Chapter 4
Valuing the Potential Impacts of GEOSS: A Systems Dynamics Approach

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Abstract Global earth observations are perceived as instrumental to attaining sustainable development goals. Methods to assess the long-run socioeconomic benefits of the emerging global Earth observation system of systems (GEOSS) as an integrated multisensor infrastructure have been missing to date. This chapter presents a systems dynamics approach to assess the effect of improvements in Earth observations across the nine societal benefit areas of the Group on Earth Observation (GEO). Two types of integration are assessed with the proposed model structure: (1) measuring benefits in an integrated assessment environment (e.g., improved weather forecasting through better measurement of cloud properties could lead to benefits in the agriculture, energy and water sectors); and (2) measuring benefits of an integrated observing system (e.g., in areas with high cloud cover, improvements in the resolution of optical sensors will lead to benefits only if linked to supplementary observing systems such a radar or ground surveys). The benefits from integration relate mostly to economies of scope on both the observation and benefit system sides. Cost reduction from economies of scale are derived from a global or large scale observing system vis-à-vis the currently prevailing patchwork system of national or regional observing systems. Results indicate that the total system benefits of GEOSS are usually orders of magnitude higher than their costs. Benefits are also policy dependent and tend to increase with the degree of implementation of mainly international environmental agreements.

Keywords Dynamic modeling • Earth observation • Earth system • Global Earth Observation System of Systems • Society benefit areas • Value of information

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4.1 Introduction

Managing global change involves managing risk in a complex system undergoing major transitions. The Earth system in the Anthropocene (Crutzen and Stoermer 2000) is defined by its interdependencies between social, economic, and environmental subsystems constituting a complex dynamic system. Appropriate management of such a system can come only from improved monitoring and understanding of the underlying processes and their interdependence. Recent developments in the fields of information technology, data infrastructures, and Earth observation enable knowledge gains and consequently higher predictive performance, which provide the basis for improved decision making across spatial scales. The Global Earth Observation System of Systems (GEOSS), coordinated by the Group on Earth Observations (GEO),[1] aims at connecting the diverse sets of monitoring systems to support decision making of policymakers, resource managers, scientists, and average citizens.

Despite the obvious advantages that Earth observations can bring to decision making, we lack appropriate theoretical and methodological frameworks to assess the economic and wider societal benefits of a GEOSS-like infrastructure (Craglia et al. 2008). There is extensive literature on the benefits of weather forecasting (Adams et al. 1995; Katz and Murphy 1997) but relatively little assessment work in other fields of Earth observation. Furthermore, the available studies are mostly sectoral and focus on particular areas, such as biodiversity (Leyequien et al. 2007; Muchoney 2008). Case studies on the value of improvements in Earth observation systems are usually very specific and not generalizable. For example, Considine et al. (2004) analyzed the benefits of improved hurricane forecasting in oil and gas production in a confined geographic area. Bouma et al. (2009) examined the effect on water quality management in the North Sea of improved in situ observation networks or remote sensing–based observing systems. Wieand (2008) quantified the effects of an integrated ocean observation system on recreational fishing. Despite their thorough, in-depth analysis and high level of sophistication, these studies do not provide a methodological framework, and integrated assessments of the total global consequences within and across all areas remain lacking.

The need for such evaluation led to a European Commission–sponsored project, Global Earth Observation—Benefit Estimation: Now, Next and Emerging (GEOBENE)[2]—the world's first attempt to systematically and comprehensively study the benefits of a global system of system of Earth observations (European Commission 2008). GEOBENE's goal is to develop methodologies and analytical tools to assess the economic, social, and environmental effects of improved quantitative and qualitative information delivered by GEOSS, in and across nine societal benefit areas (SBAs)—disasters, health, energy, climate, water, weather, ecosystems, agriculture, and biodiversity. This chapter begins with the presentation of the systems

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[1] http://earthobservations.org

[2] http://www.geo-bene.eu

dynamics model that was built to evaluate the total effects of Earth observation. The following section describes the methodology used for the systems analysis. Section 4.3 discusses a selected set of results assessing the effect of GEOSS improvements. The final section makes some closing methodological remarks.

4.2 Methods and Tools

4.2.1 Concept

The basic concept behind the work presented in this chapter is to adapt and apply methods and tools typically used in technological foresight studies for impact assessment of GEOSS scenarios. This is illustrated in Fig. 4.1. The first and principal challenge of the modeling approach is to assimilate the many heterogeneous sources of information in VOI studies carried out in the area of Earth observation into an integrated global impact study. The primary sources were direct results from GEOBENE models, impact figures from published articles and sector reports, and information obtained from expert interviews or online research. Generally, VOI studies are confined to a particular place, time and sector. Impacts are rarely reported on global aggregates or carried out using a wider economic system representation to account for the many potential feedbacks. Therefore, existing information usually needs to be adapted through aggregation to mimic effects on a global level and over long time horizons.

The next challenge is to integrate these aggregated technology storylines or economic assessment estimates in the dynamic modeling of global change. The effects across many components of the socioeconomic system are quantified using the Full of Economic-Environment Linkages and Integration dX/dt (FeliX) model. To achieve integration, a “logic model” is typically constructed first, outlining the value chain of the use of new products for Earth observation (EO). In a second step, an adapted representation of the value chain is coded in the FeliX model as a new component. The impacts of changes in the EO infrastructure are played out on a general scenario storyline that includes the major developments of global change. The basic socioeconomic and Earth system drivers are provided exogenously through socioeconomic scenarios and storylines as well as their respective Earth system projections. Assumptions on the technological development and deployment of EO technologies are harmonized with the global change storylines. Assessment of GEOSS scenarios is then carried out through the combination of the various VOI information feeds and a global change scenario.

The societal benefit areas set the boundaries of the FeliX model. For the formulation of SBA-specific model structures, literature reviews and expert consultation were carried out to identify physical properties of GEOSS improvements and how they might further propagate through the benefit system defined by the SBAs. For example, specific model structures on phenomena closely related to climate

Fig. 4.1 Basic approach aggregating and integrating VOI knowledge in GEOSS foresight studies

include atmospheric concentration of CO_2 caused by human activities and the associated carbon cycle. The basic dynamics of the climate system have been intensively researched and described in the literature (Oeschger et al. 1975; Goudriaan and Ketner 1984; Bolin 1986; Rotmans 1990; Nordhaus 1992; Fiddaman 1997), which allowed for adoption of quantitatively expressed relations of the system components in the FeliX model structure. In cases where such relations have not been quantitatively established, group model building sessions (Richardson and Andersen 1995; Vennix 1996; Andersen et al. 1997) or online research was conducted, and subject matter experts defined and quantified the relations of interest and constructed parts of the model. The outcome of this work is a system dynamics model consisting of a set of interrelated differential equations allowing for computer simulation that gives quantitative results. In our work to tease out the different relationships and links between the SBAs and the effects of GEOSS, we found the discussion around model outcomes and the creation of the model scenarios very useful. In addition to our efforts to set realistic model links and to compare the scenarios with other global projections, we found that the group model sessions provided insight into the influence of GEOSS on the SBAs and the total system.

4.2.2 *FeliX Model*

The FeliX model is a system dynamics type of model, following an approach originally developed by Forrester (1958, 1961), Meadows et al. (1972), Richardson and Pugh III (1981), and Sterman (2000). System dynamics models attempt to capture the interactions within a closed system. Most variables are therefore endogenous (i.e., contained within the system represented by a system dynamics model). To describe the system structure, the model focuses on the flow of feedbacks that occur throughout its parts (feedback loops): a change in one variable affects other variables over time, which in turn affects the original variable, and so on. The dynamic behavior then occurs when flows accumulate in stocks (e.g., atmospheric carbon). Special dynamic notions are also given by delays and nonlinear relations between the system elements. All these elements produce changes in the way the system has performed in the past and might evolve in the future.

The FeliX model, following the system dynamics approach, attempts a full systems perspective, where the underlying social, economic, and environmental components of the Earth system are interconnected to allow for complex dynamic behavior characterizing the Anthropocene (Schellnhuber 2009). A change in one area often results in changes in other areas. For instance, depletion of oil and gas, a source of energy, may affect population growth but also put pressure on the agriculture sector to produce more energy crops as a substitute. As a dynamic model, FeliX captures important stock changes (e.g., depletion of natural resources, accrual of carbon dioxide in the atmosphere) or consequences of certain policies (e.g., afforestation, emissions reduction) over time. The FeliX model was built to achieve congruence with the nine SBAs of GEO. The model structure of FeliX is illustrated in Fig. 4.2, and a detailed description of the FeliX model is provided in Rydzak et al. (2009).

At the core of the economy module is a neoclassical growth model. Capital is an accumulation of investments whereby in FeliX, investments in the energy and the GEOSS sector are accounted for separately. Growth in gross world product is driven by increases in the labor force, which is modeled explicitly in the population module, along with capital accumulation and technological change. The economy module contains a representation of the climate system and takes into account the effects of global average temperature change, according to the DICE model (Nordhaus 1992, 1994). In addition to the climate mitigation measures (i.e., reduction in emissions of greenhouse gases, GHGs) in the DICE model, the FeliX model accounts for climate adaptation to more intense storms, forest fires, droughts, floods, and heat waves and also incorporates prevention and adaptation activities. However, the range of effects from climate change is uncertain, the assumed model parameters were revised and some of the damages explicitly modeled. The DICE model is known to potentially underestimate climate impacts (e.g., Stern 2007).

The FeliX model accounts for CO_2 emissions with a detailed representation of emissions in the energy sector and land-use change. Energy production technologies differ in their carbon intensities. The model accounts for CO_2 emissions from oil, gas, coal, biomass, solar, and wind energy technologies for their full life-cycle. Furthermore, the FeliX model uses the carbon cycle model proposed by Fiddaman (1997): CO_2 emissions accumulate in the atmosphere and are reabsorbed through fluxes to the terrestrial biosphere and the ocean. The model also accounts for CO_2 flux between living biomass and humus and also distinguishes between the ocean's mixed layer and the deep ocean.

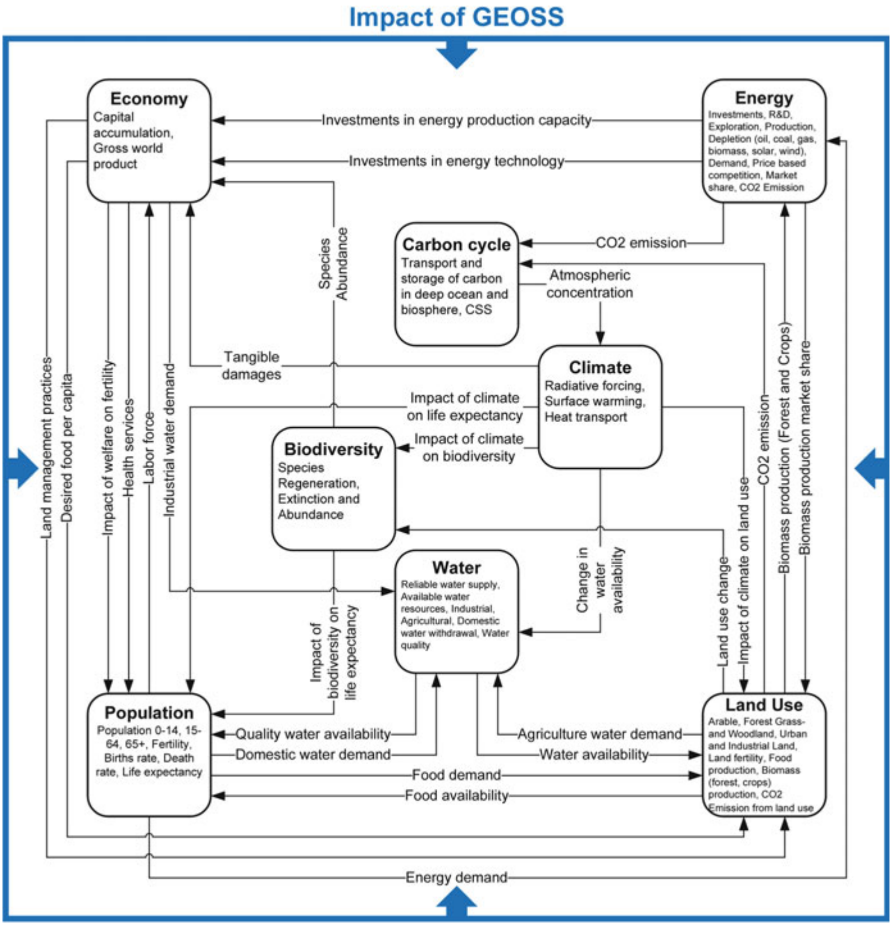

Fig. 4.2 Overview of the FeliX model structure

The FeliX model takes into account the greenhouse effect and, following Nordhaus (1994) and Fiddaman (2002), captures the additional surface warming from the accumulation of CO_2. Positive forcing increases the atmospheric and upper ocean temperatures. Additionally, heat transfer between the atmosphere and the upper ocean and deep ocean is modeled. This disturbance of the climate system, measured by changes in temperature, leads to climate change, accounted for in various sectors of the model. Thus, the consequences of climate change are spread out across the whole model, affecting land quality, population growth, and biodiversity (explicitly accounted for in a biodiversity model module).

Energy demand is driven by population development and the evolution of per capita energy demand. Exploration and production activities, investments in the deployment of energy technologies, R&D activities, and costs of energy carriers are explicitly modeled for each source of primary energy. An economic mechanism of price-based competition between energy sectors determines the market share of primary energy. Technological development is explicitly modeled in the energy and land-use sectors. R&D investments lead to increased growth of either sector- and technology-specific or economy-wide technological change. Technological change is a major driver of economic growth.

The FeliX model contains a "competition for land" module. Various social and economic activities as well as natural processes may change the characteristics of a land type and also cause transformation from one land type to another. A growing population and changing food preferences to more protein-rich diets increase the demand for food production and cause agricultural land expansion into forests and grasslands. The model accounts for more intensive agriculture due to fertilization, irrigation, and genetic improvement. Furthermore, it accounts for new demands for biomass resources for energy purposes and material use, from both forest biomass and biomass from energy crops. The intensification of competition for land between food and energy crops is explicitly modeled. Water resources are explicitly accounted for in a water module. The model allows for additional irrigation according to a water supply function reflecting marginally increasing scarcities of irrigation water.

4.2.3 Benefit Chain Definition Using FeliX

The socioeconomic benefits of GEOSS are quantified using a benefit chain approach (Fritz et al. 2008). Figure 4.3 outlines the five basic steps of benefit assessment using the FeliX model. The first step was building the basic global change model, whose components were described in the above section. The components were adapted to best address the issue of a GEOSS benefit assessment by improvements across SBAs. The basic model structure was designed based on expert consultations identifying the best model structure and feedback along with basic input data. Model components were then validated with designated SBA experts. The FeliX model maps out relations within and among the nine SBAs.

In a second step, the FeliX model was calibrated to historical data using a highly aggregated representation of the Earth system. The calibration was carried out to match multiple observations over the twentieth century. The third step was to use the calibration parameters and conjectured adjustment factors mimicking anticipated technological and societal change to construct a baseline scenario for the twenty-first century. This baseline scenario constitutes the reference for the impact analysis of GEOSS improvements. In a fourth step, the GEOSS scenarios were constructed within and across the SBAs. This step involved working with SBA experts to identify the parameter constellations that would mimic a GEOSS case and choosing the most appropriate parameter values. In the last step, the business-as-usual (BAU) scenario is compared with the GEOSS scenarios. The difference indicates the benefit that GEOSS might have across the SBAs. Multiple indicators are used, including GDP, population, ecosystem value, and the United Nation's Human Development Index.

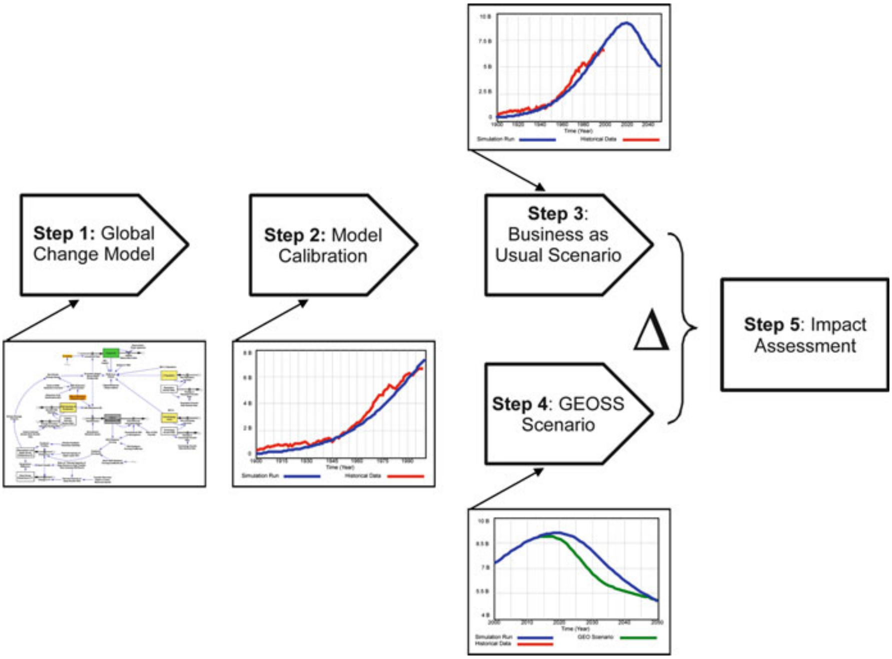

Fig. 4.3 Process of benefit assessment using FeliX

4.2.4 Example: Population Module

World population is modeled as an aging chain (Sterman 2000) and accounts for labor market participation by age and gender. Average reproductive lifetime and total fertility is influenced by the degree of economic development and environmental variables. Mortality is influenced by health services, food availability, pollution availability, and quality of health services.

The core sector structure of the population module is presented in Fig. 4.4. There are three population cohorts—*Population 0 to 14*, *Population 15 to 64,* and *Population 65Plus*. The population *Birth Rate* is determined by average *Reproductive Lifetime* and *Total Fertility*, which in turn is influenced by *World GDP per Capita Ratio*. In the GEOSS scenarios we assume that there is no direct EO impact on reproduction.

Each population cohort differs with regard to mortality. As is illustrated in Fig. 4.5 *Life Expectancy* is determined by the degree of health service provision, adequacy of food supply, and the level of pollution.

It is assumed that wealthy societies can invest more in health services and thus extend life expectancy. Health services can range from access to preventive vaccination programs to life-saving measures in case of incidences of cardiovascular diseases. Adequate food supply is determined by minimum calorie intake and the total amount of food supplied. Beyond basic food supplies, an impact function of

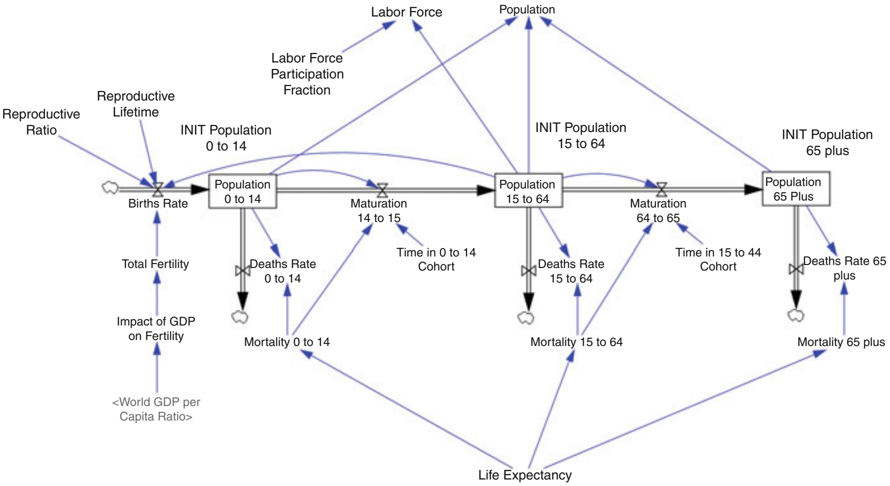

Fig. 4.4 Maturation and deaths of population cohorts

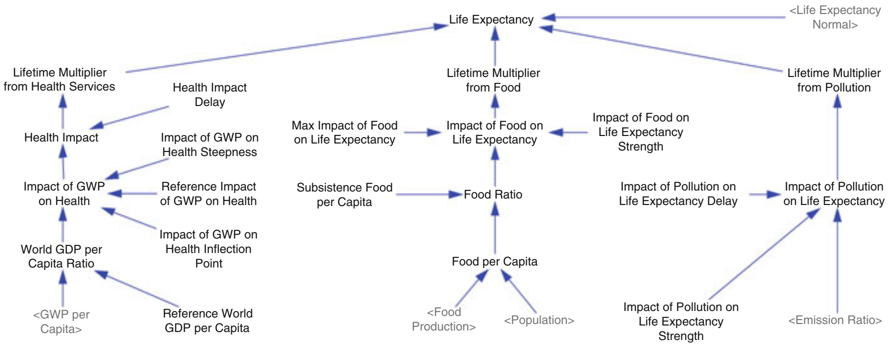

Fig. 4.5 Factors having an impact on population Life Expectancy

life expectancy mimics the degree of healthy diets. Here, indirectly, the level of technology in agriculture and competition for land are the main drivers. Pollution is a combination of air and water pollution. Air pollution is directly calculated from the energy module, where an increasing share of renewable energy is directly linked to less air pollution, and through the reduced GHG emissions, the decrease in climate change–related disaster incidences raises life expectancy. Similarly, more intensive agriculture and subsequent improved nutrition and reduced demand for industrial water consumption and associated reduced pollution levels are associated with longer life expectancy. The effects of pollution can be modeled to be active immediately or through a lag effect accounting for the delayed outbreak of chronic diseases.

4.3 Results

4.3.1 Model Calibration

The FeliX model was calibrated in an iterative process of structure formulation, parameter estimation, analysis of fit and residuals, and model reformulation. This process was conducted in two stages: (1) developing and improving sub-modules; and (2) model integration. The process was repeated until a good fit with the historical data was achieved. Calibration involved not only goodness-of-fit criteria but also the plausibility of the model per se in terms of its ability to explain the observed behavior.

Data for calibration and validation came from various sources, including IEA Key World Energy Statistics,[3] BP Statistical Review of World Energy,[4] Carbon Dioxide Information Analysis Center,[5] and FAOSTAT.[6] The calibration was conducted for a period of one century (1900 to 2000). If 100 years' worth of data was not available, the historical data for the available period were used and extrapolated.

The model went through a set of standard structure and behavior tests to build confidence in system dynamics modeling (see Sterman 1984; Oliva 1995). Figure 4.6 presents results of the calibration effort for a subset of model variables across the FeliX modules, and Table 4.1 presents historical fit summary statistics for each of the chosen variables.

4.3.2 Baseline Scenario

Once the model structure was finalized and the model calibrated to historical data constituting an acceptable representation of the Earth system, the baseline scenario was constructed by extending the model time scale to 2050. Additional policy assumptions were introduced to the model for alignment with the United Nations' Millennium Development Goals. These policies, which include investments in alternative sources of energy, improved cropping systems, and better health care, align the baseline with the spirit of the Second Earth Summit in Johannesburg, where the GEO idea was born. Thus, our baseline is more a sustainability scenario than a BAU forecast of highest likelihood. The idea is to establish a reference for GEO impact analysis. The baseline scenario was purposefully designed to assess the question of what would happen to aggregate output indicators (e.g., GHG intensity of energy production, population, ecosystem health) if particular

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[3] http://www.iea.org/stats/index.asp

[4] http://www.bp.com/productlanding.do?categoryId=6929&contentId=7044622

[5] http://cdiac.ornl.gov/

[6] http://faostat.fao.org/

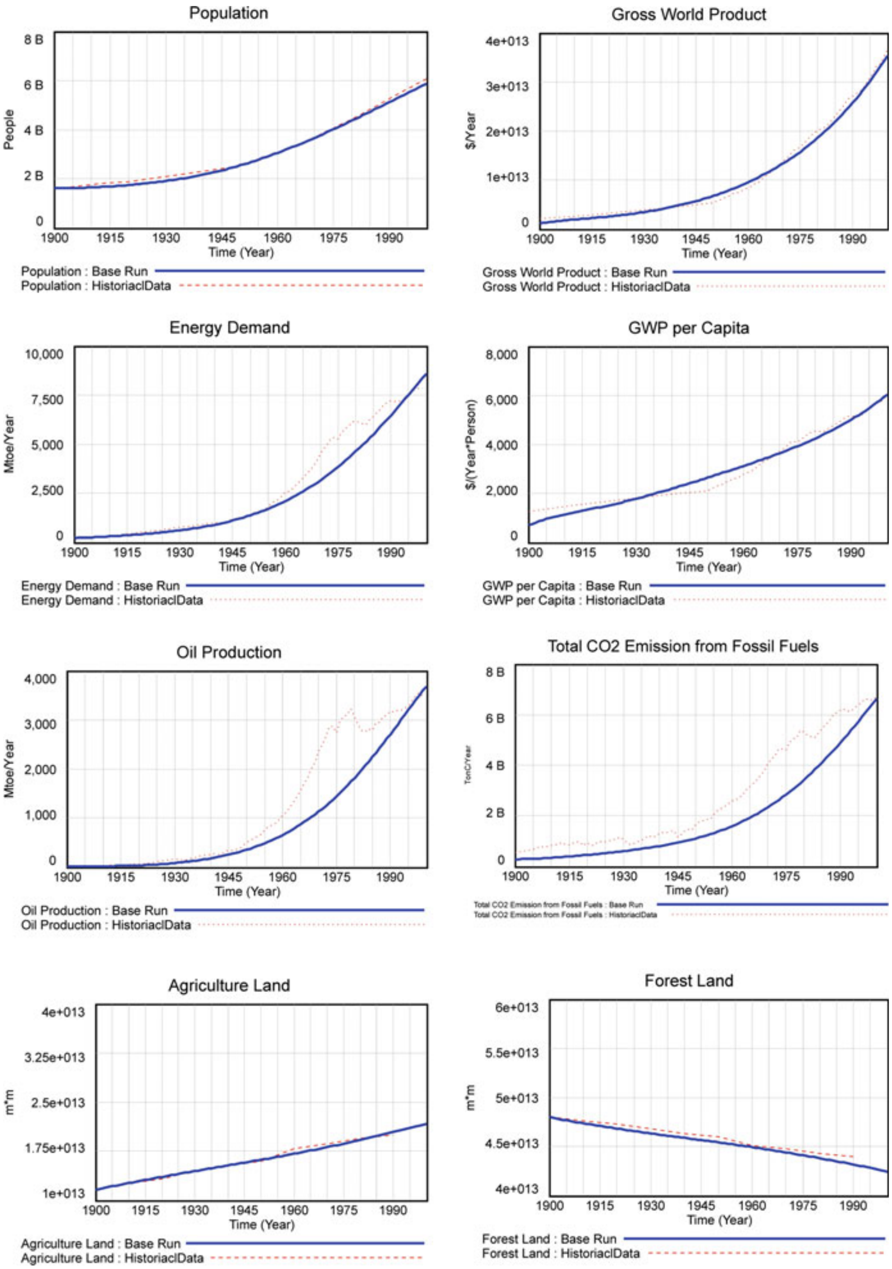

Fig. 4.6 Overview of FeliX model calibration outcome. Note: *Dashed lines* are historical data; *solid lines* are the outcomes of the calibration experiment

Table 4.1 Historical fit summary statistics (Theil inequality statistics)

	R^2	MAPE	MSE	RMSE	U^M	U^S	U^C
Population	1.000	0.01	7.84E + 15	8.86E + 07	0.41	0.56	0.03
Gross world product (GWP)	0.993	0.08	1.14E + 24	1.07E + 12	0.06	0.51	0.43
GWP per capita	0.965	0.07	6.72E + 04	2.59E + 02	0.04	0.42	0.55
Energy demand	0.964	0.14	4.27E + 05	6.53E + 02	0.34	0.14	0.52
Oil production	0.895	0.39	3.23E + 05	5.68E + 02	0.37	0.18	0.45
CO_2 emissions from fossil fuels	0.950	0.35	7.98E + 17	8.93E + 08	0.68	0.09	0.23
Agricultural land	0.986	0.02	1.25E + 23	3.53E + 11	0.02	0.08	0.90
Forestland	0.984	0.01	2.15E + 23	4.64E + 11	0.77	0.08	0.15

R^2 coefficient of determination, *MAPE* mean absolute percent error, *MSE* mean square error, *RMSE* root mean square error, U^M bias component of MSE, U^S variation component of MSE, U^C covariation component of MSE

economic, social, and environmental policies were in place but GEOSS-related improved data and data policies were not available. Figure 4.7 presents the baseline runs used for the GEOSS impact assessment.

4.3.3 GEOSS Scenarios

To assess the socioeconomic and environmental impacts of GEOSS improvement, we constructed six storylines in the energy, disaster, health, climate, agriculture, and water societal benefit areas (the other three SBAs, weather, ecosystem, and biodiversity, are considered under the six scenarios). Various storylines were expressed as incremental or more abrupt changes and new relations in the FeliX model. The range of parameter changes was either informed by particular studies or conjectured by the experts. For illustration, a few conjectured storylines that affect health outcomes are listed in Table 4.2.

Each of the six GEOSS scenarios can be considered an integrated scenario in the sense that the changes it brings to the model affect not one particular domain of interest but propagate through the whole model. For instance, changes in GHG emissions from the energy sector affect agricultural productivity. Sector-specific scenario analysis was conducted in such a way that impact assessments were performed with a sectorial view or together with the other SBA scenarios. Likewise, the effect of improved Earth observations can be analyzed from a sectorial angle or a full systems view.

Instead of considering each predefined GEOSS scenario separately, we focus here on the combined scenarios: all six GEOSS scenarios are enabled for the model simulation runs and subsequently the impact assessment. The following section presents some results of the combined scenario exercise, bringing together GEO effects on population indicators.

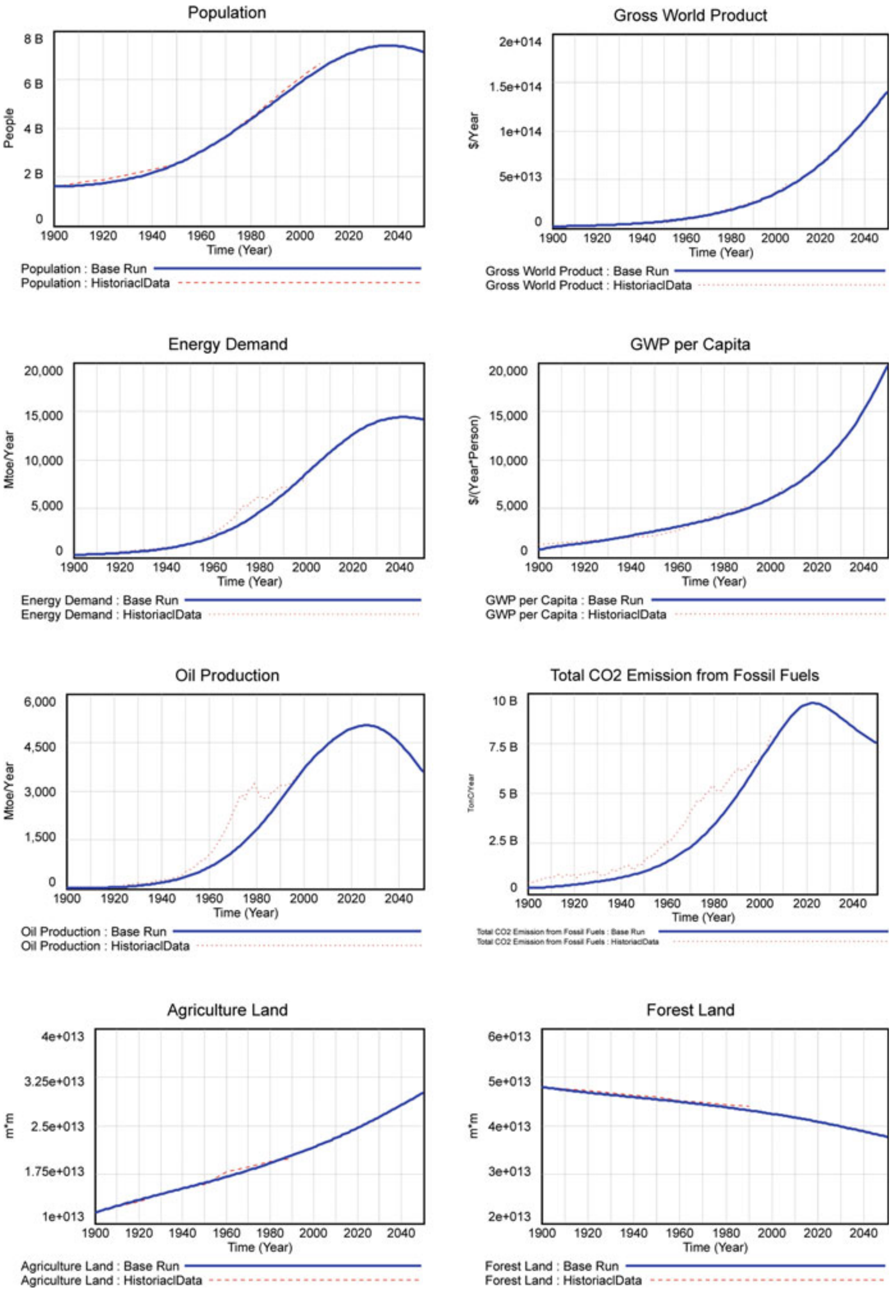

Fig. 4.7 Overview of the baseline scenario (*Dashed lines* are historical data; *solid lines* are the outcomes of the baseline scenario experiment)

Table 4.2 Example storylines influencing life expectancy

Storyline	Variable name	Base run value	Scenario value	SBA
GEOSS triggers improved prevention of cardiovascular diseases, malaria, diarrheal diseases, meningitis, and others	Life expectancy normal H	0	Ramp up to 0.14 by 2030	Health
Use of GEOSS data improves planning and commissioning of solar energy installations. Rural development is enhanced	Solar available area	5.00e + 11	Ramp up to 6e + 011 by 2020	Energy
Use of GEOSS data improves natural disaster alerts and response	Life expectancy normal D	0	Ramp up to 0.05 by 2030	Disaster
Correlation of emissions of air pollutants and GHGs reduces pollution, incidence of chronic diseases, and in long run, climate change–related hazards	Impact of CO_2 concentration on life expectancy strength	0.01	Ramp up to 0.007 by 2030	Climate
GEOSS weather forecasting enables improved crop management for consistently higher yields and global coordination of food production	Effect of GDP on agriculture management practices increment	0	Ramp up to 0.3 by 2030	Agriculture
Better water management planning and water stress monitoring reduce water pollution and increase irrigation efficiency	MAX agricultural water use	0.1	Ramp up to 0.06 by 2030	Water

4.3.4 *Benefit Assessment of GEOSS*

The approach used to measure the value of creating and improving GEOSS can be defined as deviations of the GEOSS scenarios from the baseline scenario. Since FeliX is a dynamic model, it is possible to capture the deviation of the GEOSS scenarios from the baseline scenario as it develops over time or as an accumulated value at the end of a specified period. The starting point for the GEOSS impact assessment presented here is the year 2010. An open architecture of the FeliX model (as opposed to so-called black box models) and detailed documentation of the reasoning and actual changes in model parameters let us analyze and track any differences between the GEOSS and baseline scenarios (see Rydzak et al. 2009). Model transparency is necessary when dealing with aggregated but highly interrelated complex systems.

For the purpose of illustration, only six of the storylines used for the GEOSS assessment in the GEOBENE project were chosen (see Table 4.2), all of which affect life expectancy. However, as will be illustrated, their impact spread across various SBAs.

Health, disaster, and climate storylines have a direct and, as modeled by a RAMP function, positive effect on life expectancy when compared with the baseline (dashed line in Fig. 4.8). Life expectancy starts to increase in year 2010 and causes an increase in population. To year 2050, the accumulated increase of total population in the GEOSS scenario is equal to 1.2 billion. The greatest increase (70%) is in the proportion of the population over 65 years.

Population growth has a significant effect on the global use of resources (Fig. 4.8), increasing demand for food, energy, and water. However, the GEOSS simulation scenario indicates less extensive land use compared with the baseline. Over the period of the GEOSS scenario, about 10 million km^2 of land is saved from conversion to agricultural use; of this land, 5.7 million km^2, or 57%, is forested and thus is saved from being deforested.

When tracking the reason for such outcomes in the FeliX model structure, we noticed the effect of the other storylines in the combined GEOSS scenario (Fig. 4.8). As indicated in the agriculture storyline (see Table 4.2), GEOSS enables improved crop management and thus higher yields per hectare. The yield was also increased by GEOSS-related improvements in agricultural water use management, as indicated in the water storyline (see Table 4.2): over the considered period, a total of 5,400 billion m^3 of water was saved, compared with the baseline scenario. Cumulative food production is estimated to equal ten billion vegetable-equivalent kilograms. This explains why agricultural land did not expand commensurately with the increase in population.

As a side effect of those dynamics, CO_2 emissions are lower than in the baseline scenario (Fig. 4.8). Over the considered period an accumulated difference in CO_2 emissions from land use accounts for 7.3 billion tons of carbon. However, there is also a noticeable increase in energy production. The decrease in CO_2 emissions comes not only because GEOSS enabled a more developed solar energy sector (as indicated in the energy storyline in Table 4.2) but also because of the avoided deforestation—the forest biomass that was spared from conversion to agricultural use. Both sources of energy are cleaner than fossil fuels, and that drives the decrease of CO_2 emissions even further. This climate mitigation is associated with increasing life expectancy (see the climate storyline in Table 4.2). Tracking these chains of influences, one notices important feedback loops responsible for the dynamics of the whole system. These feedback loops are able to reinforce or balance the effect of GEOSS across the SBAs.

The value of GEOSS might be assessed based on the outcomes in a particular SBA embedded into the FeliX model structure but also can be measured using such indicators as the Human Development Index and total change in ecosystem value (Fig. 4.8). For the given GEOSS scenario there is a noticeably faster human development combined with slower loss of the ecosystem value.

The outcomes of the simulation scenario described above constitute only a small portion of the GEOSS impact assessment results across all the SBAs. Although the FeliX model has an open architecture, its structure—mimicking the society-technology-environment interrelations of the Earth system—is complex, and understanding the model dynamics requires considerable time. Although this level of

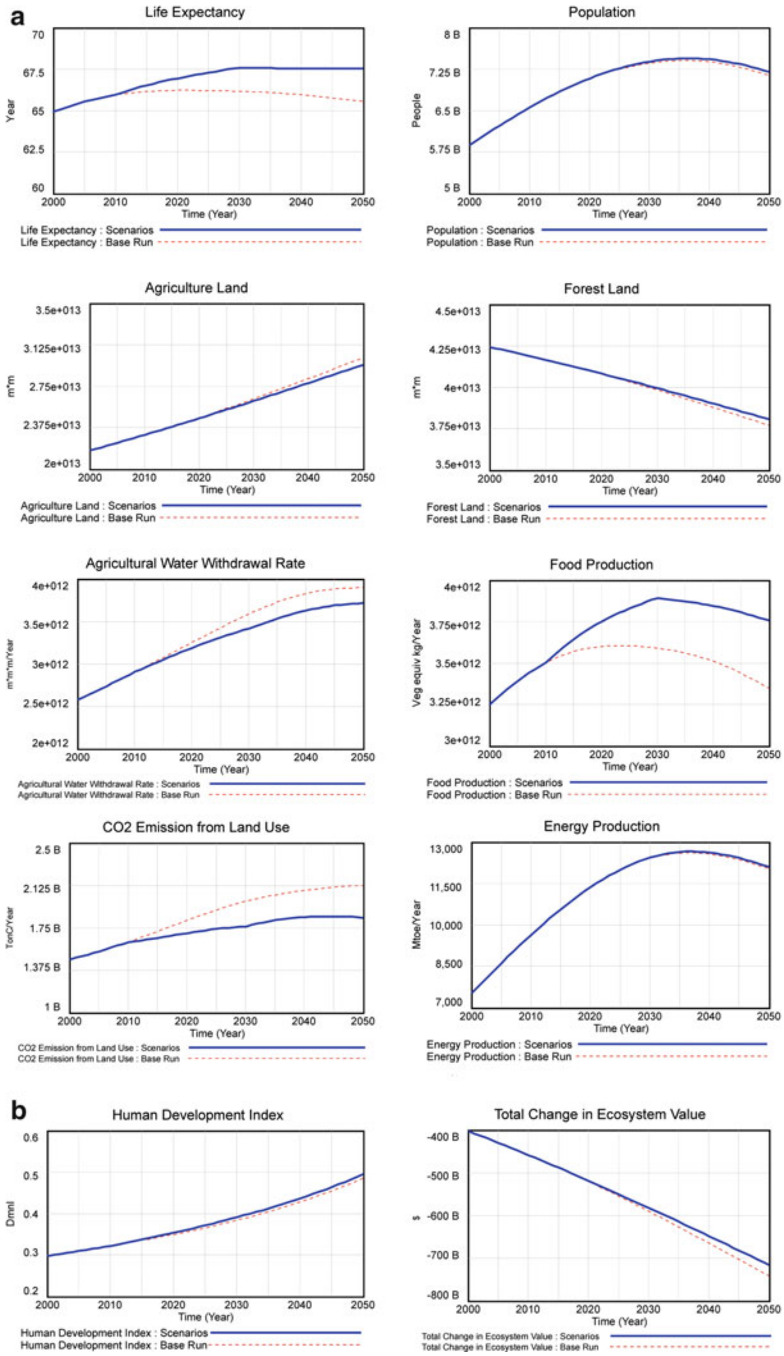

Fig. 4.8 FeliX comparison of base run and GEOSS scenarios

Run scenario(s):
1. Press **Start** button (the model starts in 1900 and runs through 110 years of history).
2. At year 2010 check which scenario (or scenarios) you would like to run.
3. Press **Next** button and observe the changes on the graphs.

☑ Scenario Energy
☐ Scenario Disaster
☐ Scenario Health
☑ Scenario Climate
☐ Scenario Agriculture
☐ Scenario Water

Fig. 4.9 FeliX simulator interface while running GEOSS scenarios

complexity is necessary, the model itself is too complicated to be directly presented to higher-level decisionmakers. For that reason the FeliX model-based simulator was constructed. As illustrated in Fig. 4.9, it is equipped with a user-friendly interface that allows for easy use and navigation through the simulations.

Users can run illustrative GEOSS-related scenarios and observe the potential consequences across all model sectors along several indicators. The simulator is an appropriate tool that enables decision makers to view the outcomes of various GEOSS scenario assumptions, extend their knowledge, and explore relationships in the system. The simulator is freely available from the GEOBENE project website.[7]

4.4 Conclusion

In these times of strained public budgets, any decision on how to develop a global Earth observation system of systems (GEOSS) requires international coordination of efficient and effective investments and operations. The FeliX model presented in this chapter was developed to assess the benefits from use of global Earth

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[7] http://www.geo-bene.eu/

observations. FeliX's open architecture was designed to support strategic decision processes to develop GEOSS and identify areas where GEOSS initiatives might have significant economic, social, and environmental benefits.

In this chapter we have developed a methodology and analytical tool and applied it to assess the societal benefits of improving GEOSS across various benefit areas, following a benefit chain concept. The basic idea is that the costs incurred by an incremental improvement in the observing system—including data collection, interpretation, and information sharing—will deliver benefits through information cost reduction or better-informed decisions. The resulting incremental societal benefit can be judged against the incremental cost of production. Since in many cases there are large uncertainties in the estimation of costs and particularly the benefits, we expressed benefits not only in monetary terms but also by social and environmental indicators. Therefore, in most cases impacts where benefits are orders-of-magnitude larger than their production costs can be regarded as robust guidance signals to support decision making in GEOSS processes.

In particular, we have assessed two categories of benefit generation from GEOSS. The first is benefits from economies of scale of a global observation system versus the current patchwork of national or regional observation systems. We call these aggregation benefits. The second category relates to economies of scope, which emerge when changes in the observation system affect multiple benefit sectors or dimensions. These integration benefits are often considered a "public good." Quantifying them proved a significant challenge.

Because of the public good nature of the benefits, GEOSS effects are highly dependent on the type of baseline policy scenario. Apart from the choice of baseline definition, there are several other limitations to the FeliX model. Some subjects may be modeled in great detail, while others that might contribute more to the benefit are covered in less detail. This uneven coverage arises where data are very sparse or where lower anticipated benefit levels attracted less investment in data development. Like any other model, the FeliX model is a purposeful simplification of reality. There are also some questions regarding the existence or strength of a particular relation defined in the FeliX model. For instance, the functional shape and parameterization of the climate change impact function is a highly contested area of research. In addition, in many areas impact functions were not available, and we had to base our assessment on knowledge from subject matter experts. To deal with the uncertainty in the FeliX model, sensitivity analysis can be conducted, which is a subject for future work with the model.

As defined by Craglia et al. (2008), the systems approach and tools similar to the FeliX model might become part of a laboratory for learning via multidisciplinary education and science. The first step in that direction has already been made with the construction of the FeliX simulator, available for free at http://www.geo-bene.eu.

Earth observation has great potential for helping to ensure a sustainable future for the planet. According to our analysis, its value is apparent, to varying degrees, across all social, economic, and environmental indicators of the Earth system. Better climate change mitigation, increased food security, sustainable water use, available land resources, and clean energy technologies are among the many examples where improved observations of the Earth system might be beneficial from a global societal perspective.

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4. Commentary: The Value of a Comprehensive Model

Molly K. Macauley

4.C.1 Introduction

In their contribution to this volume, Steffen Fritz, Ian McCallum, Michael Obersteiner, and Felicjan Rydzak use a systems engineering model of the global economy to illustrate how value could be ascribed to information obtained from Earth-observing satellites. Rydzak and coauthors constructed the model in previous research (Rydzak et al. 2010) to characterize the Earth processes and human interactions that are the focus of the Group on Earth Observations (GEO). GEO is a voluntary collaboration of 80 governments, the European Commission, and regional and other organizations. GEO seeks to coordinate the Earth-observing satellites of different countries across nine themes, called societal benefit areas: public health, climate, energy, water, agriculture, ecosystems, weather, disaster management, and biodiversity.

Rydzak and his colleagues modeled the subcomponents of their engineering model on these themes. For example, subcomponents include representation of the global carbon cycle, energy resources, and land use. With this model, Fritz and coauthors show how the model could be used to ascribe value to Earth observations. For instance, if GEO Earth observations data improve disease prevention or air quality, then the Rydzak model would show an increase in life expectancy. The value of Earth observations data in this engineering framework is expressed in changes in the physical outputs of the model (such as years of life expectancy). The examples in their chapter are hypothetical, not based on actual applications of Earth observation data.

4.C.2 Choice of the Model

An advantage of using a systems engineering model as a method to ascribe value to Earth observations information is that engineering is the language of the engineers and, although perhaps to a lesser extent, the scientists who design the satellites and their observing instruments. More challenging is the attempt to model the global economy. Discussing the Rydzak model in detail is outside the scope of

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this commentary, but as with all models of the global economy, specifying all the interrelationships and interactions of industrial sectors, natural resources, and people is difficult. The authors' example of life expectancy is a good example of the difficulty. Many factors, including existing health of the population, access to clean water and sanitation, and nutrition and diet, influence life expectancy. The "black box" in global models in which these factors combine with agricultural productivity, international trade in agriculture, peoples' behavior, technological innovation, and government policy—all of which affect life expectancy—is difficult to formulate.

Fritz and his coauthors want to use a global model because one of their objectives is to replicate the interrelationships among the GEO societal benefit areas. They argue that the value in GEO in coordinating Earth-observing systems of different countries is the complementarity of different kinds of data. To continue with their life expectancy outcome as an example, the complementarity is in data about air quality and water, which combine to influence agriculture and, in turn, life expectancy.

Such an approach is ambitious as a basis for identifying a role of Earth observations. The traceability of attribution of the role of Earth-observing information on each of these influences is difficult at best. Moreover, there are other black boxes in which actions are assumed rather than empirically accounted for: the approach doesn't permit disentangling Earth observations data from other data sources, and it assumes that the Earth observations data are in fact used by people taking action within the various subcomponents of the model.

Alternative modeling approaches are available to characterize the relationships among economic sectors, natural resources, and people. Examples of some of these alternatives include general equilibrium models and integrated assessment models.[8] These models combine physical and economic relationships of producers, consumers, and the government sector. Unlike systems engineering models and similar input-output models, these alternatives tend to emphasize the role of relative prices and the capacity of consumers and producers to make substitutions in their decisions in response to changes in prices. Depending on their purpose, the models often include international trade, assumptions about technological change, estimates of stocks and flows of natural resources, and demographic data. The models often draw some of their inputs from purely physical models. One example is integrated assessment models that use, as inputs, the outputs of global circulation models, such as centimeters of sea level rise or parts per million of atmospheric concentrations of greenhouse gases.

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[8] An example of a computable general equilibrium model is the Global Trade Analysis Program (GTAP). GTAP is optimized to characterize global trade. Examples of integrated assessment climate models include the Integrated Global Systems Model (IGSM) of the Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change, the Model for Evaluating the Regional and Global Effects (MERGE) of greenhouse gas reduction policies developed jointly at Stanford University and the Electric Power Research Institute, and the MiniCAM Model of the Joint Global Change Research Institute, a partnership between the Pacific Northwest National Laboratory and the University of Maryland.

There are many shortcomings in these alternative models, including the constraints imposed by functional forms used to characterize production and consumption decisions. The characterization of technical change and uncertainty is also problematic. An advantage of the models, however, is that they usually explicitly allow for interactions such as substitution among inputs, the effects of government policy, and as noted, changes in relative prices. Another advantage is that their outputs are usually expressed in economically relevant measures, such as changes in productivity or overall social welfare.

But even these models are subject to the same challenges as the engineering model. In all many global-scale representations, identifying the role and value of information can be a search for a needle in a haystack. In addition, changes in the quality of natural resources (air quality, water availability) or the effects of these changes (on production relationships of industry, on health and quality of life of consumers) is not typically explicit—there are no prices for these resources. This lack of explicit characterization of the role of resources further confounds the ability to identify the value of Earth observations about them.[9]

4.C.3 Other Approaches?

For the representations of the GEO societal benefit areas, a smaller-scale approach might be more tractable. Using one of the existing integrated assessment models for climate is an example. Different runs of the models under different assumptions about information would allow for a set of scenarios: “what if the Earth-observing data allow enhanced use of renewable energy” or “suppose the data show trends in allocation of land away from forests to agricultural production.” Even in these models, however, the tractability of the effect of “information” as a model input is difficult, and the effect of Earth observations data, in particular as a subset of information, is also hard to identify.

Perhaps the most important contribution of Fritz and his coauthors in their assessment of benefits from GEO is to point out the desirability of accounting for the complementarity of different types of Earth observations data. The coordination of different Earth-observing systems, owned and operated by different countries, is the overall goal of GEO. The group describes this goal as GEOSS, the global Earth observation system of systems. Fritz and his coauthors seek a comprehensive model in which, for instance, the air quality observations of one country’s satellite system together with the precipitation data of another country’s system can be valued for their joint information content. I commend this effort.

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[9] Darmstadter (2008), Banzhaf (2004), and Boyd (2008) are among the many scholars describing the desirability of including measures of natural resources, or ecological wealth, in national income accounts. This step would make it easier to identify the contribution of Earth observations information to management of natural resources.

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