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GEO-BENE

Global Earth Observation
Benefit Estimation: Now, Next and Emerging

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[Global Change and Ecosystems]

DELIVERABLE D4 (T21)
METHODOLOGY AND TOOLS REPORT

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Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission	
RE	Restricted to a group specified by the consortium (including the	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Contents

1 Purpose and Overview of Deliverable

The main goal of this deliverable is to describe the different methodologies and tools that were developed for the purposes of assessing the environmental and socio-economic benefits of GEO. GEO-BENE covers a very wide range of methods and methodologies to quantify the value of information from GEOSS. It is important for GEO-BENE to employ a wide selection of approaches to quantify the benefits of GEOSS. Clearly, there is no one silver-bullet methodology to assess benefits in all the different SBAs. In the scholarly literature (Macauley, 2006) summarizes the issues of benefit assessment most pointedly: its economic, environmental or human benefit ranges from values smaller than conventional belief might suggest while in other cases benefits turn out to be so large as to justify nearly infinite amounts of investment. The explanation lies in the characteristics of information (e.g. the SoS), how decision makers use it, and differences in how analysts model this relationship.

It is, thus, the purpose of this deliverable to

(1) Illustrate the methodologies GEO-BENE has developed;

(2) Describe the principle GEO-BENE tools that were developed;

(3) Discuss the methodological implications for decision making.

A comparative study of the different approaches will not be provided since there is already sufficient literature covering the theory of value of information and the specific applications to earth observation (e.g., Macauley, 2006). Furthermore, comparative analysis is highly contextual and can, thus, only yield reasonable insights for particular cases.

2 Revisiting the Assessment Framework and Its Implicit Methodologies

In D3 we illustrated the GEOBENE benefit assessment framework (see Figure 2.1). Within this general framework GEOBENE developed a number of methodologies which again drive the development of specific tools to be used for the specific case studies using quantitative data derived from Global Earth Observations. In order to finally arrive at the total socio-economic system value on global scales we developed a multi-tired approach.

Tire 1, called ***Shot-gun Pathway,*** is based on meta-analysis of already existing assessments published in the peer reviewed and grey literature or from other sources as well as own GEO-BENE assessments. Tire 2 will solely be based on “in-house” assessment using GEO-BENE resources aiming at the assessment of point estimates and ranges of benefits by exploring changes in benefits at the margin and cross margins. Tire 2 type analyses we coined ***Rifle Pathway***.

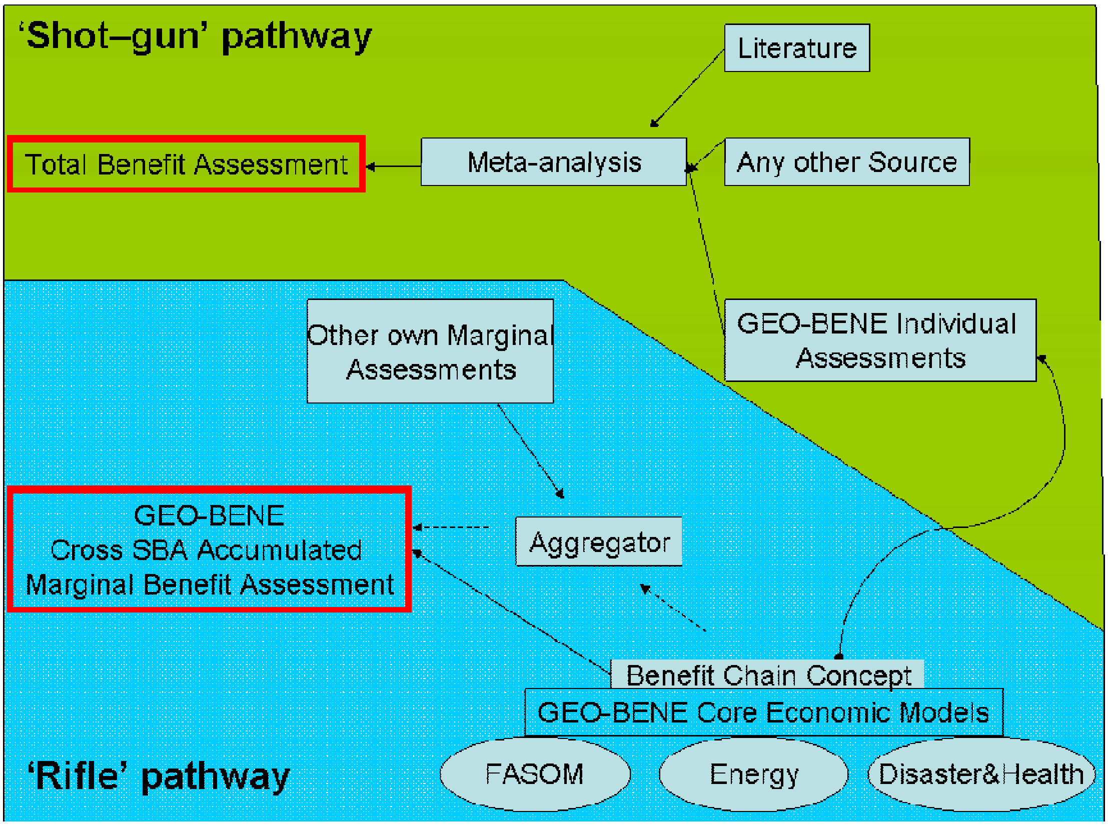

Figure 2.1: Overview of the two GEO-BENE assessment pathway.

3 Benefit Chain Concept: Different improvements of EO to which GEOSS can contribute

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 co-operation 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 one or both of 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 decision in Earth Observation systems.

3.1 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, through 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 and who shares the information, 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 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 socitial benefit areas 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 EU-funded project within the 7th framework program, aims to provide the basis for making a systematic and transparent comparison of informational benefits and costs for the different societal beneit 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 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 Organisation, is a case in point.

The second driver of change in Earth Observation 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 a global Earth Observation system, based (both out of necessity and good sense) on the preexistence of an elaborate set of partial or smaller scale subsystems.

3.2 Review of Benefit Assessments which relate to GEOSS

Apart from a quite extensive literature on the costs and benefits of weather forecasts (Katz and Murphy, 2007; Center for Science and Technology, 2007) 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 data acquisition platform. The costs of satellite missions are usually insufficiently itemized (for ENVISAT only the full program costs are given, 2.3 billion Euro) or entirely missing (e.g., the entry on Landsat 5 in the Satellite Encyclopedia) to be able to understand their incremental components. Also the OECD has identified this gap and will soon publish a study entitled “The Space economy at Glance” (OECD, 2006). Nevertheless, program cost summaries exist for some satellite missions, such as those described by Sandau (2006). 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 (Sandau, 2006).

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 European Union, each sponsoring organization only reporting their own contribution to the common budget (Höller and Banko, 2007). 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 non-governmental organisations.

As indicated above, many studies illustrate the potential benefit which could be gained from an improved weather forecast system: with respect to mitigating natural hazards (Williamson et al., 2002); increasing crop yield (Adams et al, 1995), food trading (Bradford and Kelejian, 1977) or road safety (Adams et. al, 2001). 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 (explained below) as an alternative to the usual cost avoidance approach, incorporating the commercial sector (for example, TV 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 Earth Observation. 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 (PriceWaterhouse Coopers, 2001). The second was a benefit assessment of the Global Monitoring for Environment and Security (GMES) programme (PriceWaterhouse Coopers, 2006). 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 non-existence of such a system (termed the ‘without GMES scenario’), and notes that GMES is the European contribution to GEOSS. This 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 points out that placing a monetary value on all the potential impacts of GMES is not practical, since the wider societal impacts are not amenable to monetary quantification. In addition, the relationship between the improved Earth Observation information and the potential welfare impacts is not always clear. The study therefore adopts 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 (Morgan et al. 2001). The study was criticized for not taking all benefit areas equally into account (GMES bureau, personal communication). The study used a statistical value of life defined by Frankhauser (1995). This value is different in developing countries and developed countries: an approach that has been criticized as being morally indefensible (Fearnside, 1998). Moreover, the study only presents the average of the estimates, largely ignoring the range of responses and the uncertainties involved. It does not provide insight into the incremental benefits that various alternate Earth Observation 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) are also covered. Due to the nature of the study asking 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 Macaulay (2006) attempts to apply the VOI theory and methods to show how space-based Earth Observations 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. Macauley (2006) describes three groups of ways in which value of information (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 'willingness-to-pay' principle ('contingent valuation'). In contingent valuation approaches, stakeholders are asked how much they would be willing to pay for certain categories of information.

Macauley (2006) does not clarify how welfare impacts can be attributed to the availability of improved EO information and to how the incremental costs and benefits of information might be assessed. Also, the current literature studies which evaluate the impact of improved information derived from EO look only at benefits whereas the costs of providing better EO information and in particularly the costs of sharing data and building the necessary spatial data infrastructure (EU, 2006) are seldom assessed. Due to these shortcomings we developed within our Geo-bene project the benefit chain concept which will be elaborated in the next sections.

3.3. The Benefit Chain Concept

The logic behind the benefit chain concept is that through global cooperation in Earth Observing 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 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 diretly 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 observation system change. At a very 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 (Figure 3.1).

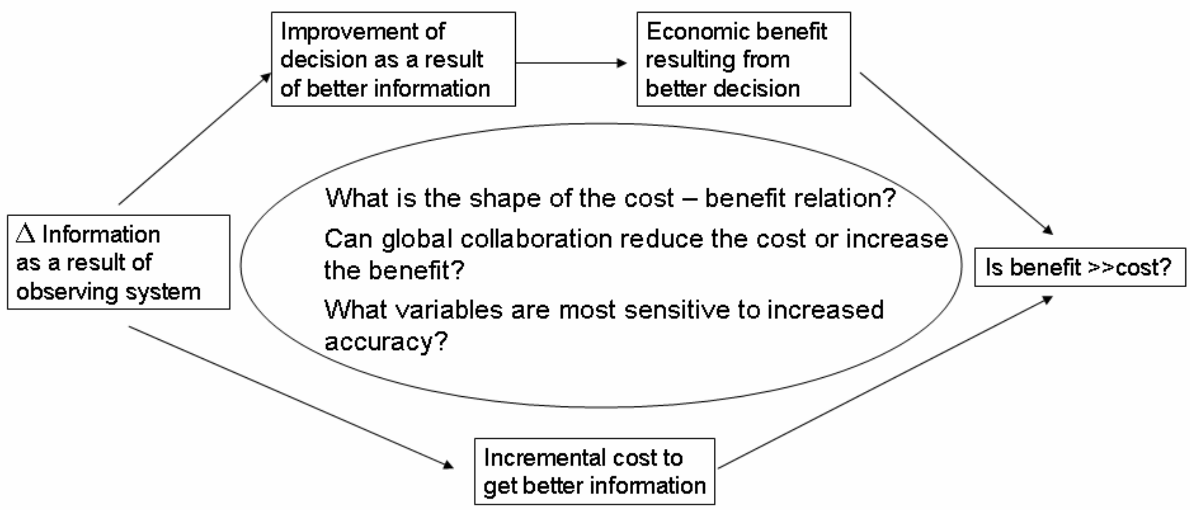

Figure 3.1: The benefit chain concept. In the benefit chain concept benefits as well as costs must be considered. The concept looks at incremental changes of costs and benefits with respect to the already existing observing system (e.g., national). A logical causal benefit pathway (in steps if necessary) 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').

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 non-transparent 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 benefits ratio, it is probably too much to ask that the cost:benefit 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 Earth Observation domain, and provides a filter to avoid high-cost, low-benefit actions.

The 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. Earth Observation agencies have discovered that societal value in this field is not synonymous with the price the market is willing and able to pay for the information. Earth Observations 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 monetisation 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 elation 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? Ie, where will the largest increase in societal benefit result? Is the incremental cost proportionately sensitive?

The benefit chain concept can be examined per societal benefit area or sub-benefit area. It can also be applied to particular GEOSS activities, such as the coordination of space observations, or standardisation 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 'globalisation' 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 Earth Observation 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 observing systems can be justified, *even if the total Earth Observation 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.

There has been an 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. (Costanza et al., 2005, Gatto and De Leo, 2000). For example, if all human life depends on the presence of water, and nothing else can take its place, then the value of water is presumably approaches infinity as the supply declines towards the minimum. That 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 earth observation effort. Given that the world already has a large investment in earth observation, 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 Figure 3.2) can vary across Social Benefit Area and depends on the type of activity (see Table 3.1, section 3.3.2) that is undertaken. If we can illustrate that the marginally-increased investment into GEOSS results a much higher marginal benefit, then the investment is well spent. On the other hand, if we clearly see that the benefit we gain is much lower than the incremental investment cost, then justification for such an activity is difficult.

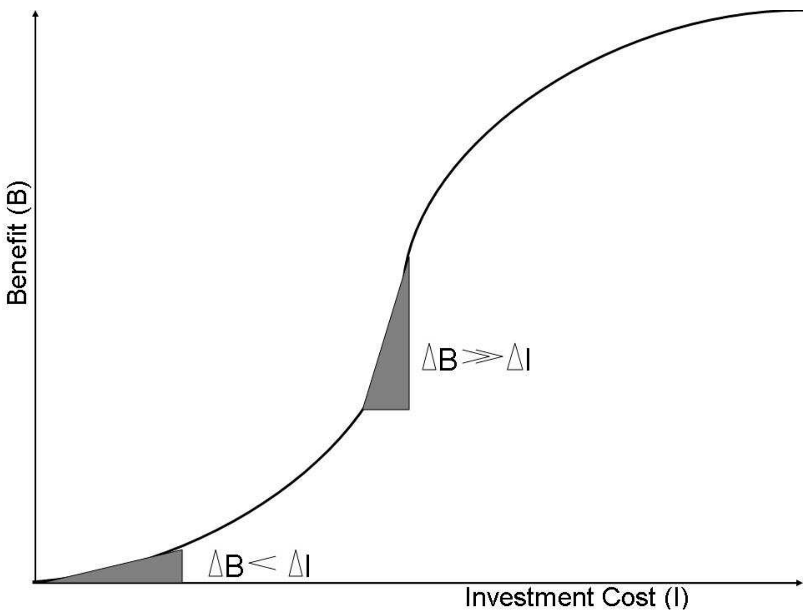

Figure 3.2: hypothetical curve of a cost benefit relationship. It is constructed by sketching a benefit-to-effort relation and a cost-to-effort relation, and then extracting the costs and benefits for a given level of effort, and building a cost-benefit curve.

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

The adoption of an 'incremental effort, incremental benefit and incremental cost' basis for investment decisionmaking in relation to EO systems makes it necessary to define a baseline. The following sections describe how the GEOSS baseline could be defined, what potential is to be realized though GEOSS and what the current limitations are to apply the entire benefit chain concept. Section provides examples of applying the benefit chain concept in three societal benefit areas.

3.3.1 Defining the baseline for 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 co-operative 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" (EU, 2006).

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 co-operation (Lubick, 2005). 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 of attributed to Earth observation information that can be reasonably attributed to activities catalysed by the GEOSS process. The 'without GEOSS' scenario does not assume a complete absence of Earth Observations. 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 are taking place on a national level independently of GEOSS it is not easy to distinguish which activities can be attributed to GEOSS, and which would have happened anyway. This difficulty was noted in the PriceWaterhouse Coopers (2006) study, but is not unique to Earth Observation 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.

3.3.2 The potential to be realized though 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, modelling and interpretation of data; and though facilitating the delivery of information to the end user, in a form that suits their needs. In the field of satellite observations, for example, 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., GCMs) 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 modelling 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 rationalisation, as well as from model inter-comparison exercises, standardisation 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 interoperability 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 standardised metadata catalogues, making data flow more efficient and therefore reducing costs. On the other hand a chain of OGC Web services can be invoked 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 (Percival, 2007).

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 global earth observation. Table 3.1 identifies the improvements where GEOSS could play a role in an illustrative and non-comprehensive manner.

Table 3.1: Improvement to be realised though GEOSS, effects and importance.

Improvement to be realised	Effect	Selected Examples	Importance within GEOSS
Optimisation of the overall observation strategy, avoiding unnecessary redundancy in EO missions and systems	Reduction of costs	Recent co-ordination between EUOMETSAT, CNES,NOAA, NASA and joint research announce-ment of the Ocean Surface topology science team (Eumetsat and CNES, 2007)	High
More frequent observa-tion 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 cellphone 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 standards	Lower development costs, greater necessary redundancy of sensors, better interoperability of data	Members in GEOSS has increased, more international initiatives Members of the Open Geospatial Consortium has increased (from 20 members in 1994) the OGC now has 250 members. Virtual constellations More free data access the GEOSS portal	High
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

3.3.3 Limitations and constraints on 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 currently 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.

In order to be able to measure the non-market value of the benefit, a number of valuation methods such as hedonic pricing, looking at opportunity costs, contingent valuation have been suggested. New and more realistic valuation methods are continuously being developed. Freeman (1993) describes the traditional approaches. The latest advances are described in detail in the 3rd chapter of the Conditions and trends working group of the Millenium Ecosystems Assessment (deFries and Pagiola, 2005).

3.4 Minimum requirements for assessment of 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 subglobal studies depend on global information? Can globalisation 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

- 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 decisionmakers 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.
- Taking a technology-maturity approach (Slocum, 1998) 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 befit curves is likely to lie.

Examples of application of the benefit chain concept

Three examples, derived from 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-market, in this case through biodiversity protection. 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.

Example one: better fire control thanks to improved weather forcasts

This case study (elaborated by Khabarov and Moltchanova, submitted, this issue) 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 bases. 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 what difference it makes having a coarse- or high-resolution dataset available or when combining remotely sensed data with *in-situ* observations.

The benefit pathway is that though better-calibrated and higher-resolution satellite data supported by *in-situ* measurements, a more targeted and efficient patrolling system is possible. The benefits 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 scenario is simulated with by using coarse-resolution weather forecast data. This is comparable with the currently available global datasets such as ECMWF one degree resolution. In Europe, as a result of international collaboration, we have 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 burnt can 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 (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 social benefit.

We are not very confident on the cost site, due to the fact that we do currently not know the full or marginal costs of the European dataset. However, the data is collected anyway, and it is estimated that making the data available real time for forest fighting (which is the incremental necessity for this application) is not a high additional cost. An expert guess which we use in this context is that the costs of making the fine resolution data available in real time will be in the order of 130 000 Euros yearly, plus 2 million EUROS for a one off filtering algorithm which removes errors in the dataset. The cost:benefit ratio clearly points towards a much higher incremental benefit than the incremental costs.

Example 2: Improved data for conservation planning

This case study demonstrates the benefits of replacing commonly available coarse scale global data 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. It then contrasts 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 biodiversity protection (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 protected area network (Freitag et al., 1998, Rouget et al., 2003; Reyers et al., 2007). 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 (Margules and Pressey, 2000; Possingham et al., 2000). 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 [e.g. Biodiversity Act (Act 10 of 2004), Municipal Systems Act (Act 32 of 2000)]. These tools require spatially explicit data on the distribution of biodiversity (species, ecosystems), threats facing biodiversity (e.g., land conversion) and current conservation efforts. These data are often available at coarse (1:1 000 000) global or continental scales (e.g., WWF ecoregions (Olson et al., 2001), GLC 2000 (Fritz et al., 2003), 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 taxa, and fine-scale land class and habitat transformation maps, are invariably lacking (Cowling et al., 2004), especially in developing countries which harbour most of the world's unprotected and vulnerable biodiversity (Balmford et al., 2002). 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 (Balmford 2003). These national scale data (1:250 000) were used to conduct a National Spatial Biodiversity Assessment (NSBA; Nel et al. 2007; Reyers et al. 2007) 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 and the outputs of the same assessment based on the coarse global scale data, 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. 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 (Frazee et al., 2003) 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 totalling 29 million euros. 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 3.2.

Table 3.2: The 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	9 000 for an area of 20 000km2	Thompson et al. submitted Rouget et al., 2006
National British bird atlas	1.43 million	www.bto.org/**birdatlas**/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 000km2	(Balmford and Gaston 1999)
South Africa local scale vegetation map		

[1] All costs are calculated in Euros for the year 2000 using annual national inflation rates and 2000 exchange rates

The coarse and fine scale analyses described above used the GLC and SANLC datasets described in Table 3.2, 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.

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 2 provides estimates of the costs of other and 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, Balmford and Gaston (1999) demonstrate 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.

Example three: North Sea water quality

An example of using stakeholder consultation for assessing the value of information is the North sea water quality case (Bouma and Van der Woerd, 2007). At present, water quality monitoring in the North Sea is mostly based on *in situ* measurement. With GEOSS-type integrated remotely sensed and *in situ* data, , 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 expected to improve the effectiveness of water quality management in the North Sea we developed a questionnaire which we sent to 25 key decision makers, experts and stakeholders. Inspired by Schimmelpfennig and Norton (2003), we asked decision makers to quantitatively estimate how they expected improved Earth Observation information would reduce the uncertainty of their decision making. The response rate was 80%. Table 3.3 shows the main results.

Table 3.3: The added value of Remote Sensing information for water quality in the North Sea

	Eutrophication		Excessive algal bloom		Sea water clarity	
	Present	*With GEO*	*Present*	*With GEO*	*Present*	*With GEO*
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 and Van der Woerd (2007).

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 (van der Woerd et al., 2005). Since without preventive action, excessive algal bloom is expected to cause an economic damage of approximately 20 million euro every 5 years (Bouma and Van der Woerd, 2007), early warning information can reduce damage costs with 18 million euro. Using the figures presented in 3 as an indication of the prior probabilities and likelihood decision makers attach to the probability that excessive algal bloom is predicted in time, the value of better EO information for predicting excessive algal bloom is estimated to be approximately 1 million euro per year. If we account for the wide variation in expert responses, the 95% confidence interval for the benefits ranges from -0.1 up to 2.1 million euro/year.

Comparing these benefits with the incremental costs of GEO information, the incremental costs of data processing are estimated to be less than 5% of the expected benefits (Van der Woerd et al., 2005). The capital investments made by the Dutch government to launch the ENVISAT satellite are however much more. Assuming a satellite lifetime of 10 years, the annual costs of the Dutch contribution to the ENVISAT satellite (which clearly generates more data than for water quality management in the North sea alone) is approximately 2.5 million euro (personal communication Dutch institute for Aeronatics and Space,NIVR). However, in addition to the benefits of having 'early warning' information, GEO information reduces water quality monitoring costs with approximately 2 million euro/year (Hakvoort, 2006). Hence, depending on the range of estimated GEO benefits, the value of GEO information for water quality management in the North sea is expected to be somewhere between -0.6 to 2.6 million euro per year (Bouma and van der Woerd 2007).

3.4. Discussion and Conclusions

In 2005 a large proposal was made to NASA to support a biomass-measurement satellite mission (Hese et. al, 2005). 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 sesor of 3 years, hence relatively high cost (Knorr, 2007, 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 Earth Observation activities in various societal benefit areas in a pragmatic and appropriate way. We have furtheremore selected 3 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 Klein (2007) 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 (Lubick, 2005)? 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 is relatively small in comparison to even a conservative estimate of the benefits which can be achieved by such a process.

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 obstacles 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.

In order to tackle these challenges we have outlined a conceptual framework and practical guidelines for assessing the benefit chain in particular case studies. 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 Global Earth observation System of Systems.

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4 The GEOBENE tool box cluster

In this section we will present the developed tools aiming at making "GEO-benefits" measurable. GEO-BENE has built tools based on the methodology as outlined above, which assess the societal benefit of a GEOSS induced information mark-up. There are several ways to categorize the individual models of the GEOBENE tools cluster. One way is to distinguish static/dynamic and deterministic/stochastic models. These models can each be run in either simulation or optimization mode.

Table 4.1: Selected GEO-BENE tools categorized by tatic/deterministic, simulations/optimization and deterministic/stochastic.

	Deterministic		Stochastic	
	Simulation	Optimization	Simulation	Optimization
static	BEWHERE-S	GLOBIOM, BEWHERE-O	-	CVaR Energy Models
dynamic	FELIX, G4M	EU-FASOM	CATSIM	Real Options

Another way to categorize GEOBENE tools as it was already outlined in the DoW is according to geographic aggregation. GEO-BENE has developed tools for assessment on three levels of geographic aggregation:

- Macro-level assessment tool (GEO-MACRO) for assessment on macro-(economic/society) level (e.g., global disaster model, FELIX).
- Geographically explicit on grid or polygon level modelling benefit generation of individual sub-benefit areas (GEO-DIM); (e.g., G4M, BEWHERE)
- Sector specific assessment tools to quantify secondary effects such as market feedbacks or leakage (GEO-SIM); (e.g., GLOBIOM)

In order to illustrate the differences in the tools and underlying methodologies defining the value of information of GEOSS a detailed description of two different tools will be given here. First a detailed description of EU-FASOM which is a deterministic model of integrated dynamic land-use covering the SBAs energy (bioenergy), whether, climate, water, ecosystems, agriculture and biodiversity. This model is especially suited to assess the integration effects of GEOSS. Secondly a description of the stochastic modeling tools which are particularly suited to assess the value of information by monetizing uncertainty reduction will be given.

4.1 The European Forest and Agricultural Sector Optimization Model

4.1.1 Introduction and Literature

Land use is a key factor to social wellbeing and has become a major component in political negotiations. Land use affects food supply, employment, energy security, water, climate, and ecosystems. Over the last few decades, technical progress and intensifications have ensured a large increase in food supply (Briunsma, 2003) enough to potentially eradicate malnutrition. However, projected population developments and their impacts on demand for food, land, energy, and water as well as feedbacks of environmental change may put additional pressure on food production technologies in the next decades.

The food and fiber production achievements of past decades in the agricultural and forest sectors have taken a toll on the environment. Particularly, these sectors are blamed for contributions to greenhouse gas emissions, ecosystem destruction and associated biodiversity losses, water shortage and contamination, and land degradation. On the other hand, land use changes in agriculture and forestry are considered as potential remedies to environmental problems (Smith et al., 2008).

The European Union has formulated ambitious objectives regarding bioenergy production, reduction of greenhouse gas emissions, and biodiversity protection (European Economic Community 1992, European Union 2003; Commission of the European Communities 2008). By 2020, the EU has committed to a reduction by at least 20% of its total greenhouse gas emissions relative to 1990 levels, a 20% share of renewable energies in its energy production, and a 10% share of biofuels in its petrol and diesel consumption. Meeting these targets will involve significant impacts on land use and land use management. These developments have raised questions regarding their effects on agricultural and forestry products markets and competition for land between forestry, food and non-food agriculture. Concern has also been growing regarding the net environmental impacts of these changes and the potential sources of leakage (for example through intensification of agricultural production leading to increased agricultural emissions or international displacements of emissions through deforestation, e.g. Rajagopal, D. & Zilberman, D. 2007). Therefore, integrated modeling approaches are needed to tackle these issues.

While the production of food, fiber, fuel, and timber is internalized through international markets, most environmental and welfare distributional impacts are not. Because markets for most environmental goods and services do not exist, private land use decisions are socially inefficient. To include external environmental costs in land use planning, political interference is required. However, land use policies without scientific guidance are dangerous. The scarcity of land and other resources and the complexity of interactions between land use and environment may turn today's solution into tomorrow's problem (Cowie et al. 2007). EUFASOM has been developed as an integrated scientific tool for the comprehensive economic and environmental analysis of land use and land use change.

To place EUFASOM in perspective, let us briefly review previously developed and applied tools. Existing economic land use assessment models can be distinguished a) regarding the flow of information in top-down and bottom-up systems, b) regarding the dominating analysis technique in engineering, econometric, and optimization approaches, c) regarding the system dynamics in static, recursive dynamic, and fully dynamic designs, d) regarding the spatial scope in farm level, regional, national, multi-national, and global representations, and e) regarding the sectoral scope in agricultural, forestry, multi-sector, full economy, and coupled economic and environmental models. Additional differences involve various modeling assumptions about functional relationships (demand, supply, factor and commodity substitution) and the applied resolution over space, time, technologies, commodities, resources, and environmental impacts with the associated data. For a more detailed survey over specific land use models we refer to Lambin et al. (2000), Heistermann et al. (2006) and van der Werf and Peterson (2007).

The variation in methods indicates that land use is a complex system, whose interdependencies cannot be appropriately captured by a single approach. Instead, different methods are applied to address different questions. Using the above described classifications, EUFASOM could be characterized as a bottom-up, optimization, fully dynamic, multi-national, agricultural and forest sector model. In addition, the model portrays detailed environmental relationships and global agricultural and forestry commodity trade.

Why build another land use model? Three major arguments can be made. First, EUFASOM and its US counterpart (Alig et al. 1998) are currently the only bottom-up models, which portray the competition between agriculture, forestry, bioenergy, and nature reserves for scarce land at large scales. These models integrate observed variation in land qualities and technologies with environmental impacts and global market feedbacks. This approach enables the quantification of economic potentials for environmental problem mitigation but also the estimation of leakage effects. Leakage of environmental impacts is perhaps the biggest threat to land use policies, yet it is typically ignored in bottom-up models. Second, EUFASOM goes beyond the majority of existing economic models in portraying the environmental effects of land use. Multiple greenhouse gas and soil state impacts are estimated with detailed environmental process models. The complex dynamic relationship between land management trajectories and soil quality is represented through Markov chains (Schneider 2007). A parallel to EUFASOM developed European wetland optimization model (Jantke and Schneider 2007) estimates the impacts of land use impacts on conservation of 69 wetland species. Thus, EUFASOM is better equipped than previous models to assess impacts and interdependencies of climate, biodiversity, soil, and food policies.

Thirdly, although searches through the scientific literature may reveal numerous integrated land use assessments, the number of maintained state-of-the-art models is small. Essentially, many land use models are dissertation products where the requirement of independent work limits the quality of data and model. EUFASOM is part of an integrated assessment framework where a large team of collaborating researchers from different countries and different disciplines synthesize data, models, and expertise. The model is available for other researchers provided that improvements are shared.

4.1.2 Data

Bottom-up models are generally data intensive both with respect to inputs and outputs. Input data for EUFASOM describe important properties of resources, production technologies, and agricultural and forestry markets. Generally, while resource data are mainly derived from observations, economic data are computed based on producer surveys or engineering methods, environmental impacts based of land management from simulations with biophysical process models, and market data from national and international statistics. The following descriptions of EUFASOM input data can only give a brief overview. Detailed information on specific data item are available from the authors.

Most raw data are not directly used in EUFASOM but undergo transformations involving model processing, aggregation, and calibration. Detailed meteorological, nitrogen deposition, and soil data over more than 1,000 homogeneous response units (HRU) within the European Union (Balkovič 2007) are used as inputs to the EPIC model. For each HRU and all land use and land management alternatives, the EPIC model simulates in daily time steps biomass growth and multiple environmental impacts concerning greenhouse gas emissions, soil organic carbon, erosion, and nutrient leaching. However, only biomass yields and environmental impacts are passed to EUFASOM. As a result, climate and soil data are only implicitly contained in EUFASOM.

Resource data in EUFASOM include region and time period specific endowments for land quality classes, existing forests, labor, and water. National soil type distributions are estimated from a European Soil Database as described in Balkovič 2007. Existing and suitable areas for five wetland types are estimated through a GIS based spatial analysis (Schleupner, 2007).

Economic data for basic agricultural management technologies are derived from the European Farm Accountancy Data Network surveys (European Commission 2008). Bioenergy data for production and processing of bioenergy are taken from results of the European Non-Food Agriculture consortium (ENFA 2008). Agricultural management costs, for which data do not exist, are estimated based on engineering equations (Hallam et al. 1999). Forest stand data are estimated with the OSKAR model based on sub-country level inventories of forest stocks, tree species and age classes covering most of Europe. The OSKAR model employs globally applicable biophysical principles, species characteristics, and expected climate change effects predicted by the LPJ global ecosystem model (Sitch et al., 2003) to estimate forest biomass, carbon storage, forestry production and forest management costs. Forest industry inputs are based on Pöyry consulting expert estimates. Forest products life time data are based on Eggers (2002).

Current production, consumption, trade, and price data for agricultural and forest commodities are taken from EUROSTAT and FAOSTAT. Assumptions about population and gross domestic product developments and technical progress are taken from GTAP.

4.1.3 Model structure

This section documents the principal mathematical structure of EUFASOM, which is relatively unaffected by data updates or model expansion towards greater detail. EUFASOM is designed to emulate the full impacts of European land use on agricultural and forest markets and on environmental qualities related to land use. The model contains several key components: natural and human resource endowments, agricultural and forest production factor markets, primary and processed commodity markets, agricultural and forest technologies, and agricultural policies. Because of data requirements and computational restrictions, sector models cannot provide the same level of detail as do farm level or regional models. Rather than trying to depict millions of individual farms, EUFASOM represents typical crop, livestock, forest, and bioenergy enterprises for 23 EU member states. Possible producer adaptation is integrated through a large set of alternative land management technologies (Table 4.2). These technologies are described through Leontief production possibilities each of it specifying fixed quantities of multiple inputs and multiple outputs. International markets and trade relationships are currently portrayed through eleven international regions.

EUFASOM is a large mathematical program. The objective function maximizes total agricultural economic surplus subject to a set of constraining equations, which define a convex feasible region for all endogenous land use decision variables. Full model activations contain more than 6 million individual variables and more than 1 million individual equations. Equations and variables are condensed into indexed blocks (see Table 4.3). Solving EUFASOM involves the task of finding the optimal levels for all endogenous variables, i.e., those levels which maximize the economic surplus subject to compliance with all constraining equations. Economic surplus is computed as the sum across time, space, commodities, and resources of total consumers' surplus, producers' or resource owners’ surplus, and governmental net payments to the agricultural sector minus the total cost of production, transportation, and processing. Basic economic theory demonstrates that maximization of the sum of consumers' plus producers' surplus yields the competitive market equilibrium. Thus, the optimal variable levels can be interpreted as equilibrium levels for land use activities under given economic, political, and technological conditions. The shadow prices on resource and commodity balance equations give market clearing prices.

To facilitate understanding of the EUFASOM structure, we will first describe the set of constraining equations and subsequently explain the objective function. Variables are denoted by capital letters. Constraint coefficients and right hand side values are represented by small italic letters. Indices of equations, variables, variable coefficients, and right hand sides are denoted by subscripts. The constraining equations depict resource and technological restrictions, intertemporal relationships, and environmental interactions.

4.1.4 Resource and technological restrictions

Supply and demand balance equations link agricultural and forest activities to commodity markets (Equation 1) and to factor markets and resource endowments (Equation 2). Specifically, for each region, period, and product, the total amount allocated to domestic consumption (DEMD), processing (PROC), and exports

(TRAD[1]) cannot exceed the total supply through crop production (CROP), bioenergy plantations (BIOM), timber harvesting (HARV), production from standing forests (TREE), nature reserves (ECOL), livestock raising (LIVE), or imports (TRAD). Note that the explicit supply variable SUPP depicts special animal feeds and agricultural commodities in non-EU regions, for which technological data are not available.

The technical coefficients $\alpha^{CROP}_{r,t,i,j,c,u,q,m,p,y}$, $\alpha^{PAST}_{r,t,i,j,s,u,q,m,p,y}$, $\alpha^{BIOM}_{r,t,i,j,b,u,q,m,p,y}$, $\alpha^{HARV}_{r,t,i,j,f,u,a,m,p,y}$, $\alpha^{TREE}_{r,t,i,j,f,u,a,m,p,y}$, $\alpha^{ECOL}_{r,t,i,j,s,u,x,m,p,y}$, $\alpha^{LIVE}_{r,t,l,u,m,p,y}$, $\alpha^{FEED}_{r,t,l,m,y}$, and $\alpha^{PROC}_{r,t,m,y}$ indicate input requirements (negative values) of output yields (positive values). The structure of Equation 1 allows for an efficient representation of multi-input and multi-output production and for multi level processing, where outputs of the first process become inputs to the next process. Supply and demand relationships for agricultural production factors are shown in Equation 2. Particularly, the total use of each production factor or resource over all agricultural and forest activities cannot exceed the total supply of these factors (RESR) in each region and period.

$$\begin{pmatrix} +\sum\limits_{m}\left(\alpha^{PROC}_{r,t,m,y}\cdot PROC_{r,t,m}\right) \\ +\sum\limits_{m}\left(\alpha^{FEED}_{r,t,l,m,y}\cdot FEED_{r,t,l,m}\right) \\ +\sum\limits_{\tilde{r}} TRAD_{r,\tilde{r},t,y} \\ +DEMD_{r,t,y} \end{pmatrix} \le \begin{pmatrix} +\sum\limits_{j,v,c,u,q,m,p}\left(\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,y}\cdot CROP_{r,t,j,v,c,u,q,m,p}\right) \\ +\sum\limits_{j,v,s,u,q,m,p}\left(\alpha^{PAST}_{r,t,j,v,s,u,q,m,p,y}\cdot PAST_{r,t,j,v,s,u,q,m,p}\right) \\ +\sum\limits_{j,v,b,u,q,m,p}\left(\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,y}\cdot BIOM_{r,t,j,v,b,u,q,m,p}\right) \\ +\sum\limits_{j,v,f,u,a,m,p}\left(\alpha^{HARV}_{r,t,j,v,f,u,a,m,p,y}\cdot HARV_{r,t,j,v,f,u,a,m,p}\right) \\ +\sum\limits_{j,v,f,u,a,m,p}\left(\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,y}\cdot TREE_{r,t,j,v,f,u,a,m,p}\right) \\ +\sum\limits_{j,v,s,u,x,m,p}\left(\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,y}\cdot ECOL_{r,t,j,v,s,u,x,m,p}\right) \\ +\sum\limits_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,y}\cdot LIVE_{r,t,l,u,m,p}\right) \\ +\sum\limits_{\tilde{r}} TRAD_{\tilde{r},r,t,y} \\ +SUPP_{r,t,y} \end{pmatrix}$$

Equation 1 Commodity balance (∀ t, r, and y)

Livestock farmers have a choice between different animal diets. These diets are depicted by the variable FEED and contain unprocessed crops, processed concentrates, and special feed additives. Depending on animal type and performance, diets have to meet certain nutritional targets. These nutritional restriction are integrated in EUFASOM as shown in Equation 3. Several things should be noted. First, restrictions are only active if the nutritional coefficients $\alpha^{LIVE}_{r,t,l,u,m,p,n}$ are non-zero. Second, the nutritional coefficients for feeds differ between animals types.

Livestock raising produces different types of animal manure. Manure can be returned as organic fertilizer to fields or digested to generate energy. EUFASOM restricts the

[1] The first index of the TRAD variables denotes the exporting region or country, the second denotes the importing region or country.

total usage of manure from animal houses as fertilizer or energy source to be equal or less than the total amount of manure produced through all livestock operations. Note that the impact of manure from grazing animals is not part of this balance but is included in Equation 9.

$$\left(\begin{array}{l} +\sum_{j,v,c,u,q,m,p}\left(\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,i}\cdot CROP_{r,t,j,v,c,u,q,m,p}\right)\\ +\sum_{j,v,s,u,q,m,p}\left(\alpha^{PAST}_{r,t,j,v,s,u,q,m,p,i}\cdot PAST_{r,t,j,v,s,u,q,m,p}\right)\\ +\sum_{j,v,b,u,q,m,p}\left(\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,i}\cdot BIOM_{r,t,j,v,b,u,q,m,p}\right)\\ +\sum_{j,v,f,u,a,m,p}\left(\alpha^{HARV}_{r,t,j,v,f,u,a,m,p,i}\cdot HARV_{r,t,j,v,f,u,a,m,p}\right)\\ +\sum_{j,v,f,u,a,m,p}\left(\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,i}\cdot TREE_{r,t,j,v,f,u,a,m,p}\right)\\ +\sum_{j,v,s,u,x,m,p}\left(\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,i}\cdot ECOL_{r,t,j,v,s,u,x,m,p}\right)\\ +\sum_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,i}\cdot LIVE_{r,t,l,u,m,p}\right)\\ +\sum_{m}\left(\alpha^{PROC}_{r,t,m,i}\cdot PROC_{r,t,m}\right)\\ +\sum_{m}\left(\alpha^{FEED}_{r,t,l,m,i}\cdot FEED_{r,t,l,m}\right) \end{array}\right)\leq RESR_{r,t,i}$$

Equation 2 Resource balance (∀ r, t, and i)

$$\sum_{l,m}\left(\alpha^{FEED}_{r,t,l,m,n^{max}}\cdot FEED_{r,t,l,m}\right)\leq\sum_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,n^{max}}\cdot LIVE_{r,t,l,u,m,p}\right)$$
$$\sum_{l,m}\left(\alpha^{FEED}_{r,t,l,m,n^{min}}\cdot FEED_{r,t,l,m}\right)\geq\sum_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,n^{min}}\cdot LIVE_{r,t,l,u,m,p}\right)$$

Equation 3 Animal feeding restrictions (∀ r, t, and n^{min}/n^{max})

$$\left(\begin{array}{l} +\sum_{j,v,c,u,q,m,p}\left(\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,i}\cdot CROP_{r,t,j,v,c,u,q,m,p}\right)\\ +\sum_{m}\left(\alpha^{PROC}_{r,t,m,i}\cdot PROC_{r,t,m}\right) \end{array}\right)\leq\sum_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,i}\cdot LIVE_{r,t,l,u,m,p}\right)$$

Equation 4 Manure balance (∀ r, t, and i)

Limits to agricultural production arise not only from technologies but also from the use of scarce and immobile resources. Particularly, the use of agricultural land, labor, irrigation water, and grazing units is either physically limited by regional endowments or economically limited by upward sloping supply curves for these private or public resources. In EUFASOM, all production, processing, and nature reserve variables (CROP, LIVE, BIOM, ECOL, TREE, HARV, FEED, and PROC) have associated with them resource use coefficients ($\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,i}$, $\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,i}$, $\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,i}$,

$\alpha^{LIVE}_{r,t,l,u,m,p,i}$, $\alpha^{HARV}_{r,t,j,v,f,u,a,m,p,i}$, $\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,i}$, $\alpha^{FEED}_{r,t,l,m,i}$, $\alpha^{PROC}_{r,t,m,i}$), which resource requirements per unit of production. The mathematical representation of physical resource constraints in EUFASOM is straightforward and displayed in Equation 5. These equations simply force the total use of natural or human resources to be at or below given regional endowments $\beta_{r,t,i}$. Economic resource constraints are part of the objective function.

$$RESR_{r,t,i} \le \beta_{r,t,i}$$

Equation 5 Resource limitations ($\forall$ r, t, and i)

4.1.5 Intertemporal restrictions

Intertemporal restrictions form an important part of EUFASOM and include initial conditions, forest and soil state transition equations, and land use change restrictions. Terminal values for forests are included in the objective function section. Initial conditions link activities in the first model period (INIT) to observed values (Equation 6). These conditions can be placed at a detailed or aggregated level. For example, while forest activities in EUFASOM include three alternative thinning regimes, observed forest inventories are only available by region, age cohort, and species. Thus, Equation 6 enforces these aggregated identities but let the model choose the optimal distribution of thinning regimes in the first period. Similarly, the distribution of existing and potential wetlands can be enforced for individual wetland types and size classes or for aggregates.

$$INIT_{r,j,v,s,u,q,m,p} = \phi_{r,j,v,s,u,q,m,p}$$

Equation 6 Initial land allocation ($\forall$ r, t, v, s, u, q, m, and p)

In each region and for each period, EUFASOM explicitly distinguishes standing forests by species composition, age cohort, ownership, management, and soil characteristics. Age cohorts and time periods are both resolved to 5-year intervals. The distribution of forest types in a certain period is constrained by planting and harvesting activities in previous time periods (Equation 7). Particularly, the area of standing and harvested forests above the first age cohort cannot exceed the area of the same forest type one period earlier and one age class lower. However, if a forest has reached the last age cohort, it will remain in this cohort in the next period as well.

$$\begin{pmatrix} +TREE_{r,t,j,v,f,u,a,m,p}\big|_{a>1} \\ +HARV_{r,t,j,v,f,u,a,m,p}\big|_{a>1} \end{pmatrix} \le \begin{pmatrix} +TREE_{r,t-1,j,v,f,u,a-1,m,p}\big|_{t>1\wedge a>1} \\ +TREE_{r,t-1,j,v,f,u,a,m,p}\big|_{t>1\wedge a=A} \\ +INIT_{r,j,v,f,u,a,m,p}\big|_{t=1} \end{pmatrix}$$

Equation 7 Forest transition ($\forall$ r, t, j, v, f, u, a, m, and p)

While new forest plantations are not affected by Equation 7, EUFASOM limits the possible species change via reforestation (Equation 8). Particularly, only if the parameter $\vartheta_{r,f,\tilde{f}}$ has a value of 1, then species $\tilde{f}$ can be fully planted on all previously harvested areas of species f. For values less than 1, allowed reforestation of $\tilde{f}$ on harvested areas of f is accordingly reduced. No restriction is currently placed on afforestation, i.e. if agricultural land is converted to forest, all possible species for this region can be planted.

$$\left(\begin{array}{l} + \sum_{v,\tilde{f},m,p} \vartheta_{r,f,\tilde{f}} \cdot TREE_{r,t,j,v,\tilde{f},u,a,m,p} \Big|_{a=1} \\ +LUCH_{r,t,j,f,u,-} \end{array} \right) \le \left(\begin{array}{l} + \sum_{\tilde{t},v,m,p} HARV_{r,\tilde{t},j,v,f,u,a,m,p} \Big|_{\tilde{t}\le t} \\ +LUCH_{r,t,j,f,u,+} \end{array} \right)$$

Equation 8 Reforestation (∀ r, t, j, and f)

The land management path over time influences crop yields and emissions. While reduced tillage may sequester soil organic carbon on previously deep-tilled soils, positive net emissions may occur if reduced tillage is employed after several decades of zero tillage. The complex relationship between management dynamics and soil fertility is approximated in EUFASOM by a Markov Process (Equation 9). Different soil states are represented by the index v. The soil state transition probability matrices $\rho_{r,j,\tilde{v},s,u,x,m,p,v}$ for crops, biomass plantations, forests, and ecological reserves contain the probabilities of moving from soil state $\tilde{v}$ to soil state v after one time period. These matrices are exogenously derived from EPIC model simulations (Schmid et al. 2007). Transition probabilities differ across regions, soil textures, planted species, and management alternatives. A more detailed technical explanation and application to the effects different tillage methods is contained in Schneider (2007).

$$\left(\begin{array}{l} + \sum_{c,u,q,m,p} CROP_{r,t,j,v,c,u,q,m,p} \\ + \sum_{s,u,q,m,p} PAST_{r,t,j,v,s,u,q,m,p} \\ + \sum_{b,u,q,m,p} BIOM_{r,t,j,v,b,u,q,m,p} \\ + \sum_{f,u,a,m,p} TREE_{r,t,j,v,f,u,a,m,p} \\ + \sum_{s,u,x,m,p} ECOL_{r,t,j,v,s,u,x,m,p} \end{array} \right) \le \left(\begin{array}{l} + \sum_{\tilde{v},c,u,q,m,p} \left(\rho^{CROP}_{r,j,\tilde{v},c,u,q,m,p,v} \cdot CROP_{r,t-1,j,\tilde{v},c,u,q,m,p} \right) \\ + \sum_{\tilde{v},s,u,q,m,p} \left(\rho^{PAST}_{r,j,\tilde{v},s,u,q,m,p,v} \cdot PAST_{r,t-1,j,\tilde{v},s,u,q,m,p} \right) \\ + \sum_{\tilde{v},b,u,q,m,p} \left(\rho^{BIOM}_{r,j,\tilde{v},b,u,q,m,p,v} \cdot BIOM_{r,t-1,j,\tilde{v},b,u,q,m,p} \right) \\ + \sum_{\tilde{v},f,u,a,m,p} \left(\rho^{TREE}_{r,j,\tilde{v},f,u,a,m,p,v} \cdot TREE_{r,t-1,j,\tilde{v},f,u,a,m,p} \right) \\ + \sum_{\tilde{v},s,u,x,m,p} \left(\rho^{ECOL}_{r,j,\tilde{v},s,u,x,m,p,v} \cdot ECOL_{r,t-1,j,\tilde{v},s,u,x,m,p} \right) \end{array} \right)$$

Equation 9 Soil state transition (∀ r, t, j, and v)

Dynamic changes in the agricultural and forest sector include changes in land allocation between forests, crop production, bioenergy plantations, and nature reserves. For each period, EUFASOM traces these land use changes (LUCH) explicitly, both with respect to the preceding period (
Equation **10**) and with respect to the initial allocation (Equation 11). Changes to the preceding periods are penalized with adjustment costs in the objective function. Land use changes with respect to the initial situation are restricted to maximum transfer $\eta_{r,t,j,s,u,\{+,-\}}$. These upper bounds on land use changes are determined by geographical

analyses regarding suitability. Suitability criteria for wetland restoration are described in Schleupner (2007). If $\eta_{r,t,j,s,u,\{+,-\}}$ equals zero, then Equation 11 is not enforced.

$$\mathrm{LUCH}_{r,t,j,s,u,\{+,-\}} \geq \psi_{\{+,-\}} \cdot \left(\begin{array}{l} + \sum\limits_{v,q,m,p} \left(\mathrm{CROP}_{r,t,j,v,s,u,q,m,p} - \mathrm{CROP}_{r,t-1,j,v,s,u,q,m,p}\Big|_{t>1} \right) \\ + \sum\limits_{v,q,m,p} \left(\mathrm{PAST}_{r,t,j,v,s,u,q,m,p} - \mathrm{PAST}_{r,t-1,j,v,s,u,q,m,p}\Big|_{t>1} \right) \\ + \sum\limits_{v,q,m,p} \left(\mathrm{BIOM}_{r,t,j,v,s,u,q,m,p} - \mathrm{BIOM}_{r,t-1,j,v,s,u,q,m,p}\Big|_{t>1} \right) \\ + \sum\limits_{v,a,m,p} \left(\mathrm{TREE}_{r,t,j,v,s,u,a,m,p} - \mathrm{TREE}_{r,t-1,j,v,s,u,a,m,p}\Big|_{t>1} \right) \\ + \sum\limits_{v,x,m,p} \left(\mathrm{ECOL}_{r,t,j,v,s,u,x,m,p} - \mathrm{ECOL}_{r,t-1,j,v,s,u,x,m,p}\Big|_{t>1} \right) \\ - \sum\limits_{v,q,m,p} \phi_{r,j,v,s,u,q,m,p} \Big|_{t=1} \end{array} \right)$$

Equation 10 Land use change ($\forall$ r, t, j, s, u, and $\{+,-\}$)

$$\mathrm{LUCH}_{r,t,j,s,u,\{+,-\}} \leq \eta_{r,t,j,s,u,\{+,-\}}\Big|_{\eta_{r,t,j,s,u,\{+,-\}} \geq 0}$$

Equation 11 Land use change limits ($\forall$ r, t, j, s, and u)

4.1.6 Environmental Interactions

The quantification of interactions between regulated and unregulated environmental qualities and agricultural, forest, and nature conservation activities is a major component for integrated land use analyses. The basic EUFASOM contains accounting equations a) for environmental fluxes (Equation 12), i.e. greenhouse gas, nutrient, and soil emissions, and b) for environmentally important stocks (Equation 13) other than resources accounted in Equation 2. These stocks include dead wood pools in forests but also wood product pools both of which impact greenhouse gas balances. The mathematical formulation of Equation 12 is a simple summation of activity levels multiplied by impact coefficients over species, soil qualities, management, sites, and policies. The environmental impact coefficients, i.e. $\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,e}$, $\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,e}$, $\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,e}$, $\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,e}$, $\alpha^{PROC}_{r,t,m,e}$, and $\alpha^{FEED}_{r,t,l,m,e}$, form one part of the link from biochemophysical process models to EUFASOM.

$$
\mathrm{EMIT}_{r,t,e} = \left(\begin{array}{l}
+ \sum_{j,v,c,u,q,m,p} \left(\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,e} \cdot \mathrm{CROP}_{r,t,j,v,c,u,q,m,p} \right) \\
+ \sum_{j,v,c,u,q,m,p} \left(\alpha^{PAST}_{r,t,j,v,c,u,q,m,p,e} \cdot \mathrm{PAST}_{r,t,j,v,c,u,q,m,p} \right) \\
+ \sum_{j,v,b,u,q,m,p} \left(\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,e} \cdot \mathrm{BIOM}_{r,t,j,v,b,u,q,m,p} \right) \\
+ \sum_{j,v,f,u,a,m,p} \left(\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,e} \cdot \mathrm{TREE}_{r,t,j,v,f,u,a,m,p} \right) \\
+ \sum_{j,v,s,u,x,m,p} \left(\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,e} \cdot \mathrm{ECOL}_{r,t,j,v,s,u,x,m,p} \right) \\
+ \sum_{s,u,m,p} \left(\alpha^{LIVE}_{r,t,s,u,m,p,e} \cdot \mathrm{LIVE}_{r,t,s,u,m,p} \right) \\
+ \sum_{s,u,\{+,-\}} \left(\alpha^{LUCH}_{r,t,s,u,\{+,-\},e} \cdot \mathrm{LUCH}_{r,t,s,u,\{+,-\}} \right) \\
+ \sum_{m} \left(\alpha^{PROC}_{r,t,m,e} \cdot \mathrm{PROC}_{r,t,m} \right) \\
+ \sum_{m,l} \left(\alpha^{FEED}_{r,t,l,m,e} \cdot \mathrm{FEED}_{r,t,l,m} \right) \\
+ \sum_{d} \alpha^{STCK}_{r,t,d,e} \cdot \left(\mathrm{STCK}_{r,t,d} - \mathrm{STCK}_{r,t-1,d} \right)
\end{array} \right)
$$

Equation 12 Emission accounting equation (∀ r, t, and e)

$$
\mathrm{STCK}_{r,t,d} = \left(\begin{array}{l}
+\partial_{r,t-1,d} \cdot \mathrm{STCK}_{r,t-1,d} \\
+ \sum_{j,v,f,u,a,m,p} \left(\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,d} \cdot \mathrm{TREE}_{r,t,j,v,f,u,a,m,p} \right) \\
+ \sum_{j,v,f,u,a,m,p} \left(\alpha^{HARV}_{r,t,j,v,f,u,a,m,p,d} \cdot \mathrm{HARV}_{r,t,j,v,f,u,a,m,p} \right) \\
+ \sum_{f,u} \left(\alpha^{LUCH}_{r,t,f,u,-,d} \cdot \mathrm{LUCH}_{r,t,f,u,-} \right)
\end{array} \right)
$$

Equation 13 Dead wood and commodity stock equation (∀ r, t, and d)

Equation 13 computes the current stock levels as sum of discounted previous stocks plus stock additions from current activities. Stock discounts are derived from dead wood decomposition and product lifetime functions (Eggers 2002).

All environmental qualities (EMIT, STCK, RESR) can be subjected to minimum or maximum restrictions[2]. In addition, objective function coefficients on emission or technology variables allow the representation of environmental taxes and subsidies. Note that the basic model setup establishes only a one-directional link from environmental impact models to EUFASOM. Environmental feedbacks can be included via iterative links. Similarly, inconsistencies between aggregated and geographically downscaled EUFASOM results could be decreased through iterative procedures.

[2] The corresponding equations are trivial and therefore omitted.

4.1.7 Objective Function

EUFASOM simulates detailed land use adaptations, market and trade equilibrium changes, and environmental consequences for political, technical, and environmental scenarios related to agriculture, forestry, and nature. The objective function incorporates all major drivers for these changes, i.e. cost coefficients for land use and commodity processing alternatives, adjustment costs for major land use changes, market price changes for commodities and production factors, trade costs, political incentives and disincentives, and terminal values for standing forests. Mathematically, EUFASOM maximizes consumer surplus in final commodity markets plus producer or resource owner surplus in all price-endogenous factor markets minus technological, trade, adjustment, and policy related costs plus subsidies and terminal values. Future costs and benefits are discounted by an exogenously specified rate.

$$
\text{Maximize WELF} = \sum_t \left(\partial_t \cdot \left(\begin{array}{l}
\sum\limits_{r,y} \left[\int\limits_{y} \varphi^{DEMD}_{r,t,y} \left(\mathrm{DEMD}_{r,t,y} \right) d(\cdot) \right] \\
-\sum\limits_{r,y} \left[\int\limits_{n} \varphi^{SUPP}_{r,t,y} \left(\mathrm{SUPP}_{r,t,y} \right) d(\cdot) \right] \\
-\sum\limits_{r,i} \left[\int\limits_{n} \varphi^{RESR}_{r,t,i} \left(\mathrm{RESR}_{r,t,i} \right) d(\cdot) \right] \\
-\sum\limits_{r,j,v,c,u,q,m,p} \left(\tau^{\mathrm{CROP}}_{r,t,j,v,c,u,q,m,p} \cdot \mathrm{CROP}_{r,t,j,v,c,u,q,m,p} \right) \\
-\sum\limits_{r,j,v,s,u,q,m,p} \left(\tau^{\mathrm{PAST}}_{r,t,j,v,s,u,q,m,p} \cdot \mathrm{PAST}_{r,t,j,v,s,u,q,m,p} \right) \\
-\sum\limits_{r,j,v,b,u,q,m,p} \left(\tau^{\mathrm{BIOM}}_{r,t,j,v,b,u,q,m,p} \cdot \mathrm{BIOM}_{r,t,j,v,b,u,q,m,p} \right) \\
-\sum\limits_{r,j,v,f,u,a,m,p} \left(\tau^{\mathrm{HARV}}_{r,t,j,v,f,u,a,m,p} \cdot \mathrm{HARV}_{r,t,j,v,f,u,a,m,p} \right) \\
-\sum\limits_{r,j,v,f,u,a,m,p} \left(\tau^{\mathrm{TREE}}_{r,t,j,v,f,u,a,m,p} \cdot \mathrm{TREE}_{r,t,j,v,f,u,a,m,p} \right) \\
-\sum\limits_{r,j,v,s,u,x,m,p} \left(\tau^{\mathrm{ECOL}}_{r,t,j,v,s,u,x,m,p} \cdot \mathrm{ECOL}_{r,t,j,v,s,u,x,m,p} \right) \\
-\sum\limits_{r,l,u,m,p} \left(\tau^{\mathrm{LIVE}}_{r,t,l,u,m,p} \cdot \mathrm{LIVE}_{r,t,l,u,m,p} \right) \\
-\sum\limits_{r,m} \left(\tau^{\mathrm{PROC}}_{r,t,m} \cdot \mathrm{PROC}_{r,t,m} \right) \\
-\sum\limits_{r,l,m} \left(\tau^{\mathrm{FEED}}_{r,t,l,m} \cdot \mathrm{FEED}_{r,t,l,m} \right) \\
-\sum\limits_{r,j,u,\{+,-\}} \left(\tau^{\mathrm{LUCH}}_{r,t,j,s,u,\{+,-\}} \cdot \mathrm{LUCH}_{r,t,j,s,u,\{+,-\}} \right) \\
-\sum\limits_{r,\tilde{r},y} \left(\tau^{\mathrm{TRADE}}_{r,\tilde{r},t,y} \cdot \mathrm{TRAD}_{r,\tilde{r},t,y} \right) \\
-\sum\limits_{r,e} \left(\tau^{\mathrm{EMIT}}_{r,t,e} \cdot \mathrm{EMIT}_{r,t,e} \right)
\end{array} \right) \right)
+ \sum_{r,j,v,f,u,a,m,p} \left(\nu^{\mathrm{TREE}}_{r,j,v,f,u,a,m,p} \cdot \mathrm{TREE}_{r,T,j,v,f,u,a,m,p} \right)
$$

Equation 14 Economic surplus maximizing objective function

The technical realization of EUFASOM's objective function is displayed in Equation **14**[3]. Note that consumers' and producers' surplus is not directly calculated. Instead, EUFASOM computes the difference between the areas underneath all demand curves minus the areas underneath all supply curves. For competitive markets, this technique is equivalent to surplus maximization. Moreover, the theoretically nonlinear supply and demand area integrals in EUFASOM are linearly approximated. The approximation is given in the appendix. Supply and demand curves are specified as linear or constant elasticity functions. To avoid infinite integrals, constant elasticity demand functions are truncated. A truncated demand curve is horizontal between zero and a small demand quantity and downward sloping thereafter.

To place EUFASOM solutions in perspective, alternative objectives can be specified. In particular, Equation 15 allows the computation of commodity supply frontiers and technical limits on emission reductions. Alternative objectives can be activated for single or multiple regions, periods, commodities, and emission accounts by assigning a value of one to exogenous control parameters ($\theta^{DEMD}_{r,t,y}$, $\theta^{ECOL}_{r,t,j,v,s,u,x,m,p}$, $\theta^{EMIT}_{r,t,e}$). If the sum over all control parameters is non-zero, EUFASOM automatically deactivates the primary surplus maximizing objective and uses the alternative objective function. The use of Equation 15 provides not only model and data insight but also shows important differences between economic and technical constraints.

$$\text{Maximize}\,\text{OBJ2} = \begin{pmatrix} +\sum\limits_{r,t,y}\left(\theta^{DEMD}_{r,t,y}\cdot \text{DEMD}_{r,t,y}\right) \\ +\sum\limits_{r,t,j,v,s,u,x,m,p}\left(\theta^{ECOL}_{r,t,j,v,s,u,x,m,p}\cdot \text{ECOL}_{r,t,j,v,s,u,x,m,p}\right) \\ -\sum\limits_{r,t,e}\left(\theta^{EMIT}_{r,t,e}\cdot \text{EMIT}_{r,t,e}\right) \end{pmatrix}$$

Equation 15 Alternative objective function

4.1.8 Conclusions

This paper describes the mathematical structure of the European Forest and Agricultural Sector Optimization Model. The model has been developed to assess the economic and environmental impacts of political, technological, and environmental change on European land use. EUFASOM goes beyond existing approaches in portraying the interdependencies between food, water, bioenergy, climate, wildlife preservation, and soils. Despite a huge amount of data, variables, and equations, the model is built on simple principles. These principles are captured through 14 fundamental equations. The large model size results from repeated implementations of these equations over space, time, commodities, technologies, and environmental qualities.

The strength of EUFASOM lies in its simultaneous representation of observed resource and technological heterogeneity, global commodity markets, and multiple environmental qualities. Land scarcity and land competition between traditional

[3] In displaying the objective function, several modifications have been made to ease readability: a) the linearly approximated integration terms are not shown explicitly, b) artificial variables for detecting infeasibilities are omitted, and c) conditions are omitted.

agriculture, timber production, nature reserves, livestock pastures, and bioenergy plantations is explicitly captured. Environmental change, technological progress, and policies can be investigated in parallel. Consequently, EUFASOM is well-suited to a) examine the competitive economic potential of agricultural and forestry based mitigation of environmental problems and contrast these to technical or economic potentials without market feedbacks, b) estimate leakage, i.e. how European environmental policies affect non-European land use and c) analyze synergies and trade-offs between different environmental objectives.

Finally, several limitations should be noted. First, EUFASOM is a partial equilibrium model and does not adequately account for income effects. Second, EUFASOM does not value benefits and damages from different environmental qualities but considers only exogenous values, i.e. carbon prices or ecosystem values. Third, due to data constraints, validation of EUFASOM is limited to comparisons between the base period solution and observations. Fourth, the quality of the model reflects the quality of the input data and the quality of linked models. Fifth, EUFASOM results are derived from the optimal solution of a mathematical program and as such constitute point estimates without probability distribution.

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Table 4.2: Major indexes in EUFASOM

Index	Symbol [1]	Elements
Time Periods	t	2005–2010, 2010-2015,…, 2145–2150
Regions	r	25 EU member states, 11 Non-EU international regions
Species	s	All individual and aggregate species categories
Crops	c(s)	Soft wheat, hard wheat, barley, oats, rye, rice, corn, soybeans, sugar beet, potatoes, rapeseed, sunflower, cotton, flax, hemp, pulse
Trees	f(s)	Spruce, larch, douglas fir, fir, scottish pine, pinus pinaster, poplar, oak, beech, birch, maple, hornbeam, alnus, ash, chestnut, cedar, eucalyptus, ilex locust, 4 mixed forest types
Perennials	b(s)	Miscanthus, Switchgrass, Reed Canary Grass, Poplar, Willow, Arundo, Cardoon, Eucalyptus
Livestock	l(s)	Dairy, beef cattle, hogs, goats, sheep, poultry
Wildlife	w(s)	43 Birds, 9 mammals, 16 amphibians, 4 reptiles
Products	y	17 crop, 8 forest industry, 5 bioenergy, 10 livestock
Resources/Inputs	i	Soil types, hired and family labor, gasoline, diesel, electricity, natural gas, water, nutrients
Soil types	j(i)	Sand, loam, clay, bog, fen, 7 slope, 4 soil depth classes
Nutrients	n(i)	Dry matter, protein, fat, fiber, metabolizable energy, Lysine and
Technologies	m	alternative tillage, irrigation, fertilization, thinning, animal housing and manure management choices
Site quality	q	Age and suitability differences
Ecosystem state	x(q)	Existing, suitable, marginal
Age cohorts	a(q)	0-5, 5-10, …, 295-300 [years]
Soil state	v	Soil organic classes
Structures	u	FADN classifications (European Commission 2008)
Size classes	z(u)	< 4, 4 - < 8, 8 - < 16, 16 - < 40, 40- < 100, >= 100 all in ESU (European Commission 2008)
Farm specialty	o(u)	Field crops, horticulture, wine yards, permanent crops, dairy farms, grazing livestock, pigs and or poultry, mixed farms
Altitude levels	h(u)	< 300, 300 – 600, 600 – 1100, > 1100 meters
Environmental qualities	e	16 Greenhouse gas accounts, wind and water erosion, 6 nutrient emissions, 5 wetland types
Policies	p	Alternative policies

[1] Parent indexes are given in brackets

Table 4.3: Major variables in EUFASOM

Variable	Unit	Type	Description
CROP	1E3 ha	≥ 0	Crop production
PAST	1E3 ha	≥ 0	Pasture
LIVE	mixed	≥ 0	Livestock raising
FEED	mixed	≥ 0	Animal feeding
TREE	1E3 ha	≥ 0	Standing forests
HARV	1E3 ha	≥ 0	Forest harvesting
BIOM	1E3 ha	≥ 0	Biomass crop plantations for bioenergy
ECOL	1E3 ha	≥ 0	Wetland ecosystem reserves
LUCH	1E3 ha	≥ 0	Land use changes
RESR	mixed	≥ 0	Factor and resource usage
PROC	mixed	≥ 0	Processing activities
SUPP	1E3 t	≥ 0	Supply
DEMD	1E3 t	≥ 0	Demand
TRAD	1E3 t	≥ 0	Trade
EMIT	mixed	Free	Net emissions
STCK	mixed	≥ 0	Environmental and product stocks
WELF	1E6 €	Free	Economic Surplus

Table 4.4: Major parameters in EUFASOM

Symbol	Description
α	Technical coefficients (yields, requirements, emissions)
τ	Objective function coefficients
φ	Supply and demand functions
∂	Discount rate, product depreciation, dead wood decomposition
β	Resource endowments
ϑ	Soil state transition probabilities
η	Land use change limits
ϕ	Initial land allocation
ψ	Sign switch ($\psi_+ = 1$, $\psi_- = -1$)
θ	Alternative objective function parameters

4.2 Real Options Modeling and Portfolio Selection for Earth Observation Benefit Assessment

Synopsis

Satellite missions are one instrument of earth observation targeted at obtaining information for improved decision-making in sustainable development. Moreover satellites cannot only carry research and observation equipment, but can also provide services that can commercially be sold, for example through the distribution of GPS devices. Still, satellite missions are expensive undertakings involving large sunk costs and facing uncertain benefit streams. Whether a satellite will be launched depends thus not only on the costs of doing so, but also on the uncertainty surrounding the benefits that can be extracted from the mission. Especially in the area of avoiding damages through e.g. better weather forecasts, the socio-economic benefits might be enormously high, but also enormously difficult to quantify. When incentives for private investments are missing, the government has to step in to provide these services. As public officials consider their contributions to the new Global Earth Observation System of Systems (GEOSS), it becomes an important task to give an estimate of the socio-economic value of such earth observation information (Macauley, 2006).

The purpose of this report is to present and illustrate the merits of some relatively new methodologies, which have become indispensable in the toolbox of research on decision-making under uncertainty. Originating in finance, both options theory and portfolio selection have been adapted to also deal with investment or the commitment of resources to real assets or projects, which involve sunk costs and where adaptation ex post is expensive. In other words the investment undertaken is irreversible and resources once committed cannot – or at least to a substantial extent - be recovered ex post.

Since earth observation features all these characteristics (irreversibility/sunk costs, uncertainty of future net benefits, flexibility to time the launch of satellites and other earth observation equipment), real options theory is a suitable approach for analyzing the optimal timing of such projects. In addition, it offers a good methodology to also estimate the merits of better information due to earth observation by enabling the analyst to estimate the expected value of information by comparing decisions under uncertainty and under certainty. This has been done in other areas like energy planning (Fuss, Johansson, Szolgayova and Obersteiner, 2008) and can be applied to e.g. the launching of a satellite mission in a straightforward manner.

While real options theory is risk-neutral as method and thus strictly relies on the expected net present value in each possible state of the world, portfolio selection offers a framework where risk aversion plays a major role and where the analyst can thus capture the benefits from diversification: in a world where it is uncertain, which observation technology will be most effective in finding the decisive information, it can easily be imagined that a portfolio of technologies can insure decision makers against missing the most important information. Likewise, portfolio theory can provide insights to policy makers in the light of uncertain events that can drive them to foster a portfolio of policies that will result in robust results across these uncertain events. It might not be that obvious at first glance, but observation does not only help in

prevention through e.g. early warning ex ante, but also in mitigation in terms of e.g. better informed and targeted rescuing missions after the occurrence of a disaster.
The report will be organized as follows: first, an overview of portfolio theory will be given starting with a simple example and then with the theoretical background involving some of the existing literature in non-financial portfolio selection modeling. Particular emphasis will be given to the fact that – specifically in the case of natural disasters - benefits or losses will most probably not be normally distributed, which makes standard mean-variance portfolio frameworks less appropriate for the analysis. It is therefore important to provide information about alternative risk measures that also take information about the possibly fat tail of the distribution fat into account.

Next, real options theory will be explained, again by pointing out a simple example in the beginning and then giving more insight into the theory. Applications in other areas than earth observation show that this is indeed also a good methodology to estimate the expected value of information – not only economically but also in terms of e.g. potential CO2 emissions savings or avoided damages from natural disasters in the case of earth observation, which can lead to e.g. early warning systems that can thus save lives and alleviate misery.

Finally, some preliminary results will be presented to illustrate the usefulness of real options theory and expected value of information estimation for the assessment of the socio-economic benefits of earth observation. These results are from a real options modeling exercise where a satellite launch is considered in the face of rising yet uncertain benefits when the stream of benefits that accrue from the sale of commercial services like those through GPS is relatively certain, but also relatively low.

4.2.1 Tool Box for Decision Making under Uncertainty[4]

Portfolio Selection

As much as the origins of real options theory are rooted in finance, the same is true for portfolio theory pioneered by Nobel laureate Markowitz (1952) and further developed by Merton (1969, 1971), Samuelson (1969) and Fama (1970). The theory starts out from the observation that most investors are risk averse, i.e. they refrain to a certain extent to buy assets that exhibit a large variance in their returns. To quote Markowitz himself, "[...] the investor does (or should) consider expected return a desirable thing and variance of return an undesirable thing," (Markowitz, 1952, page 77). Investors thus compose their portfolios of assets that exhibit lower expected rates of return, but which are relatively secure, and of assets that have a high expected rate of return, for which they have to accept a higher level of variance. It is the tradeoff between expected return and variance that matters for the investor and leads to a diversification of the portfolio. The main result concerning this tradeoff is that investors should select portfolios that maximize expected returns given a pre-specified level of variance or minimize variance given a desired level of return or more.[5]

Let us look more closely at what such a tradeoff means by giving a simple example now.

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[4] Sections 2.1 and 2.2 follow closely the literature review in Fuss (2008).
[5] See any standard textbook on portfolio theory for a more formal derivation of this result, e.g., Elton and Gruber (2003) or Brealey and Myers (2005).

The Merits of Diversification

Suppose you are an investor and you have 10,000€ at your disposal for buying assets. If you spend all 10,000€ for the acquisition of shares in a car-manufacturing company, you will suffer a huge drop in returns if car taxes are increased, gasoline prices rise and fuel-inefficient cars are banned by regulation. Then it would have paid off to spend at least part of the money on shares in a company offering public transport, since the demand for public transport and thus also the value of the shares might increase in response to the lower demand for transport by car. By the same reasoning, it would not be wise to include too many shares that might be affected in the same way by the same events into your portfolio. For example, buying exclusively commodity futures that are both negatively affected by adverse weather conditions will enforce the downward spiral of your returns when such weather manifests.

It is thus clear that it is through the combination of assets whose returns do not correlate or correlate negatively that the maximum amount of return can be ensured for a given (co)variance of (and between) individual assets' returns. This is what is generally referred to when talking about the benefits of diversification.

Vice versa, you can minimize risk subject to a minimum expected return constraint. It depends on your preference for expected return versus your acceptance of risk. People that are willing to accept a lower expected return in exchange for a relatively low level of risk are called risk-averse and this is what makes the tradeoff between risk and return interesting and what actually brings about the merits of diversification. If you were risk-neutral, you would always go for the asset with the highest expected return. We will see that this is a principle inherent in the real options approach presented in the next chapter.

Theoretical Background

Let us first define the variance of a portfolio.[6] If we have a portfolio composed of N assets, total portfolio variance is defined as:

$$V_{pf} = \sum_{i=1}^{N} \sum_{j=1}^{N} \sigma_{ij} x_i x_j \tag{4.1}$$

where x_i stands for the extent to which the portfolio is composed of asset i; likewise x_j is the fraction of asset j in the portfolio. σ_{ij} is the covariance between assets i and j, and if i = j, then σ_{ij} is just the variance of asset i. In finance, a stock's risk is then measured by its β, which is the covariance between the stock's and the market return relative to the variance of the market return.[7] A β larger than 1 implies that this stock will amplify the movements in the market, whereas a stock with β smaller than 1 will move in the same direction as the market - only less quickly. In general, the market portfolio exhibits a relatively low degree of variability, which is also more or less constant. We call it therefore "market risk". At the same time, smaller portfolios with only a few individual securities will be more risky. The difference between the two

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[6] This exposition draws heavily on the literature review in Fuss (2008).

[7] The market return is measured by the portfolio return of a large number of representative securities.

measures of volatility is called “unique risk”. The more securities are added to the portfolio, the more it becomes diversified and the more will this unique risk decline, until the portfolio risk is equal to the market risk.

The more assets are added to the portfolio, the more does diversification help to reduce risk. However, it is not possible to reduce the unique risk beyond the market risk. This is because the more assets are included, the more covariance terms enter the calculation in Equation (4.1).[8]

By suggesting that the average investor is a risk averse and profit-maximizing agent, Markowitz (1952, 1959) was referring to a relationship between return and risk that has been mentioned in the introduction of this chapter. Looking at Figure 4.1, there are a number of securities listed in a graph with expected return R on the vertical and return volatility measured by the standard deviation $\sigma_{pf} = \sqrt{V_{pf}}$ on the horizontal axis. By composing a portfolio with different shares of these securities, any point within the heavy line can be attained.

However, what a risk averse and return-maximizing investor will do is to opt for any possibility that moves him/her vertically up (higher return) and to the left (lower standard deviation). Consequently, he will always prefer a portfolio on the heavy line over one that lies inside the line. Markowitz therefore calls all portfolios along the heavy line “efficient" portfolios and the line itself is known as the efficient frontier. The reason why the efficient frontier (also called the portfolio possibilities curve) is concave above the point where the risk the minimal is straightforward: it can be shown (see e.g. Elton et al., 2003) that combinations of assets cannot exhibit more risk than the level of risk found on a straight line connecting two assets, i.e. the efficient frontier can never become convex above the point where we find the global minimum variance portfolio. If two points in Figure 4.1 were connected by a straight line, this would imply that their returns are perfectly correlated. For any correlation factor smaller than 1, the curve must therefore be concave.

If the investor can lend at a risk-free rate, r_f (e.g. by buying treasury bonds), which is typically smaller than the risk-free rate at which he can borrow, r_f' (e.g. from the bank), the shape of the efficient frontier will be different: all combinations of risk free lending and borrowing lie on straight lines with r_f and r_f' as origins, as can be seen in Figure 4.1. The straight line emanating from r_f is tangent to the efficient frontier in point B and the borrowing line touches the curve in point A. Beyond A the efficient frontier will therefore be a straight line through point C and before B the frontier will be a straight line starting from r_f. Only in between points A and B is a concave part, where it would be optimal for the investor to hold combinations of risky assets.

[8] Please refer to Brealey and Myers (2005) or Markowitz (1959) or Elton et al. (2003) for a more detailed and formal treatment of this.

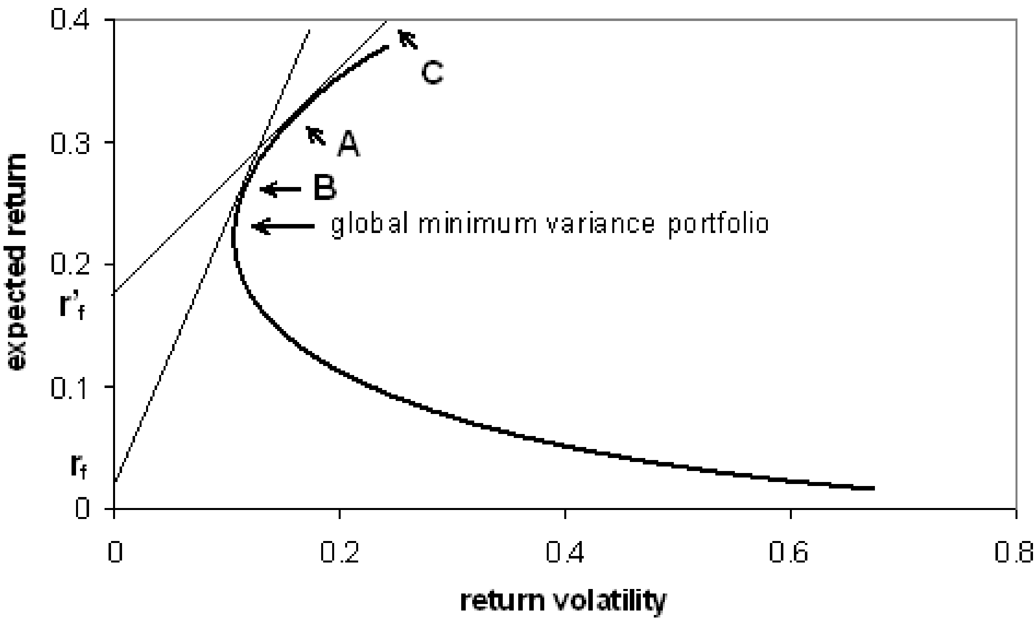

Figure 4.1: Efficient Frontier (Risk averse investors prefer efficient portfolios along the frontier, which are therefore superior to the points marked inside the frontier).

In mathematical terms, let R_{pf} be the total yield on a portfolio pf, i.e.:

$$R_{pf} = \sum_{i=1}^{N} R_i \cdot x_i \tag{4.2}$$

where R_i is the random yield of a particular security i and the rest of the notation is unchanged. To use Markowitz' (1952) own notation, let μ_i be the expected return on security i. Then, the expected return on the whole portfolio is

$$E\{R_{pf}\} = \sum_{i=1}^{N} \mu_i \cdot x_i \tag{4.3}$$

And the corresponding variance is as in Equation (4.1) above.

For fixed (probability) beliefs about the development of μ_i and σ_{ij}, the efficient portfolio can then be calculated by maximizing Equation (4.3) subject to Equation (4.1). Conversely, it is also possible to minimize Equation (4.1) subject to a given expected return. This will also deliver all optimal combinations of $E\{R_{pf}\}$ and V_{pf}. The different combinations of $E\{R_{pf}\}$ and V_{pf} that solve this problem will then trace out the efficient frontier introduced in Figure 4.1. Markowitz calls this the EV-rule (Markowitz, 1952, page 82).

One important flaw of the Markowitz framework is that the mean-variance approach maximizes only quadratic utility, i.e. it is not a valid method to tackle problems involving preferences for higher-order return moments. As an example, return distributions might be skewed and have fat tails, which would imply higher losses beyond a certain threshold. Section 2.1.4 will come back to this problem and offer some solutions in the form of different risk measures than variance.

4.2.3 Application of Portfolio Selection to Non-financial Assets

Two decades later, financial portfolio theory was adapted and applied to real assets as well. Examples include the valuation of offshore oil leases (Helfat, 1988) and the valuation of financing long-term projects (Seitz and Ellison, 1995). Applications involving energy planning date back as far as 1976 (Bar-Lev and Katz, 1976). Lately, interest in the topic has arisen again; see e.g. Awerbuch and Berger (2003), Awerbuch (2006) and Roques et al. (2006).

The Importance of Choosing the Right Risk Measure

As already commented upon in Section 4.2 the standard Markowitz mean-variance approach is only an appropriate tool for decision making when the involved distributions are normal. In that case, no information is lost when just considering the first two moments, mean and variance.

However, when it comes to the benefits of earth observation, normal distributions cannot be expected as the standard. In fact, natural disasters can be characterized as high impact, low frequency events and thus loss distributions mostly feature fat tails. The variance can then not capture this information.

Other risk measures are not subject to this deficiency. A measure frequently employed these days is the so-called Value-at-Risk (VaR). Let us define the VaR first: The β-VaR of a portfolio is the lowest amount α such that, with probability β, the portfolio loss will not exceed α, whereas the β-CVaR is the conditional expectation of losses above that amount α, where β is a specified probability level. This is illustrated in Figure 4.1, where it can clearly be seen that the β-VaR corresponds to the β-percentile of the distribution, whereas the β-CVaR is the mean of the random values exceeding VaR.[9]

The shortcomings of VaR compared with CVaR relate to its usefulness in risk management and its technical properties. Losses exceeding the threshold value are not taken into account by VaR, but by CVaR. Moreover, VaR is only a coherent risk measure in the sense of Artzner et al. (1999), if distributions can safely be assumed to be normal. Generally, VaR is neither subadditive nor convex. In contrast, CVaR is always a coherent risk measure. Furthermore, the results in Rockafellar and Uryasev (2000, 2002) make computational optimization of CVaR readily accessible. Note that, under certain conditions, the minimization of VaR and CVaR and the MV framework yield the same optimal portfolio allocations provided that underlying distributions are normal.[10] This does not apply if the assumption of normality is violated.

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[9] See Rockafellar and Uryasev (2000, 2002) for more detailed information and all corresponding derivations for the portfolio approach.

[10] The CVaR approach can thus be viewed in some sense as a generalization of the MV approach when dealing with non-normal or non-symmetric distributions.

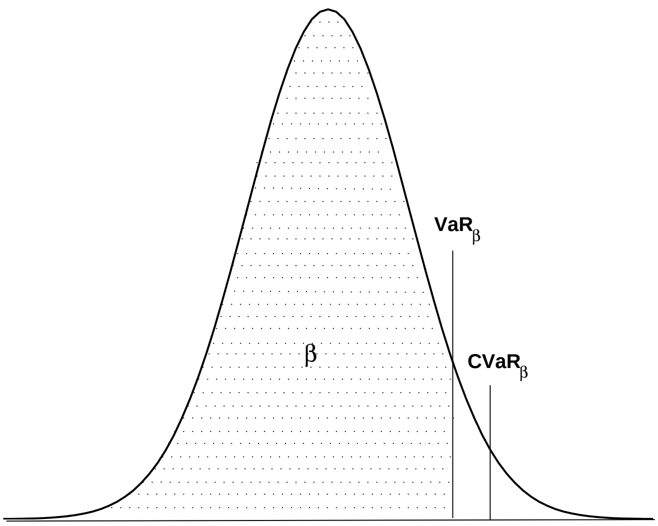

Figure 4.2: Illustration of β-VaR and β-CVaR for a Normal Loss Distribution

Fortin, Fuss, Hlouskova, Khabarov, Obersteiner and Szolgayova (2007) combine a CVaR-portfolio framework with real options theory by using the return distributions for individual technologies as an input for the portfolio optimization. They show that, for the model that they develop and the data parameter setting they use, "both the univariate distributions and the joint distribution (copula) of the returns, which are the results from the real options procedure, do not seem to be normal."

Real Options Theory[11]

The special features of the electricity sector (uncertainty, irreversibility and the flexibility to postpone investments) make standard investment rules relying on the Net Present Value (NPV) inappropriate because they treat investment opportunities as "once-and-for-all" chances and therefore ignore the options involved in the sequence of decisions.

A very simple, graphical example illustrates this clearly. In Figure 4.3 an investment option that can be exercised at time zero will deliver a profit of π immediately. However, at time t' two different scenarios are possible and only at time t' the uncertainty will be resolved, which of the two will materialize. In one case the profits rise to π', in the other case there will be a loss of π''. Thus, by postponing investment, the investor might forgo the striped area of immediate profit flows, but can at the same time avoid the loss represented by the dotted area. As long as the latter exceeds the first, i.e. the gains from waiting exceed the opportunity costs of not investing, waiting will be optimal.

[11] This exposition draws heavily on the literature review in Fuss (2008).

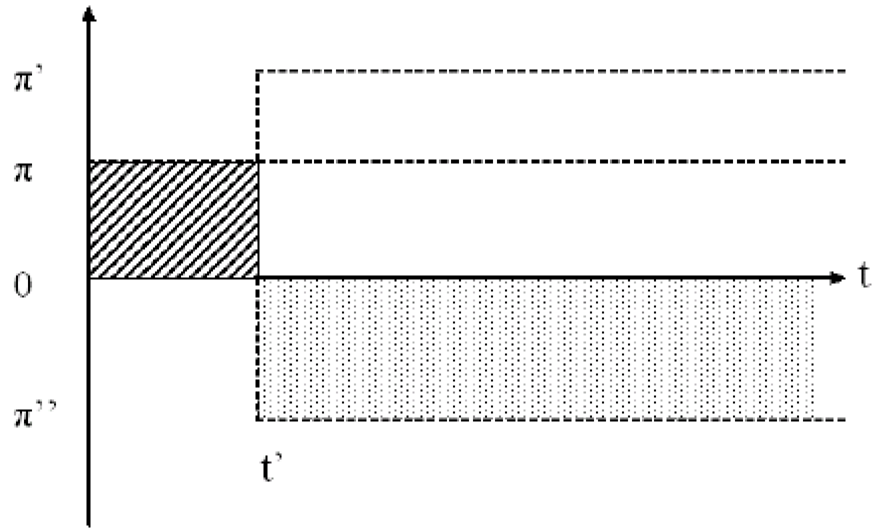

Figure 4.3: Graphical Example of the Option Value

A very simple, graphical example illustrates this clearly. In Figure 4.3 an investment option that can be exercised at time zero will deliver a profit of π immediately. However, at time t' two different scenarios are possible and only at time t' the uncertainty will be resolved, which of the two will materialize. In one case the profits rise to π', in the other case there will be a loss of π''. Thus, by postponing investment, the investor might forgo the striped area of immediate profit flows, but can at the same time avoid the loss represented by the dotted area. As long as the latter exceeds the first, i.e. the gains from waiting exceed the opportunity costs of not investing, waiting will be optimal.

A Simple Example for Sequential Decision-Making

Pindyck (1993) presents a case where an investment of $1 is required at first, after which there is a probability of 50% that the project will be finished successfully. However, there is also a 50% chance that another investment of $4 will be necessary to complete the project. The completed project will have a certain payoff of $2.8, so with an expected cost of $3 the NPV is negative and the traditional NPV rule would advise not to invest. More precisely though, the investor would take into account that he has the option to abandon the project after phase one and so the NPV adjusted for the option value is 50%×$2.8-$1=$0.4, which is greater than zero, so at least the first phase should be undertaken. The option value can then be calculated as the difference between the traditional and the adjusted NPV. According to Pindyck (1993) this reasoning can be used to explain the fact that so many new nuclear power plants close to completion were cancelled in the United States in late 1982, a time during which there was much uncertainty about construction costs, which had started to rise considerably after some projects had already been launched. It is important to note that the term "option" in this context should not be understood as a synonym for choice or alternative. An option as it is meant here is the right, but not an obligation, to realize an investment opportunity.

Theoretical Background

In order to demonstrate the principles of the approach, first consider an investor, who can postpone the decision to invest. Furthermore, the value of the investment is uncertain, and once committed, the cost of the investment cannot be recovered anymore. This implies that the investor can possibly gain by waiting until some of this uncertainty is resolved. If V is the present value (PV) of the project to be undertaken and C is the cost of the investment to be made, then the traditional NPV rule indicates that investment should only be conducted if V ≥ C. However, if V evolves stochastically, the true current value of the project will most likely be higher, since we also have to value the option to postpone the investment. Suppose V follows a geometric Brownian motion,[12] where dV is the change in V, μ is a drift parameter, σ is the volatility parameter and dW the increment of a Wiener process:

$$dV = \mu V dt + \sigma V dW$$
$$dW = \varepsilon_t \sqrt{dt}, \quad \varepsilon_t \sim N(0,1), \quad E\{\varepsilon_i \varepsilon_j\} = 0 \quad \forall i, j \quad i \neq j \tag{4.4}$$

The expected PV of the option to invest shall now be maximized. Following Pindyck (1991) in the maximization of the expected PV, we denote the option value by a function F(V):

$$F(V) = \max_t E\{\exp(rt) \cdot (V - C) \tag{4.5}$$

where we omit to denote the dependence of V on t for simplicity. t has to be chosen so as to maximize the expected value of the project. r is the discount rate. The expected return from postponing investment is E{dF(V)}/dt, which has to be equal to the opportunity cost (i.e. the interest that could be earned on F(V), which is received upon investment, in the meantime) of postponing. This leads us to the following arbitrage equation, also referred to as Bellman equation (see e.g. Dixit and Pindyck (1994) for more background information).

$$E\{dF(V)\}/dt - r \cdot F(V) = 0 \tag{4.6}$$

Intuitively, you could explain Equation (4.6) by noting that it equates the marginal costs of waiting with the marginal benefits of doing so. In other words, the investor can earn F(V) upon immediate investment and earn interest on that amount, but if investment is postponed these gains are foregone. These opportunity costs therefore have to be equal to the gains from waiting, which accrue from changes in F(V) -- a sort of “appreciation” of the underlying asset. Since we need to differentiate F(V) to find the solution, we make use of Itô's Lemma (see e.g. Mikosch (1999)).

$$dF(V) = F'(V)dV + (1/2) \cdot F''(V)(dV)^2 \tag{4.7}$$

[12] This process is simply the exponential of a Brownian motion with drift and was initially suggested by Black and Scholes (1973) and Merton (1973) as a response to the weakness of the standard Brownian motion with drift to also assume negative values (since it is a Gaussian process after all), which is not a realistic property for modelling price behaviour, which is what we intend to use this approach for.

Now we substitute the expression for dV from Equation (4.4) into Equation (4.7) and take expectations. It is important to note that E(dW)=0 by definition of the process (see above), so the terms related to dW drop out. This delivers

$$E\{dF(V)\} = \mu \cdot V \cdot F'(V)dt + (1/2) \cdot \sigma^2 \cdot V^2 \cdot F''(V)dt \tag{4.8}$$

Substituting (2.2.5) into Equation (2.2.3) gives

$$\mu \cdot V \cdot F'(V)dt + (1/2) \cdot \sigma^2 \cdot V^2 \cdot F''(V) - r \cdot F(V) = 0 \tag{4.9}$$

The corresponding boundary conditions can be found in Equation (4.10), where a tilde denotes the value of a variable at the optimum. The first condition conveys that the option value will be zero, if the project has a value of V=0. The second one requires F(V) to be smooth and continuous around the optimum point, which only applies if the increase in F at $\tilde{V}$ is equal to the increase in V at its optimum, i.e. if the slopes are equal. Since the derivative of V with respect to $\tilde{V}$ is 1 at this point, F'($\tilde{V}$) has to be equal to 1 as well. This condition is also widely known as the “smooth-pasting” condition (Dixit and Pindyck, 1994). Finally, at this optimum point, the net payoff, V-C, will be equal to the option value, F(V).

$$F(0) = 0$$

$$F(\hat{V}) = \hat{V} - C$$

$$F'(\hat{V}) = 1 \tag{4.10}$$

For this problem, it is possible to solve Equation (4.9) subject to the constraints in (4.10). To solve more complicated versions of the Bellman equation, sophisticated computing methods are needed. The approach via partial differential equations may not always be the most efficient or even possible way to deal with this. Therefore, dynamic programming is often combined with Monte Carlo simulation techniques or multinomial decision trees in order to find the most efficient and flexible solution algorithm.

Solving Equation (4.9) in the style of Pindyck (1991), we guess a functional form and determine by substitution ex post:

$$F(V) = \alpha \cdot V^{\beta} \tag{4.11}$$

where α can be derived by substituting Equation (4.11) into boundary condition number 2 in (2.2.7). α is therefore equal to ($\tilde{V}$ -C)/($\tilde{V}$ β). Similarly, $\tilde{V}$ is the result of plugging the first derivative of F(V) in Equation (4.11) into the smooth pasting condition:

$$\tilde{V} = \beta / (\beta - 1) - C \tag{4.12}$$

β is composed of the parameters as follows:

$$\beta = 1/2 - \mu/(\sigma^2) + \sqrt{[\mu/(\sigma^2) - (1.2)]^2 + 2 \cdot (r/\sigma^2)} \tag{4.13}$$

In order to illustrate the difference between the standard NPV rule and the real options rule note that there is a wedge driven between the NPV and the "true" current value of the project by the existence of uncertainty and the flexibility of timing the investment differently. If we were following the standard NPV rule, then investment would be profitable at $\tilde{V} = C$, so this wedge referred to above is exactly defined as $\beta/(\beta-1)$, which will always be greater than 1, as $\beta \geq 1$. Therefore, we can conclude that under uncertainty the value of the project at the exercise date must exceed the mere cost of the investment. Furthermore, an increase in uncertainty, proxied by an increase in σ will actually raise the wedge and, other things equal, lead to a postponement of investment because there is more to gain by waiting longer.

4.3 The Expected Value of Information—Some Applications with Real Options and Other Stochastic Modeling Techniques

As pointed out by Macauley (2006) most information models find that the value of information largely depends on four important factors: (1) the extent of uncertainty on behalf of the decision makers, (2) the cost of making a decision, which is not optimal in the light of better information, (3) the cost of making use of the information and incorporate it into decisions, and (4) the price of the next-best substitute for the information. In other words, the value of information could be interpreted as the willingness to pay for them by the concerned decision makers.

With a simple example Macauley (2006) shows that the value of information is zero when the decision maker attaches a probability of zero or 1 to the events that are thus no longer uncertain in his view. The other cases where information has no value is when there are no alternative actions available, even if information can be obtained, and where a wrong decision will not result in any costs. In the same vein, information is most valuable when the costs associated with a wrong action are high, when a lot of alternative actions are available and when the decision maker has no extreme preference for one or more of the alternatives.

She then goes on to categorize the methods by which the expected value of information has previously been measured into two subsets: (a) studies that use wage and/or housing prices to infer the value of e.g. weather information because the latter can be expected to be capitalized in the prices and so it makes sense to deduce the value from existing time series; this is what Macauley (2006) calls "hedonic pricing studies". Category (b) includes all studies that measure the value of information by gains in output or productivity, even though the value of information is generally found to be rather small in most of the studies. Macauley (2006) attributes this to the fact that people are obviously only willing to pay for information ex ante and often they are not aware of the severe consequences that the lack of information in the case of an uncertain event can have. Similarly, people often only attribute a very low probability to catastrophic events and then choose not to pay for information that might as well be rather costly.

In the end, she deems the computation of expected values of information a very suitable tool for the valuation of earth observation benefits, where the availability of information can save costs, lives and alleviate misery in the light of disasters.

In economics – and more specifically in the area of climate change policies—the expected value of information has been a well-known tool for years. Peck and Teisberg (1992), Manne and Richels (1992), Nordhaus and Popp (1997) are all examples (the work by Manne and Richels (1992) is an exception) that adopt a cost benefit approach aiming to find the optimal policy response to climate change damages and to estimate how much the world would be better off economically, if for example the climate sensitivity and level of economic damages where known, see Peck and Teisberg (1992) and Nordhaus and Popp (1997). In general, these studies use multi-stage optimisation where all information about the correct level of the uncertain parameters arrives in one time instance. Others, like Fuss, Johansson, Szolgayova and Obersteiner (2008) use stochastic dynamic programming allowing for a much richer description of the evolution of the uncertain parameters but with the disadvantage of having much less scope in terms of controls and states.[13]

In this study they present a real options model with multiple options that are evaluated in the presence of each other, so that the mutual effect of the individual options on each other is accounted for. They apply this to the electricity sector, which is stylized to encompass three typical technology families based on fossil fuel, fossil fuel with carbon capture and storage (CCS) and renewable energy respectively. By testing different CO2 price processes (geometric Brownian motion versus jump process), they mimic carbon policies that are frequently adapted to the arrival of new insights from climate science, economics and politics and carbon policies that have longer commitment periods, during which the CO2 price rises without any fluctuations.

For their computations, they chose the Monte Carlo simulation (remember that this is the numerical technique often used when an analytical solution cannot be obtained). By optimizing recursively they obtain a multidimensional matrix containing the optimal action for every time period, state and price, which can be interpreted as a set of strategies or a recipe for decision-making in the face of uncertainty. They then simulate 10,000 possible CO2 price paths and extract the corresponding decisions from the output. The results are thus computed in two independent steps: (1) the recursive optimization part determining the strategies for the optimal decision of the producer for each possible state and price; and (2) the simulation of future price paths and extracting the corresponding decisions from the previously obtained strategies. For the calculation of the expected value of information for the electricity producer and the expected carbon benefit (i.e. the CO2 emissions that could have been saved if the information had been available) from having information they use the simulated 10,000 CO2 price paths and compute the cumulative emissions and the net present value (NPV) cost using the stochastic dynamic programming approach described

[13] Multi-stage optimisation has the tendency to become computationally intensive when there are many periods and scenarios, since it requires decision-making at each stage depending on the prior history of states. In the case of stochastic optimal control problems (e.g., as real options models) similar dimensionality problems might arise when there are many possible states or controls. Since in our study we are investigating a long time horizon (150 years) a relatively modest state and control space, multi-stage optimization is not the optimal solution method for our problem. Cheng et al. (2004) compare the two approaches and their advantaged and disadvantages in more detail.

above and compare these results with the results obtained from a deterministic dynamic programming model, where the evolution of each of these 10,000 price paths are known ex ante. [14] By comparing the average NPV costs and the expected cumulative CO2 emissions in the stochastic case with those of the deterministic case (with 10,000 identical CO2 price paths), a measure is obtained of the uncertainty effect - or the lack of information - that has kept the investor from finding the same optimum strategies as in the deterministic cases and thereby measure the expected value of information. The expected value of information is estimated in relative terms based on the cost of the policy. Thus, it is the difference in extra technology costs due to the CO2 policy and CO2 payments that are compared in the stochastic and deterministic cases so as to give an estimate of the expected value of information.

Their results show that it has advantages to have climate change policies that are stable over a certain length of time, since less frequent fluctuations reduce the expected value of information not only for the cost-minimizing investor/producer, but also for potential CO2 reductions, which then also increases the effectiveness of the policy itself. This also emphasizes the need for better information about climate sensitivity, for example, which would help the policy maker in implementing better informed decisions that are thus more stable, since they do not need to be adapted so frequently. Earth observation therefore holds strong potential gains also in the area of climate change policy decision-making.

Another area is the estimation of the above-mentioned merits of early warning systems. Lave and Apt (2006) employ a stochastic cost-benefit framework to the valuation of control structures, such as dams and levees, and mitigation policies such as construction standards, in the face of natural disasters such as storms, and the benefits of information for early warning and evacuation in the United States. Especially for the latter they find large scope for improvement through better information. Also the availability of information ex ante should lead people to make better decisions about e.g. the areas that they settle down in. The authors stress that economically much could be saved by informing people that they will have to bear the consequences when they move to high risk areas because the lack of opportunity for moral hazard will lead them to refrain from their decision when they expected government and insurance to alleviate their losses.

[14] Technically, this means that the 10,000 price paths simulated for the stochastic model were saved and then used for the deterministic version, i.e. there are also 10,000 instances of decisions in the deterministic model, with the difference that investors know the price path on beforehand.

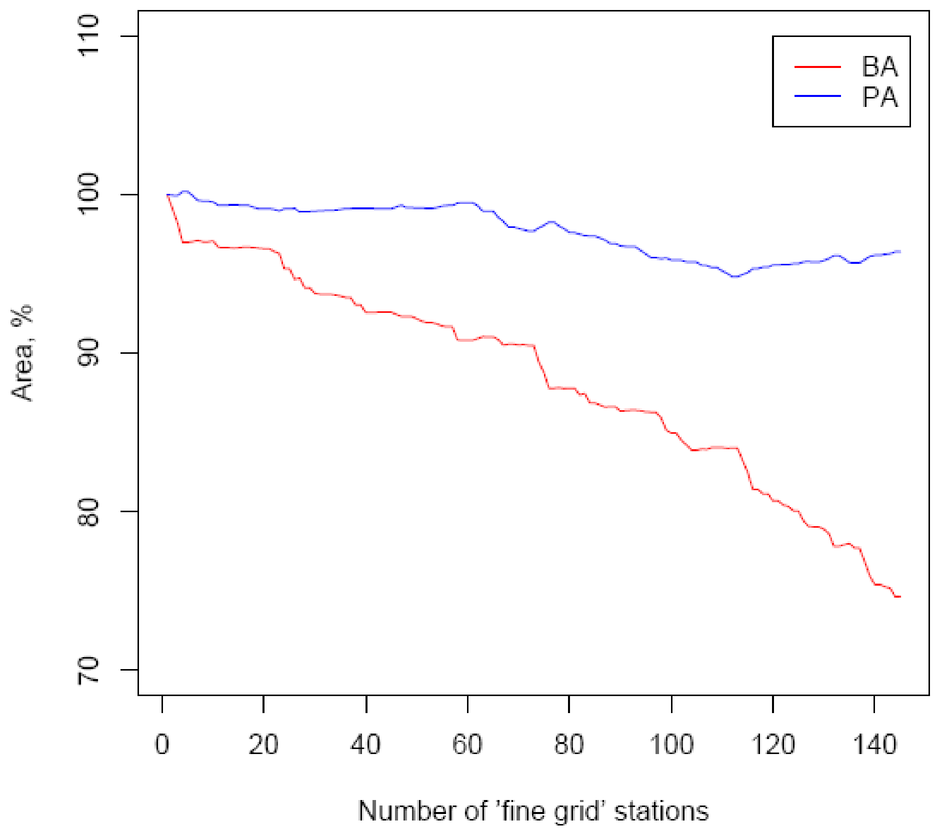

Figure 4.4: Dependence of the Burnt (BA) and Patrolled (PA) Areas on the Number of Added Weather Stations

A similar conclusion is found by Khabarov, Moltchanova and Obersteiner (2008), who conduct simulation studies to estimate the benefits of a finer grid of weather stations are more frequent patrols in forest areas, so that wild fires can be detected earlier and – if not prevented—at least limited or put out before they can spread to a larger area and thus cause economic damage and endanger the life of humans and animals. Figure 4.4 shows that the addition of more weather stations indeed reduces the fraction of the area burnt by wild fires.

Other studies show that not only the ex ante prophylactic actions are facilitated by better observation information, but also the losses that can be expected after catastrophe has struck might be significantly reduced if e.g., rescuing teams could be better informed and coordinated.

Let us consider the example of an earthquake: while there is definitely no possibility to avoid the occurrence of an earthquake and the scope for early warning systems are limited by the lack of understanding of the involved deep underground geophysical processes, it is important to note that a high percentage of the deaths caused by an earthquake is actually due to the people that die after the earth quake because long response times jeopardize the success of rescue operations. These response times could be significantly shortened by obtaining better information that can then serve to accelerate the assignment of rescue brigades to specifically damages areas, for example. Moltchanova, Khabarov and Obersteiner (2008) use a stochastic framework to model the dependence of an earthquake rapid response system (in a virtual city of standard size) on available information and resources.

Figure 4.5 displays the efficiency of the rescuing brigades in saving lives after an earth quake, where the red line represents the graph for less observation information and the blue line results from better informed operations.

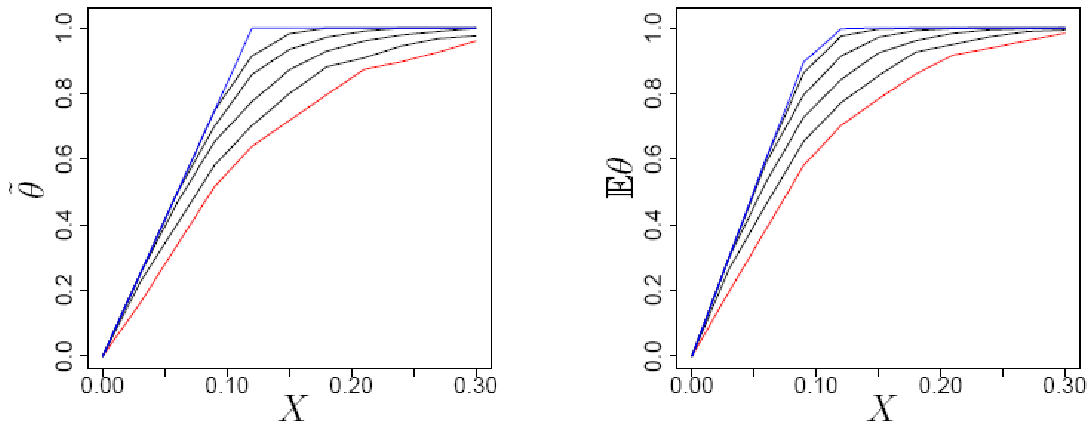

Figure 4.5: Efficiency in Life-Saving and Expected Life-Saving Efficiency over Available Resources

It is clear that for any level of available (rescuing) resources, X, the efficiency of saving lives is higher when those involved are better informed and can thus coordinate operations in a much more efficient way: for resources of 0.10, more than 80% can be saved in the case of better information, while less than 60% are saved with limited information.[15]

4.4 Applicability to Earth Observation Benefit Assessment

While the last section has clearly shown that real options frameworks and other stochastic optimization methods are very suitable for estimating the willingness to pay for information on part of the decision-maker (the investor would be willing to pay for information because making more informed decisions will increase profits, whereas the policy maker would pay for information for the sake of inducing decisions that indeed reduce carbon emissions in the desired way), portfolio theory has its merits for earth observation benefit assessment as well.

Fuss, Szolgayova, Khabarov and Obersteiner (2008) perform an analysis using the framework by Fortin, Fuss, Hlouskova, Khabarov, Obersteiner and Szolgayova (2007), which also examines the impact of the volatility CO2 prices. They find that such uncertainty affects individual power plant owners and thus reshapes the return distributions for the individual technologies considered. Knowing this, large investors will diversify their portfolio and adopt more renewables. In other words, uncertainty at the firm level can make the policy designed to reduce emissions more successful, as the funds provided for energy generation are also spread out to renewables. This gives

[15] This also points to the problem that in countries, where not enough resources are available for such rescue missions, even the acquisition of best information would largely be in vain.

the rather pessimistic outlook given by the pure real options model mentioned at the end of the last section a more optimistic outlook deriving from the benefits of diversification that a portfolio approach can account for.

4.5 Conclusion

This report has shown that new methodologies to assess the value of a project or an investment that have been derived from financial economics and have already been applied to decision-making concerning non-financial assets are applicable to also assess the benefits of earth observation. Real options analysis is very well suited to derive the optimal decisions under uncertainty but also in the face of known information, the value of information can be computed in a straightforward way as the difference between the two. It has been shown that this does not only apply for the computation of the economic expected value of information, but also for other (social or environmental) benefits like the potential to save emissions through different investment patterns in the energy sector.

Portfolio theory on the other hand has been less focused on dynamic issues in the area of non-financial investment so far, but it offers the clear advantage to account for the benefits that accrue from the opportunity to diversify over technologies, strategies and policies. In this way, the value of information obtained through earth observation might even be enhanced, since it can also inform the decision whether to hold a portfolio of strategies or technologies or policies, which might lead more flexibility in damage prevention and mitigation.

Especially in the face of rising damages from natural disasters that are at least partially linked to the increased rate of global warming over the last decades, it is important to keep open-minded to the application of modern valuation techniques that can inform decision-makers to commit resources to earth observation that can in turn inform decisions that can avoid or reduce economic damages and save human lives.

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