers wide-ranging econometric analyses) methodologies are increasingly consolidated that provide robust economic assessments across different space segments (e.g., satellite manufacturing and operations). However, when it comes to EO, a much wider spectrum of benefit types comes into play - from advancements in scientific knowledge, to supporting decision-making and environmental monitoring at different levels—and transdisciplinary, multi-scalar approaches would be needed. The lack of perfectly fitted methodologies is made particularly acute also due to the difficulty in gathering input data that are needed for reliable analyses: in fact, the needed data span across a wide range of sources and traditional indicators are not suitable to express the whole of perceived EO socio-economic value. Communication is likewise affected: experience shows that, alongside economic figures, evidence about the links between satellite data and impacts on society needs to be exposed through credible narratives based on real instances capable of resonating with the audience.

In this article, we have described possible ways in which benefits studies could be improved to better meet ESA needs. In particular, we have described multiple complementary activities aimed at addressing the above challenges and to pinpoint areas where improvements could and should be achieved. The currently identified ones are discussed in this article and summarised as follows:

1) A first element where progress would be needed relates to the valuation of EO-derived benefits in innovation and scientific knowledge and their spillovers: some preliminary assessments have been performed for the Agency, which highlighted the non-negligible extent of the phenomenon and there is no doubt that advances in this area would be needed.
2) Another area for improvement relates to the value of EO-derived information as a support to decision-making. This is key to showing the benefits of EO but remains complex as it requires massive amounts of realistic user information that can link data use to concrete impacts on the users' side and support the formulation of solid assumptions. ESA looks for assessments that couple robustness of methodology with a sound representation of the value of information, at least for core applications of interest. In this respect, credibility is of the essence and the interaction with key users is fundamental for a thorough understanding of the case. On the plus side, the experience of the Sentinels Benefits Study interestingly shows that users often embrace VOI analyses that can be useful also from their own perspective. This suggests that the elaboration of easy-to-use guidelines such as the ones being developed by Sawyer and Papadakis (2020) could help to channel contributions from practitioners, supporting the harvesting and comparability of use cases. In the long term, the accumulation of diverse, yet comparable case studies is expected to support the exportability of the core modelling assumptions, as well as related sensitivity analyses. The use of VOI also in an ex-ante perspective is being tested through a pilot study and will be pursued in support to programme proposals.
3) The contribution of EO to existing frameworks of indicators, especially global ones such as the Essential Climate Variables or the UN's Sustainability Development Goals, remains the flagship representation of the universal values of EO in support of human development and advancements in knowledge. Additional potentially relevant frameworks will be explored, particularly those that could help to describe the benefits brought by EO data in a more holistic way.

ESA will continue efforts to expand its current framework and to improve its robustness and reliability. In particular, ESA aims to improve its ex-ante assessments of the projected socio-economic value of space proposals submitted to the Ministers for decision. It is also exploring possible ways to measure non-economic aspects in a way that is sufficiently structured and acceptable to its decision-makers. To build its knowledge, ESA regularly analyses the benefits accrued in the past, in close interaction with data users and beneficiaries through e.g. collection of use cases, expert interviews and surveys. Theoretical, potential benefits are tested on the ground against real-life examples, and the lessons learnt from the analysis of the benefits actually accrued feed the forecast of those that have not yet materialised (from future missions but also from current, underexploited ones). As more studies become available and experience is gained worldwide, ESA is examining the possibility of methodologically reinforcing its activities, including through meta-analyses of past and third-party studies. In the future, it should become easier to benchmark findings and compare them with results from past studies, recurrently drawing lessons to further fine-tune approaches. These should provide for more opportunities to compare results with similar studies performed by other space agencies in Europe and elsewhere. In this context, the EU's Destination Earth initiative is expected to trigger improvements in modelling and predictive capacities that expand beyond the geo-bio-physical observables and include social and economic modelling supporting the delineation of potential value-of-information alternative scenarios, thereby also contributing to increased knowledge including in terms of impacts assessments.

ESA engages in critical reviews and cooperates with different entities to ever increase the robustness of its analyses. It works together with its Member States, the European Commission, the OECD and other stakeholders to identify appropriate methodologies. It has set up a Space Economy Expert Group composed by experts from its Member, Associate and Cooperating States that engages in sharing good practices and advises and assists the Executive in the identification of Member States' priorities (e.g., in terms of areas to be assessed and measured in support of their national resources allocation processes). The Agency also joins national and international efforts and encourages scientific research in view of setting shared foundations for valuing EO data and information. Furthermore, it cooperates with other agencies and groups with whom relevant research projects for new methodologies and evaluation approaches are in the making, such as the GEOValue community of practice and the European Council for Nuclear Research. By making its efforts and strategies openly available, ESA aims at further reinforcing its ties with academia and at stimulating research in the different areas concerned, bringing together economic and social scientists to advance knowledge and practice in the field.

AUTHOR CONTRIBUTIONS

AT and AL contributed for all matters related to Earth Observations, including EO-specific indicators and use cases. SW, LL and CM are economists and contributed for all the economic aspects including across space applications other than Earth Observations.

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