A Conceptual Framework for Assessing the Benefits of a Global Earth Observation System of Systems

Steffen Fritz, Robert J. Scholes, Michael Obersteiner, Jetske Bouma, and Belinda Reyers

***Abstract*—The aim of the Global Earth Observation System-of-Systems (GEOSS) is to improve the information available to decision makers, at all levels, relating to human health and safety, protection of the global environment, the reduction of losses from natural disasters, and achieving sustainable development. Specifically, GEOSS proposes that better international cooperation in the collection, interpretation, and sharing of Earth observation information is an important and cost-effective mechanism for achieving this aim. While there is a widespread intuition that this proposition is correct, at some point the following question needs to be answered: how much additional investment in Earth observation (and specifically, in its international integration) is enough? This leads directly to some challenging subsidiary questions, such as how can the benefits of Earth observation be assessed? What are the incremental costs of GEOSS? Are there societal benefit areas where the return on investment is higher than in others? The Geo-Bene Project has developed a "benefit chain" concept as a framework for addressing these questions. The basic idea is that an incremental improvement in the observing system (including its data collection, interpretation and information-sharing aspects) will result in an improvement in the quality of decisions based on that information. In turn, this will lead to better societal outcomes, which have a value. This incremental value must be judged against the incremental cost of the improved observation system. Since in many cases there will be large uncertainties in the estimation of both the costs and the benefits, and it may not be possible to express them in comparable monetary terms, we show how order-of-magnitude approaches and a qualitative understanding of the shape of the cost and benefit curves can help guide rational investment decisions in Earth Observation Systems.**

***Index Terms*—Benefit assessment, conceptual framework, cost-benefit analysis, Global Earth Observation System-of-Systems (GEOSS).**

I. Introduction

ALL SOCIETIES make observations about the environment that surrounds them, and make decisions based to some extent on this information. This is true for all cultures, in all parts of the world, and at all levels of organization: from the farming family that anxiously scans the sky for rain to multinational high-cost efforts, such as programs that observe the Earth from space. Therefore, Earth Observation Systems, broadly defined, are nothing new and societies have implicitly adjusted the amount of effort that they put into such activities such that it satisfies some intuitive balance with the benefits that are expected from the activity. With the emergence in modern times of nation-states, and the rise of science as the dominant mode of making and interpreting such observations, much of the formal activity in Earth observation has been institutionally concentrated at the level of national technical agencies. For example, virtually every country in the world has some form of weather service that collects climate data, and a statistical office that collates agriculture and natural resource information. Clearly, people see benefit in collecting and sharing information and that there are economies of scale to doing so at a national level. The central premise of the Global Earth Observation System-of-Systems (GEOSS), implemented by the intergovernmental Group on Earth Observations (GEO) at its third summit in Brussels in February, 2004 (IPTT 2004), is that these benefits and economies extend to a supra-national scale as well. But whereas political and technical mechanisms exist at the national level to "right-size" Earth observation activities (at least in principle, although there is little evidence that they have in fact been optimized), no such mechanisms exist at the international level. If the GEOSS concept is to become a sustained and operational reality it is necessary to move beyond the gut-feeling that the benefits of international collaboration in this field far outweigh the incremental costs, to actually providing a rational, quantified, and persuasive argument for a particular magnitude of investment. Nine benefit areas to society have been defined, which would profit from such an investment. These are health, biodiversity, ecosystems, weather, climate, agriculture, disaster, energy, and water. The Geo-Bene Research Project, an European Union (EU) funded project within the sixth framework program, aims to provide the basis for making a systematic and transparent comparison of informational benefits and costs for the different societal benefit areas as well as for GEOSS as a whole. This paper elaborates the conceptual framework of the Geo-Bene Project.

GEOSS and an assessment of it seem to be more important than ever since two major drivers of Earth Observation Systems have dramatically changed over the past few decades. The first is the understanding that there are powerful biospheric and socio-economic processes that operate at scales greater than the nation. An example of the former is the phenomenon of global climate change and of the latter is the globalization of trade. These can have important (even dominant) consequences

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for the wellbeing of the inhabitants of a particular country, but cannot be observed, understood or predicted by systems that confine themselves to national boundaries. As a result, the major powers have developed Regional or Global Observation Systems, largely for their own purposes. Smaller, poorer, and less technologically-advanced societies have been unable to do so, and depend on what they can glean from local observations and what is made available from global systems. Clearly, there are cost efficiencies to be gained by integrating the efforts of all nations at this scale, and benefits to be had from distributing the information more broadly. The strong development of international collaboration in weather observations, through the World Meteorological Organization, is a case in point.

The second driver of change in Earth Observation (EO) Systems is technology. There are now ways of observing the Earth that were previously impractical (such as measurement of the sea-surface temperature in remote parts of the ocean), and for sharing, through information and communications technology, unprecedented volumes of information, very rapidly and broadly. These two drivers have created the conditions for the emergence of GEOSS, based (both out of necessity and good sense) on the preexistence of an elaborate set of partial or smaller scale subsystems.

II. Review of Benefit Assessments Which Relate to GEOSS

Apart from a quite extensive literature on the costs and benefits of weather forecasts [10], [30] there is relatively little available literature on these values in other fields of EO (e.g., biodiversity, water). The cost side, in particular, shows a current lack of compiled information. This is true both for big, concerted efforts such as satellite missions, but also for *in-situ* networks, such as weather stations or river hydrographs. It is especially true for determining the incremental costs of the information dissemination systems that follow downstream of a data acquisition platform. The costs of satellite missions are usually insufficiently itemized (for ENVISAT only the full program costs are given, 2.3 billion Euros) or entirely missing (e.g., the entry on Landsat 5 in the Satellite Encyclopedia) to be able to understand their incremental components. Also, the Organization for Economic Cooperation and Development OECD has identified this gap and will soon publish a study entitled “The Space Economy at a Glance” [38]. Nevertheless, program cost summaries exist for some satellite missions, such as those described by [46]. This study points out that costs can be reduced by a factor of 2–10, if “virtual constellations” of collaborating satellite platforms are put in place [45].

The extremely distributed nature of *in situ* observation systems makes estimation of the total or incremental costs difficult. For example, in Europe, investment costs are largely unknown due to the fragmented ownership and funding structure of the EU, each sponsoring organization only reporting their own contribution to the common budget [15]. Even within a single country, there are often several agencies collecting essentially the same data—for example, in South Africa, rainfall data are collected by the South African Weather Service, the National Department of Agriculture, and the Department of Water Affairs and Forestry, not to mention hundreds of private individuals, corporations, and nongovernmental organizations.

As previously indicated, many studies illustrate the potential benefit which could be gained from an improved weather forecast system: with respect to mitigating natural hazards [49], increasing crop yield [1], food trade [9], or road safety [2]. These studies attempt to measure the value of improved weather information in absolute terms. They show that simulation modeling can provide insight into the relationship between improved weather information and the resultant economic gain. Other research has attempted to use contingent valuation (willingness-to-pay) as an alternative to the usual cost avoidance approach, incorporating the commercial sector (for example, television and film companies, recreation and sports, agriculture, hotel and catering, and institutions such as sports and hospitals).

More recent studies have started to look at other aspects of EO. For example, two studies have been conducted by Pricewaterhouse Coopers on contract to the European Space Agency. The first was to support the development of a business plan for the GALILEO Programme [43]. The second was a benefit assessment of the Global Monitoring for Environment and Security (GMES) Programme [44]. Whereas the study on GALILEO did not consider it in the context of GEOSS, the GMES study explicitly investigates the impact of an existing and functional GMES system versus the nonexistence of such a system (termed the “without GMES scenario”), and notes that GMES is the European contribution to GEOSS. The GMES study is the only current extensive study which tries to assess the benefit of the European part of GEOSS. The Pricewaterhouse Coopers study undertook a strategic as well as a quantitative analysis. The strategic analysis looked at strategic benefits in order to determine what GMES as a strategic and political investment is trying to achieve. In a second, so-called “bottom up” study, which encompassed a quantitative as well as a qualitative assessment, the macro-economic benefits and economic efficiency savings were assessed, largely through consultation of key stakeholders.

The Pricewaterhouse Coopers study pointed out that placing a monetary value on all the potential impacts of GMES was not practical, since the wider societal impacts were not amenable to monetary quantification. In addition, the relationship between the improved EO information and the potential welfare impacts was not always clear. The GMES study, therefore, adopted an approach of consultation with key stakeholders. A large group of experts were asked to prioritize benefit areas and to assess what the most important benefits of GMES were expected to be. The advantage of using expert consultation is that it is a relatively quick way to get an indication of the range of expected benefits. The disadvantage is that outcomes strongly depend on the experts consulted. The attribution of benefits usually remains anonymous. The risk is that only those stakeholders who are really interested in the project will provide information. As a result, some benefit areas will be described in more detail and the study will be biased, typically with an optimistic view of benefits. It is crucial that expert consultation studies are transparent about who was consulted and the range of answers provided [44]. The GMES study was criticized for not taking all benefit areas equally into account (GMES bureau, personal communication). Furthermore, it used a statistical value of life de-

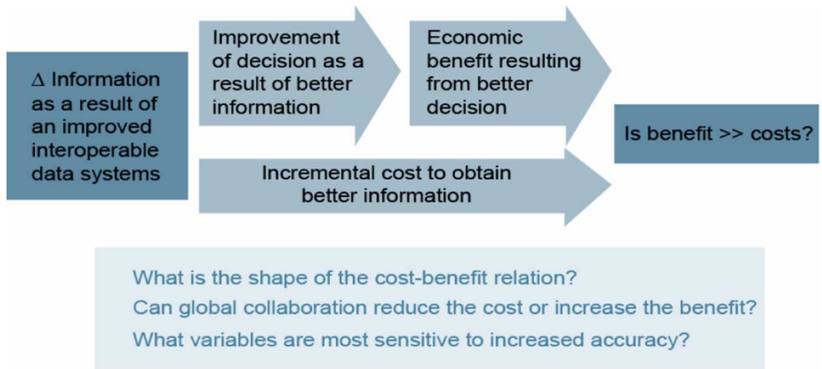

Fig. 1. Benefit chain concept. In the benefit chain concept benefits as well as costs must be considered. The concept looks at incremental changes of costs and benefits with respect to the already existing observing system (e.g., national). A logical causal benefit pathway (in steps if necessary) is established and much of the analysis is semi-quantitative ('is the benefit an order of magnitude greater than the cost') or qualitative (what is the shape of the cost-benefit curve).

fined by [19] which differs between developing and developed countries: an approach that has been criticized as being morally indefensible [19]. Moreover, the study only presented the average of the estimates, largely ignoring the range of responses and the uncertainties involved. It did not provide insight into the incremental benefits that various alternate EO investments could have, nor the relative importance of improved EO information for the wider value chain.

Another expert opinion-based study of the benefits of GEOSS was carried out by the Environmental Protection Agency (EPA) of the United States of America. The EPA created an interactive US map, allowing the user to view a fact sheet on the benefits of GEOSS for each state. The fact sheet for each state contained information from expert consultation mainly covering the natural disaster benefit area: looking at tornadoes, hurricanes, floods, earthquakes, and droughts. In some states, benefit areas such as health (e.g., air quality, harmful aquatic blooms) and ecosystems (e.g., reduction of erosion, pollution in watersheds, fish stocks) were also covered. Due to the nature of the study consulting experts in each state separately, some of the global issues such as tracking global change are mentioned in some states, but not consistently in all states.

Value of Information (VOI) theory has been developed by economists working in fields as diverse as stock market trading and manufacturing. A working paper by Macauley [35] attempts to apply the VOI theory and methods to show how space-based EO can improve natural resource management. This study found that the value of space-derived data depends largely on four factors: 1) how uncertain decision makers are; 2) what is at stake as an outcome of their decisions; 3) how much will it cost to use the information to make decisions; and 4) what is the price of the next best substitute for the information. Reference [35] describes three groups of methods in which VOI can be measured. In the first group, the value of information is measured by gains in output or productivity. In the second group the value of information is inferred under the hypothesis that it is capitalized into the prices of goods and services (hedonic pricing). The third group tries to estimate the value of improved information based on the contingent valuation. In contingent valuation approaches, stakeholders are asked how much they would be willing to pay for certain categories of information.

Reference [35] does not clarify how welfare impacts can be attributed to the availability of improved EO information nor does it demonstrate how the incremental costs and benefits of information might be assessed. Finally, all of these studies described, which evaluate the impact of improved information derived from EO, assess only benefits whereas the costs of providing better EO information and in particularly the costs of sharing data and building the necessary spatial data infrastructure [15] are seldom assessed. In response to these shortcomings, we developed a benefit chain concept within our Geo-Bene Project, which will be elaborated in Section III.

III. Benefit Chain Concept

The logic behind the benefit chain concept is that through global cooperation in EO systems, improved information (in terms of quality, quantity or topical coverage) will become available to the decision maker. Better-informed decisions will lead to a societal benefit relative to the probable outcome without improved information. This benefit can be in some circumstances be measured and directly compared to the incremental costs of global collaboration. In other circumstances it will be more difficult to directly estimate the benefits—for instance, in the case of not directly marketable benefits such as biodiversity, or for certain downstream or indirect benefits.

We postulate that it is not possible to go from an incremental increase in effort in the observation system to an incremental gain in human wellbeing in a single step, given the multiple factors that influence human wellbeing. It is necessary to build a plausible causal chain that establishes a *prima facie* case that all or part of the benefit is traceable to the EO system change. At a minimum this logical chain has two steps: demonstrating that the improved observations have some impact on decision-making; and then that the resultant decisions led to an improvement in wellbeing (see Fig. 1).

We suggest that the costs can be adequately assessed in a single-step process. The difficulties lie mostly in accessing the information in a way that allows the incremental component to be quantified. Most such investments are made by public agencies, so in principle the costs should be documented, available in the public domain and already in monetary terms. However, in practice costs are often reported in a nontransparent and aggregated way, or are distributed across so many cost centers that it is hard to assemble them in a coherent fashion. With respect to the cost benefit ratio, it is probably too much to ask that this ratio be lower for the choice of action under consideration than for any other possible action that could have been taken, since that would lead to "analysis paralysis"—the alternatives are effectively infinite, and the uncertainties are high. But accounting for both the costs and benefits of additional GEO investments does provide a rational way of prioritizing between a small set of alternatives within the EO domain, and provides a filter to avoid high-cost, low-benefit actions.

The benefit value we refer to is the economic value rather than the financial value. In other words, it is the value of the benefit to the society as a whole, not just to the entities providing the information. EO agencies have discovered that societal value in the environmental field is not synonymous with the price the market is willing and able to pay for the information. EO are generally "public goods," not traded in a marketplace. The beneficiaries may, for instance, be the poor, who have no way of paying the true value of the information.

"Value" does not necessarily have to be expressed in monetary terms, though it is often convenient to do so. It can, for instance, be expressed as the number of human lives saved, or as a ranked set of preferences. Assigning a monetary value to the benefit should not become an obsession. Rather, it is the final step in a logical chain that links the action to the benefit. The real intellectual effort should go into establishing the causal chain by which that value is realized, and understanding whether the value will increase proportionally with increased observational effort, less than proportionally or more than proportionally. Even if quantifying the monetary value is not possible—the qualitative shape of the cost:benefit relation, and a rough ranking of the cost:benefit ratios provides enough information for rational guidance of the GEOSS.

Hence, even though it will not always be possible to attribute a reliable monetary value to the economic benefit, which results from a better decision, it is usually possible to know the shape of the relation between benefit and increasing observation effort, and the corresponding relation between cost and effort. Do the benefits increase disproportionately to the increased observational effort, due to synergies or efficiencies achieved, or do they tend to saturate as the problem becomes less and less information-limited? Do the costs rise steeply because new technology needs to be deployed or very little because the fixed-cost part of the investment is already made? Can we say, on the basis of order-of-magnitude calculations, that the benefit will be much higher than the incremental cost? If so, we are probably far below the hypothetical optimum point where the cost and benefit curves intersect, and further investment is called for. Another question to ask is: What variables are most sensitive to improvements in accuracy?, i.e., where will the largest increase in the benefit to society be seen? Is the incremental cost proportionately sensitive?

The benefit chain concept can be examined per societal benefit area or sub-benefit area. It can be also applied to particular GEOSS activities, such as the coordination of space observations, or standardization of communication protocols. However, the more indirect the benefits, the more difficult the value of information will be to assess. The particular role of GEOSS is the "globalization" of the observing system. The particular question which must be asked in this context is whether global collaboration can either reduce the costs, or increase the benefit, of EO systems. If this can be demonstrated, and the incremental benefits are judged to exceed the incremental costs, then the effort involved in establishing collaboration in global EO systems can be justified, *even if the total EO system costs exceed the total benefits, or if the total costs and benefits are unknown*. Basically, all that needs to be known is whether the incremental effort is moving things in the right direction, or not.

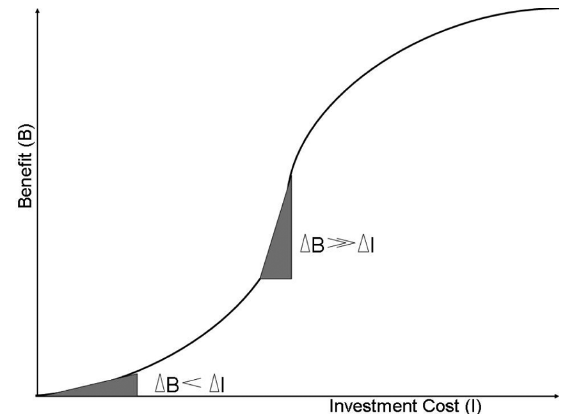

Fig. 2. Hypothetical curve of a cost benefit relationship. It is constructed by sketching a benefit-to-effort and a cost-to-effort relation, and then extracting the costs and benefits for a given level of effort, and building a cost-benefit curve.

There has been extensive debate about whether or not it is appropriate to calculate a "total benefit" for goods or services which are essential to life, and non-substitutable [11], [24]. For example, if all human life depends on the presence of water—and nothing else can take its place—then the value of water presumably approaches infinity, as the supply declines towards the minimum. This is just one of many examples. We, therefore, find it more appropriate to think in terms of the marginal benefit—in other words, the increased benefit that results ultimately from a small increase in the EO effort. Given that the world already has a large investment in EO, and that GEOSS is explicitly built upon this framework, it is also inescapable that we should be looking at the incremental cost of enhancing the system, rather than the total cost. The curve itself (see Fig. 2) can vary across Societal Benefit Areas and depends on the type of activity (see Table I, Section III-B) that is undertaken. If we can illustrate that the marginally-increased investment into GEOSS results in a much higher marginal benefit, then the investment is well spent. On the other hand, if we clearly see that the marginal benefit we gain is much lower than the incremental investment cost, then justification for such an activity is difficult. In order to identify at which point we are on this cost-benefit curve it is necessary to get a rough estimate of additional investment required to result in some at least qualitatively measurable benefit. Moreover, it might be possible to understand at which point further investment will not lead to a substantial increase in the benefit. For example, at a certain point the resolution of a sensor will be sufficient to gain most of the benefit, further investment in an increased resolution will only lead to a negligible extra benefit.

We feel that the benefit chain concept is a broad and robust way of looking at the cost-benefit ratio. It can be used in conjunction with a variety of specific methods to quantify particular steps in the chain: for instance, stakeholder surveys, modeling tools, decision theory, and meta-analysis. However, there are a

TABLE I
IMPROVEMENT TO BE REALIZED THROUGH GEOSS, EFFECTS, AND IMPORTANCE

Improvement to be realized	**Effect**	**Selected Examples**	**Importance within GEOSS**
Optimization of the overall observation strategy, avoiding unnecessary redundancy in EO missions and systems	Reduction of costs	Recent co-ordination between EUOMETSAT, CNES, NOAA, NASA, National Geographic and joint research announcement of the Ocean Surface topology science team (Eumetsat and CNES, 2007)	High
More frequent observation due to better co-ordination, e.g. by having constellations of satellites, wider swathes and automated in situ systems	Better temporal resolution, ability to resolve rapid or short-duration phenomena	The shortened revisit time that can be achieved by combining the optical-band observations by Modis (2x), MERIS and SeaWIFS	Medium
Better sensors (e.g. more bands, different technologies, greater sensitivity)	More types of observations available, greater accuracy	Case study on hyper spectral sensors	Medium
More timely information delivery	Near-real time observations for issues that require quick response	The AFIS fire warning system integrates data from MSG and Modis thermal sensors with weather data and sends a message to the cellphones of people in the fire path within minutes of fire detection	Medium
Better integration of satellite and in-situ EO measurements	Calibration and validation of satellite products; better interpolation of in situ measurements; synergistic hybrid products.	EU fosters research in in-situ and satellite integration studies	High
Models with higher predictive capacity	More accurate representations of reality and better prediction	See page climate models etc.	Low
Better international co-operation on satellite design and data exchange	Lower development costs, greater necessary redundancy of sensors, better	Members in GEOSS has increased, more international initiatives Members of the Open Geospatial Consortium has increased	High
standards	interoperability of data	(from 20 members in 1994) the OGC now has 250 members.. Virtual constellations More free data access the GEOSS portal	
Long term continuity and emphasis on systems operationally	Guarantee of continuous observations for operational purposes	The GMES project? Which focuses on operational systems	High
Identification and closing of observation or information gaps	Spatially and topically comprehensive system	Upper atmosphere observation over Africa currently limit the predictive capacity of weather forecast models over a wider area	High
User engagement and user-oriented system design	A system that better addresses societal needs	There is currently no operational system for biodiversity observation, despite the urgent need and the existence of treaty based targets for reducing biodiversity loss	High
Improvement though model and data comparison	Improvement of quality and agreement in models	The TRANSCOM intercomparison of atmospheric transport as predicted by GCMs, against in situ observations of tracer gases	Low

currently a number of limitations to this approach, which need to be considered. These are outlined in Section III-A.

A. *Limitations to the Approach*

We currently do not know the incremental costs of certain components of GEOSS. In particular, we know too little about the costs of a global spatial data infrastructure. Since we cannot assess the costs of national systems, we will have problems in estimating the costs for a global system. The statement made by David Rhind (2000), former Chief Executive of the Ordnance Survey of Great Britain is partially still valid today and shows the problem we face:

> "We know very little about how much money and other resources are actually being expended on maintenance of the existing national Spatial Data Infrastructures, let alone on creation of enhanced versions of them, or who is providing these resources. In broad terms, we do not know whether these resources are being applied wisely."

It would seem helpful, therefore, to carry out some sound accounting of this expenditure: arguments for adding to it or for using it more effectively or efficiently are unconvincing if we do not know the present practice. Even though we do not know the costs associated with globalization of the system, we should still try though various methods (e.g., expert opinion surveys) to get first estimates of the incremental costs. We are not necessarily looking at absolute figures, but trying to get an understanding of where we are on the cost-benefit curve.

B. *Minimum Requirements to Assess the Benefit Chain*

We acknowledge that a complete assessment of the full benefit chain for all observations and impacts is not practically achievable. We therefore propose a minimum information guideline. If GEOSS is justified using this conservative approach, more elaborate assessments should only increase the confidence in the finding.

1) Identify the actions that are proposed to improve the quantity or quality of information. These constitute "increments of observational effort."
2) Describe the pathway by which the increase in information leads to a welfare benefit. How will the information be used by the policy makers and what are the options available to them? Do these options change if more information becomes available? Is the probability of their success improved with more or better information?
3) Describe, and if possible, quantify the incremental cost components that would be associated with the actions.
4) Describe the shape of benefit-effort and cost-effort curves in the vicinity of the current state. Such information can be gained by expert consultation.
5) Attempt to make order-of magnitude estimates of potential incremental costs and benefits.

If it is possible to upscale the information from local or regional case studies to a global level, what global conclusions can be drawn from this exercise? To what extent do these sub-global studies depend on global information? Can globalization of the information that is used in them, or produced by them, lead to a greater net benefit?

If possible, assessments should attempt to go beyond this minimum by for instance, the following:

- assessment of the entire value chain, including incremental costs;
- examination of the geographical distribution of costs and benefits, qualitatively or quantitatively;
- determination of the degree to which the societal issue is information limited. For instance, will decision makers actually have the resources to take action based on the improved information?
- undertaking sensitivity studies in order to understand which variables (or in which part of the world) better observation will lead to the greatest improvement of welfare;
- using a technology-maturity approach [32] in order to have an insight into the comparative investment strategy between societal benefit areas; this would help to identify where the steepest part of the cost and benefit curve is likely to lie;
- examination of the cross benefit effects since benefits in one area can have multiple benefits in other societal benefit areas; linkages between benefit areas are outlined in the GEOSS implementation plan [25].

The adoption of an "incremental effort, incremental benefit and incremental cost" basis for investment decision-making in relation to EO systems makes it necessary to define a baseline. Sections III-C–III-E describe how the GEOSS baseline could be defined, what potential is to be realized through GEOSS and what the current limitations are to apply the entire benefit chain concept. Section III provides examples of applying the benefit chain concept in three societal benefit areas.

C. Defining the Baseline of GEOSS

In order to be able to assess, quantitatively or qualitatively, the value of improved information brought by GEOSS, it is necessary to define what GEOSS actually is. A working definition can be found in the GEOSS Implementation Plan: "The GEOSS is to be a "distributed system of systems," building upon current cooperative efforts among existing observing and processing systems, working within their own mandates, and delivering a system that provides timely, useful and accurate data, information, products and services to any and all legitimate users around the world. GEOSS will also encourage and accommodate the addition of new components to fill existing knowledge and service gaps" [14].

Therefore, GEOSS is not an entirely new system. Its aim is to link existing and independent systems into an integrated network that will appear, from the user's perspective, as if it were a single system. It is a natural extension to what has already been achieved between international organizations in terms of data sharing cooperation [34]. GEOSS is about connecting the dots—linking current existing national programs into a global system of systems, and then filling the gaps that become apparent from the unified view of the system.

Therefore, the incremental cost of GEOSS includes only: 1) the costs of interaction between existing systems, such as increased bandwidth that may be necessary and the reprogramming needed to make data accessible to an integrated system and 2) the cost of filling any gaps identified by the GEOSS and deemed to be necessary to fill in order to achieve its objectives. Note that the costs are substantially more than simply the costs of sustaining the GEO Secretariat and its work program. Most of the real incremental costs will be borne by national programs.

The incremental benefit is that fraction of the total benefit attributed to EO information that can reasonably be attributed to activities catalyzed by the GEOSS process. The "without GEOSS" scenario does not assume a complete absence of EO. It allows for what existed and was globally accessible prior to 2004 and its likely subsequent growth as independent systems. The evaluation of the "without GEOSS" baseline means hypothesizing about what would have happened if GEOSS had not been implemented and determining the degree to which the resultant information gaps could have been substituted from other sources. Due to the fact that a number of EO activities exist on a national level independently of GEOSS it is difficult to distinguish which activities can be attributed to GEOSS, and which would have happened anyway. This difficulty was noted in the [44], but is not unique to EO assessment studies. Baselines are always counterfactual. There is no fully objective way of measuring what would have happened if the current path had not been chosen. For example, one of the key baselines in the widely-used Intergovernmental Panel on Climate Change scenarios is conceptually "business-as-usual" case (although it is not called that, but given the bland title "A1"). It is not a simple forward projection of current trends, but assumes that certain energy efficiency actions would take place anyway without regulatory intervention. The decision of what to include and exclude in the baseline is subjective, but needs to be explained and justified in narrative text. The test is the reasonableness of the scenario, not absolute proof that it would have happened that way.

D. Potential to be Realized Through GEOSS

These improvements brought about by GEOSS can occur in a number of different ways: though technical improvements in the field of observations, both *in-situ* and satellite-based; through greater reliability and information content gained in the synthesis, modeling, and interpretation of data; and through facilitating the delivery of information to the end user, in a form that suits their needs. In the field of satellite observations, international coordination of space platforms and the instruments they carry, along with the data systems that distribute the information, would improve the reliability and frequency of observations, the number of spectral bands that can be realized, and the spatial resolution that can be achieved. A denser and better-located network of interconnected and intercalibrated *in-situ* sensors would increase the timeliness, coverage and reliability of information on the many topics that cannot adequately be observed from space alone. More sophisticated, higher-resolution models (e.g., Global Circulation Models) are being continuously developed and improved, and interact synergistically with better input data from space and the Earth's surface to convert raw observational data into information that helps the user to make better decisions. It is not beneficial for GEOSS to completely eliminate "duplication of effort" in the modeling domain, because having several independent models serves to foster innovation and increase the confidence in the predictions. But there is benefit to be had from some rationalization, as well as from model inter-comparison exercises, standardization of inputs and outputs, collaboration in capacity building, and sharing of modular code where it clearly represents best practice.

The particular emphasis of GEOSS is to foster international collaboration and international standards defined by the Open Geospatial Consortium (OGC). As outlined in the 10-year implementation plan, the success of GEOSS will depend on data and information providers accepting and implementing a set of interoperability arrangements. These standards allow the information flow of geographic feature (e.g., Web Feature Service) or raster data (e.g., Web Map Service) over the Internet. On the one hand these standards allows simple searching facilities of the standardized metadata catalogues, making data flow more efficient and therefore reducing costs. On the other hand, a chain of OGC Web services can be invoiced using standard web chaining mechanisms to produce value-added products. These value added information products are produced by automated procedures involving different data and process servers on the internet [41].

One of the tasks of GEOSS is to identify current data and information gaps (spatially, temporally, or with respect to topical coverage), and to contribute to the long term continuity of GEO. Table I identifies the improvements where GEOSS could play a role in an illustrative and non-comprehensive manner. The benefit chain concept can be applied to any improvements, which will be realized in the future. However, some of the improvements cannot be exclusively realized though GEOSS, but need to be supported by other national and sub-national activities and other institutional mechanisms. However, in particular for the high priority areas (importance high, see Table I) of GEOSS, we can apply the benefit chain concept and attribute the benefits exclusively to GEOSS.

E. Examples of Application of the Benefit Chain Concept

Three examples, derived from early stages of the Geo-Bene Project, are used to illustrate how the benefit chain concept works. The first example, from the natural disaster societal benefit area, uses a model to examine the dependence of fire fighting success on higher resolution weather forecast information. The second example illustrates how the benefit chain concept can be applied in a case where the benefits are non-marketable, in this case through biodiversity conservation. The third example shows that a stakeholder survey can be designed in a way that information on the incremental benefit in relation to incremental costs can be acquired.

1) Example One—Better Fire Control Thanks to Improved Weather Forecasts: This case study (elaborated by [31]) considers a simple model of success in fighting forest fires in Spain and Portugal. The Nesterov fire index is used to assess fire danger on a daily basis. It is assumed that the index is used as the basic indicator for decision making. Official aircraft-based forest patrolling rules are applied (based on those in force in the Russian Federation). In the model, total area burned and the total observed area are considered in terms of the benefit of having either coarse- or fine-resolution data available.

The benefit pathway is that through better-calibrated and higher-resolution satellite data supported by *in-situ* measurements, a more targeted and efficient patrolling system is possible. The benefit can be expressed both through reductions in the area burned and through having to spend less money on patrolling. The decision that is based on EO data is the optimal path and effort that is spent in patrolling for fires.

The baseline in the data-poor (or non-GEOSS) scenario is simulated by using coarse-resolution weather forecast data. This is comparable with the currently available global datasets such as degree resolution data from the European Center for Medium Range Weather Forecasting (ECMWF). In Europe, as a result of international collaboration, there are better and higher-resolution forecasts available, informed by *in situ* meteorological observations. This is the "GEOSS scenario." It is possible to model the stochastic process of fire spread and thus to estimate how much area could be saved if the fire is detected quickly as a result of an appropriately-designed patrolling pattern. In addition, we are able to simulate how *in-situ* data used in combination with remote sensing data contributes to the benefit achieved. Simulation results reveal that by using the higher resolution GEOSS scenario (corresponding to the European 50–km GRID) results in a reduction of area burnt of around 21% as well as an overall reduction of patrols of 4%. Given the increase of forest fires over the last decades and the high damage caused by these fires in Portugal and Spain a reduction of 21% of the area burnt would lead to an enormous societal benefit. In order to get an estimate of the costs saved we calculated the saved timber and its economic value by using FAO statistics of the year 2000. The timber saved is estimated to be approximately 4 Million Euro. This number is derived from the following: 22 169 ha burned area saved, 44 m^3/ha, 20% economic accessibility, 40% Stem Volume, 50 EUR/m^3 $(FAO\text{-Stat} + \text{Expert})$.

Our knowledge of the incremental costs of these data is uncertain, but we estimate that they approximate making the data available real time for forest fighting (which is the incremental necessity for this application). This cost will be in the order of 130 000 Euros annually, plus 2 Million Euro for a once off filtering algorithm, which removes errors in the dataset. The cost/benefit ratio points towards a higher incremental benefit than the incremental costs.

2) Example Two—Improved Data for Conservation Planning: This case study demonstrates the benefits of replacing commonly available coarse scale global data (the non GEOSS scenario) with finer scale data in conservation decision making. These finer scale data are comparable with those expected from GEOSS and can thus be used to estimate the potential benefits of GEOSS data. We then contrast the benefits of these data improvements with the costs of the improvements.

South Africa, like most countries, is attempting to increase the amount of land and water area under some form of conservation (e.g., national parks, conservancies, easements). The current extent of the formal protected areas network is approximately 6% and biased towards mountainous or tourist areas often with low agricultural potential resulting in large gaps in the national conservation area network [21]. Efforts to reduce these gaps must ensure that new protected areas are optimally located so as to represent a full sample of the country's biodiversity in the most cost efficient manner. A sophisticated set of systematic conservation planning tools is available for this purpose [36], [42]. These tools identify spatially explicit priority areas for conservation action (e.g., land acquisition, land stewardship and management, easements, finer scale planning) and feed into land use decision making processes across the country from local to national scales supported by legislation. These tools require spatially explicit data on the distribution of biodiversity (species, ecosystems), threats facing biodiversity (e.g., land conversion, alien invasive plants) and current conservation efforts. These data are often available at coarse (1:1 000 000) global or continental scales (e.g., WWF ecoregions [40],[22], African Mammal Databank (http://www.gisbau.uniroma1.it/amd/index.htm). Several authors have highlighted that comprehensive data sets such as point locality data for specific tax and fine-scale land class and habitat transformation maps are invariably lacking [12], especially in developing countries which harbor most of the world's unprotected and vulnerable biodiversity [5]. South Africa is fortunate as an exception to this rule in that it is both a "biodiversity-rich" country and has relatively good biodiversity data [6]. These national scale data (1:250 000) were used to conduct a National Spatial Biodiversity Assessment [37], [44], which identified broad scale priority areas for national conservation action. As part of this assessment, a comparison was made of the outputs of the NSBA (the GEOSS scenario) and the outputs of the same assessment based on the coarse global scale data (the non GEOSS scenario), in an effort to assess the benefits of improved national scale data.

The coarse scale data led to a 9% overestimate of priority areas identified by the national scale data and a 10% underestimate in other areas (Jonas pers comm.). Turning these differences into benefit estimates is complex. A simple proxy would be the cost consequences of these over or underestimates. Estimates of conservation costs developed in the Cape Floristic Region of South Africa [20] found that implementing a conservation area network (of protected areas and other off reserve mechanisms) of 2.8 million hectares would result in a once off cost of 627 million Euros with annual costs totaling 29 million Euros (all costs are calculated in Euros for the year 2000 using annual national inflation rates and 2000 exchange rates). By just applying these costs to the priority areas identified in the NSBA a 9% (or 5 million ha) overestimate would cost over 1.2 billion Euros in once off costs with annual management costs of the overestimated area equivalent to 57 million Euros. It is important to note that the priority areas identified in the NSBA were not intended to become a conservation area network necessarily, but rather to direct future sub-national conservation efforts and finer scale conservation plans. The cost differences are however a useful indication of the potential benefits of improved data. The costs or loss of benefits associated with the underestimates are more complex to assess and are still in progress.

Calculating the costs associated with improved datasets presents a challenge as these data have been built up over a number of years by a number of institutions. The datasets are also highly variable in the time and effort taken to collate them. Costs of biodiversity data that are available are provided in Table II.

The coarse and fine scale analyses described previously used the GLC and SANLC datasets described in Table II, respectively. SANLC covers an area of less than 1% of the Earth's land surface covered by the GLC. Assuming a linear relationship between area covered and cost we extrapolated that the costs of developing a similar data layer to the SANLC at a global scale would be 100 times more than the GLC (approximately 200 million Euros). When one compares this cost estimate (200 million Euros) with the costs of not having finer scale data (1.2 billion Euros) it appears that the benefits of improved data outweigh the costs by almost an order of magnitude.

TABLE II
COST OF OBTAINING BIODIVERSITY OBSERVATIONS

Database	**Cost (in Euros)**[1]	**Source**
Global land cover (GLC)	2 million	Bartholome, 2004
South Africa National Land Cover (SANLC)	1.76 million	M Thompson pers comm
South Africa Local scale land cover	9000 for an area of 20 000km^2	Rouget et al 2006
National British bird atlas	1.43 million	www.bto.org/**bird atlas**/fundraising/frbritain.htm
National SA Bird Atlas	222 000	sabap2.adu.org.za/faq.php
Uganda Local scale species data	1.12 million for an area of 15 000km^2	(Balmford and Gaston 1999)

Land cover data are only one input data layer in conservation decision making processes, and arguably even finer scale data than SANLC would be required for conservation decisions. Table II provides estimates of the costs of other finer scale biodiversity datasets. These local scale costs allow us to begin to understand the relationship between costs of data development and the benefits of improved data. It would appear that the benefits of moving from global to national data are large and provide significant savings in land acquisition and management costs of conservation. Work is currently in progress to see if these benefits begin to saturate with increased observational effort in collecting local scale data. The costs of these data improvements are variable and seem to depend on the scale and the type of biodiversity data collected. Simple maps of land cover and vegetation types appear to represent a good investment at all scales, while costs of data on detailed species surveys increase significantly at local scales. Despite these costs, [4] demonstrates that investment in high quality biodiversity inventories at a local scale are a very good conservation investment and help ensure cost efficiency in the implementation of expanded protected areas and their management. Given these findings, there is probably still scope for higher-resolution observational effort to yield net benefits to conservation planning in South Africa.

3) Example 3—North Sea Water Quality: An example of using expert and stakeholder consultation for assessing the value of information is provided by the North Sea water quality case [8]. At present, water quality monitoring in the North Sea is mostly based on *in situ* measurement. With GEOSS-type integrated remote sensing information, the temporal and geographical availability of water quality information increases and early warning information becomes available with regard to the prediction of excessive algal bloom. To estimate how such information is required to improve the effectiveness of water quality management in the North Sea we developed a questionnaire that

TABLE III
ADDED VALUE OF REMOTE SENSING INFORMATION FOR WATER QUALITY IN THE NORTH SEA

	Eutrophication		Excessive algal bloom		Sea water clarity	
	Present	*With GEOSS*	*Present*	*With GEOSS*	*Present*	*With GEOSS*
Average expectation of water quality being well monitored	63%	75%	50%	73%	26%	69%
Range in answers	50-100%	80-100%	10-90%	50-100%	10-50%	20-90%

Source: Bouma et al (2008)

we sent to 25 key decision makers, experts and stakeholders. Inspired by [47], we asked decision makers to quantitatively estimate how they expected improved EO information to reduce the uncertainty of their decision making. The response rate was 80%. Table III shows the main results.

The large range in answers is partly related to the differences between stakeholders and experts: leaving out the stakeholders strongly reduces the answer range. To assess the value of information we had to link this information to the potential welfare impacts of possible changes in decision making. In the case of eutrophication and sea water clarity, decision makers could basically do little with the additional information and the main welfare impact was a reduction in monitoring costs. For the example of excessive algal bloom, however, better information makes it possible to transfer fishing nets preventively at 10% of the damage costs [51], whereas without preventive action excessive algal bloom is expected to cause economic damage of approximately 20 million Euro every 5 years [8].

To calculate the economic value of an early warning system for preventing potentially harmful algal blooms, we used Bayesian Decision Theory (see, for example, [28]). Taking the information presented in Table III as the conditional likelihood of information correctly predicting state 1 (potentially harmful algal bloom) and assuming a type II error of 10% (i.e., the probability that the information system incorrectly predicts potentially harmful algal bloom), we could estimate the value of information. Basically, with a 2% probability per week of having potentially harmful algal blooms (for a critical period of approximately 10 weeks), the value of an early warning system would be 74 000 Euro/week. Since this is less than the costs of establishing and maintaining an early warning system, investing in an information system for preventing potentially harmful algal blooms seems to be an economically efficient investment to make.

Outcomes do strongly depend on the assumed accuracy of information (the type II error) and the variance of the respondent results. Accounting for the range in respondent perceptions, the 95% confidence interval for the value of information ranges from 34 000–103 000 Euros/week. Given a break-even point of approximately 50 000 Euros/week, there is a 75% probability that benefits exceed costs. However, if the type II error is larger than 10%, this is no longer the case. In fact, with a type II error of 20%, the value of information becomes nil. Hence, for assessing the value of information it is important to account for the accuracy of the information system, and the range in expert perceptions as well.

IV. DISCUSSION AND CONCLUSION

In 2005, a large proposal was made to DLR (with additional funding from NASA) to support a biomass-measurement satellite mission [27]. Whereas the proposal described all the benefits and the technical requirements of the proposed mission, no information on the cost-benefit relationship was given. The main reason the project was not funded was due to technical limitations as well as the short lifetime of a laser sensor of 3 years, hence relatively high cost (Knorr, personal communication). Even though the proposed mission would have delivered valuable information for the climate research and policy community the project was not funded. This example shows that costs do matter and to be able to at least qualitatively assess the cost/benefit ratio is vital.

We have shown in this conceptual framework paper that it is possible to evaluate the incremental costs and benefits of EO activities in various societal benefit areas in a pragmatic and appropriate way. We have furthermore selected three case studies, where we illustrate the use of the benefit chain concept. As we have pointed out, the incremental costs—benefit relationship is not always equally distributed around the world. Therefore, an important question is how and where these differences occur. For example, in the case of a natural disaster such as a drought, the remedial action a decision maker can take will depend on where the decision maker is (in the drought-affect country or in an aid-donating country) and where the drought is (in a developing or developed country).

The more general question which arises is whether better information necessarily leads to better decision making. As outlined by [33], there are many obstacles to overcome in order to make an optimal decision based on the information content available.

Will GEOSS work better if more nations are involved [34]? Even though we may be able to say that the global incremental benefits of GEOSS outweigh the global incremental costs, this global analysis may not be true at a national scale, for instance in a developing country with an absolute limit on affordability, very pressing competing demands on public resources and major constraints in terms of ability to use the information effectively.

A fully comprehensive cost/benefit assessment of GEOSS is neither possible nor necessary. An order of magnitude estimate will typically be sufficient to demonstrate that an activity is still far from the point at which the incremental costs exceed the incremental benefits. In general, the incremental costs to exchange data and make it accessible and searchable are relatively small in comparison to even a conservative estimate of the benefits achieved by such a process.

Another point which needs to be raised in this context is that sometimes the national systems in isolation might insufficiently address societal benefits. The Group on Earth Observation itself can help to improve the coordination and role of Earth Observation with respect to societal benefits in each country. By providing the GEO forum for different groups to come together has increased the utility of EO on a national as well as trans-national level. Such coordination of different groups requires little or no investment.

The aim of the Geo-Bene Project is to make a "sufficiently comprehensive" assessment of the incremental benefits and costs of GEOSS that the participating (and potentially participating) nations and agencies can justify their continued involvement. To reach this goal a number of challenges need to be overcome. The first big challenge is to construct and document a defensible causal chain between the incremental effort involved in GEOSS, and the societal benefits that could logically result from it. The second challenge is to quantify the benefits in economic terms, particularly the indirect and non-market benefits. The third challenge is to arrive at a reasonable estimate of the incremental costs. The three case studies presented here represent the beginnings of addressing these challenges, but they and other ongoing case studies require refinement, upscaling, and sensitivity analyses before they will serve their full purpose.

In order to tackle these challenges, we have outlined a conceptual framework and made practical guidelines for assessing the benefit chain in a particular case study. We believe that accumulation of a sufficiently rich set of case studies, across many societal benefit areas, parts of the world, and scales of assessment, will permit a meta-analytical evaluation of the GEOSS.

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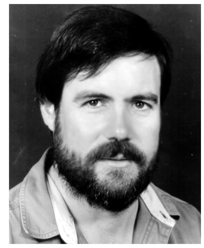

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