International Journal of Spatial Data Infrastructures Research, 2010, Vol.5, 216-243

Impact of Global Earth Observation – Systemic View across GEOSS Societal Benefit Areas[1]*

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Abstract

The work of the Group on Earth Observation (GEO) is perceived as instrumental to attain sustainable development goals and to be a major driver of how the society–technology–environment system is managed. However, appropriate scientific methodologies to assess the benefits of the Global Earth Observation System of Systems (GEOSS) and validate investments in Earth observation infrastructure have been missing. This paper presents a systems approach to measure and analyze the impact of Global Earth Observation across the nine Societal Benefit Areas defined by GEO. The methodological framework presented here was developed and applied to be complete across space, time and sectors through integration and aggregation. Apart from the general assessment framework, we present some specifics of the numerical tool, which is based on System Dynamics modeling and simulation technique. Our results indicate that though the total system benefits are strongly policy dependent, improvements of GEOSS per se and data availability and interoperability, the accrued benefits are large and have a great potential shaping mankind's course to sustainability.

Keywords: Earth observation, benefits assessment, modeling, simulation, system dynamics

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[1] Support provided by EC FP6 Project GEO-BENE No. 037063, EC FP7 Project EuroGEOSS No. 226487 and EC FP7 Project EnerGEO No. 226364

DOI: 10.2902/1725-0463.2010.05.art9

1. INTRODUCTION

The Earth System in the Anthropocene (Crutzen and Stoermer, 2000), as defined by its interdependencies between social, economic and environmental sub-systems constitutes a complex dynamic system. An appropriate management of such a complex system can come only from improved 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 international effort to build a Global Earth Observation System of Systems (GEOSS), coordinated by the Group on Earth Observations (GEO)[2] aims at connecting the diverse sets of monitoring systems to finally support decision making of policymakers, resource managers, scientists all the way to common citizens.

Despite the obvious advantages the geo-spatial information can bring to decision making, there is still a lack of 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 forecast (Adams et.al, 1995, Katz and Murphy, 1997) while there has been relatively little assessment work carried out on in other fields of Earth Observation. Furthermore, the available studies are mostly sectorial and focus on one particular Societal Benefits Area (SBA), for instance biodiversity (Leyequien, 2007, Muchoney, 2008).

Case studies on the value of improvements in Earth observation systems are usually very focused. 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 impact on water quality management in the North Sea of improved in-situ observation networks or remote sensing based observing systems. Wieand (2008) quantified the impact of an Integrated Ocean Observation System on recreational fishing. All these studies conduct a thorough, in-depth analysis of particular issues. However, a methodological framework and an integrated assessment of the total global impact within and across all societal benefits areas has not been carried out yet.

The need for such evaluation led to the European Commission sponsored project “Global Earth Observation – Benefit Estimation: Now, Next and Emerging”

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[2] http://earthobservations.org

(GEOBENE)[3] – world's first systematic study of the benefits of Global Earth Observation (European Commission, 2008). GEOBENE's project goal was to develop methodologies and analytical tools to assess the economic, social and environmental effects of improved quantitative and qualitative information delivered by the GEOSS, in and across nine Societal Benefit Areas – Disasters, Health, Energy, Climate, Water, Weather, Ecosystems, Agriculture and Biodiversity. This paper starts with the presentation of the Systems Dynamics model that was built to evaluate the impact of Global Earth Observation across all Societal Benefit Areas of GEO.

The following section describes the methodology used for the systems analysis. Section 3 discusses a selected set of results assessing the impact of GEOSS improvements. It also discusses the use of a freely available simulator to run scenarios illustrating the impact of GEOSS. The final section makes some closing methodological remarks.

2. SYSTEMS APROACH TO ANALYZE THE IMPACT OF GLOBAL EARTH OBSERVATION

The portfolio of assessment approaches used and assessed in the GEOBENE project covered a wide number of quantitative and qualitative methods and types of earth observation[4]. Many of the approaches concentrated on the quantification of the Value of Information (VoI) confined to a particular geography, timeframe and sector. The variety of findings and understanding gained through the use of these approaches require, however, ***integration*** in order to cross boundaries and illustrate propagation of GEO benefits across all nine SBAs, and also ***aggregation***, in order to capture implications on global issues such as Climate Change. For this reasons the **FeliX** (**F**ull of **E**conomic-**E**nvironment **L**inkages and **I**ntegration d**X**/dt) model was developed.

The FeliX model is a System Dynamics type model, which is an approach originally developed by Jay Forrester at MIT in the 1950s (Forrester, 1958, Forrester, 1961). Unlike reductionism, breaking the problem into smaller and smaller pieces in order to understand the nature of complex phenomena, System Dynamics is trying to look at the full system.

The *system* is defined here as a collection of elements that interact with each other to form a unified whole and *dynamics* refers to changes over time following these interactions. Thus, the preliminary notion of System Dynamics is that structure determines performance. System Dynamics views the structure of a

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[3] http://www.geo-bene.eu
[4] See GEOBENE website (http://www.geo-bene.eu) for review of various techniques and tools used for GEO impact evaluation

system as the primary cause of the problem behaviors it is experiencing, as opposed to seeing these behaviors as being “foist upon” the system by outside agents (Richardson and Pugh, 1981). For that reason, the System Dynamics models attempt to capture as many as necessary aspects of interactions within a closed system.

The variables are therefore “endogenous” or contained within the system represented by a System Dynamics model. In order to describe the system structure System Dynamics focuses on the flow of feedback that occurs throughout the parts of a system (feedback loops) – a change in one variable affects other variables over time, which in turn affects the original variable, and so on. The dynamic behaviour then occurs when flows accumulate in stocks (e.g. such as 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 (Sterman, 2000).

The FeliX model, following the System Dynamics approach guidelines, 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 results also in changes in other areas – for instance depletion of natural resources being a source of energy may impact population growth but also put a pressure on agriculture sector in order to produce more energy crops as a substitute of such natural resources as oil or gas.

Being a dynamic model FeliX captures important stock changes (e.g. depletion of natural resources, accrual of carbon dioxide in the atmosphere) or impacts of certain policies (e.g. afforestation, emission reduction) over time. Figure 1 illustrates the correspondence of the FeliX model structure vis-à-vis the nine SBAs of GEO and its use for benefit assessment.

Figure 2 outlines the methodological steps to estimate the VoI using the benefit chain approach (Fritz et al, 2008). The first step is about constructing the model. The FeliX model was formulated to best address the issue of benefit assessment of improvements of GEOSS measured across SBAs. For that reason, the Felix model maps out relations within and between nine SBAs.

The particular SBAs determined mostly the areas for literature review and expert consultation on data, models, reports and analysis to be used for the purpose of FeliX model construction. In this process, Earth system components and their interdependencies were defined and represented using a Systems Dynamics approach. It constituted the first step of the adopted GEO impact analysis methodology, as illustrated in Figure 2.

In the second step (Figure 2), the FeliX model was calibrated to historical data using a highly aggregated representation of the Earth system. The calibration was carried out to match observations from the last century as longer time series are not available. Using the calibration parameters and conjectured adjustment factors mimicking anticipated technological and societal change a baseline scenario was constructed for the 21st century.

The baseline scenario constitutes the reference for the impact analysis of GEOSS improvements. The construction of the baseline scenario is indicated as Step 3 (Figure 2). In step 4, mainly working with the subject matter experts, the GEOSS scenarios were constructed within and across the SBAs. In the last step, the baseline scenario was compared to GEOSS scenarios. The difference indicates the impact improvements in GEOSS might have across the SBAs. Each step of the methodology will be presented in more details in the following part of the paper.

Figure 1: Integrating and Aggregating Role of FeliX System Dynamics Model in GEOBENE project

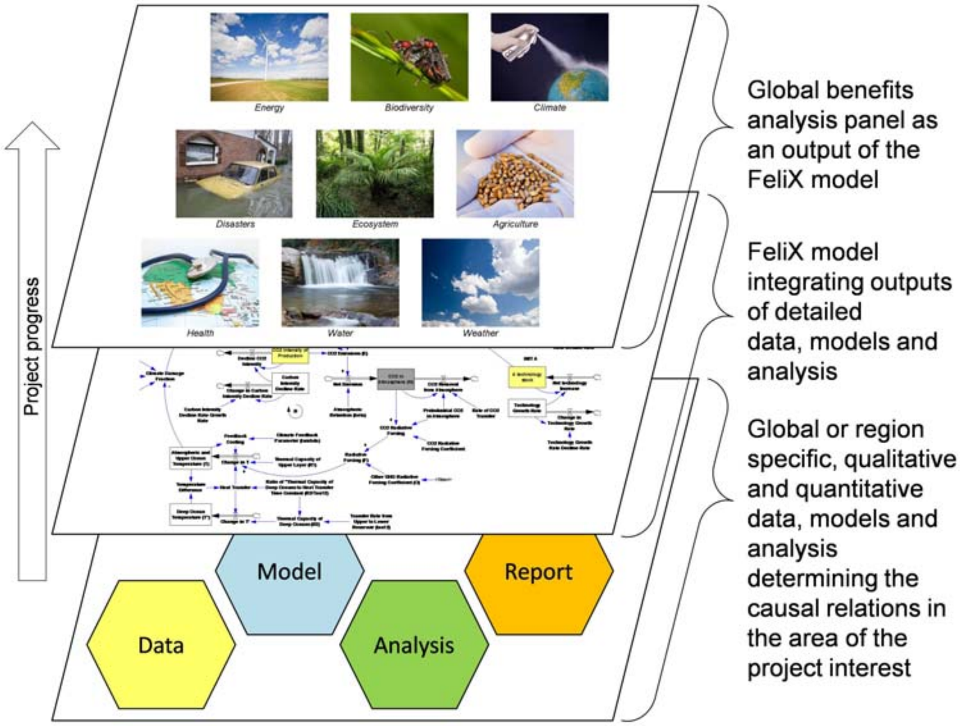
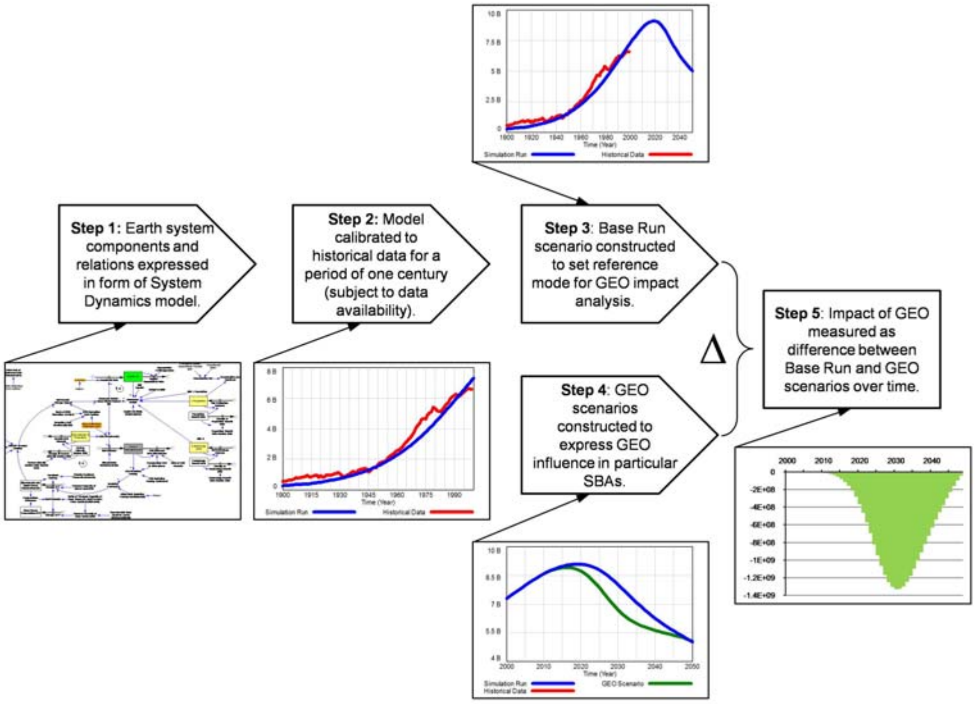


Figure 2: Methodology Steps of the GEO Impact Analysis



2.1. The FeliX Model Structure

The SBAs 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 the Climate SBA include atmospheric concentration of CO_2 caused by human activities and 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 Kettner, 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.

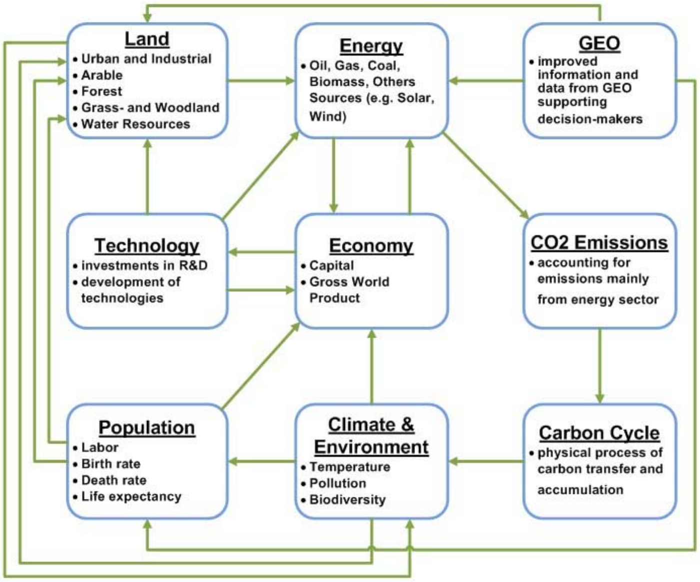
In case such relations have not been quantitatively determined in the literature, which often occurred in cases where relations between SBAs had to be clarified, Group Model Building sessions (Richardson and Andersen, 1995; Vennix, 1996; Andersen et al, 1997) were conducted during which the subject matter 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 and obtaining quantitative results.

Navigation across the model was optimized by defining nine separate subsystems or modules – Economy, CO_2 Emission, Carbon Cycle, Climate and Environment, Population, Energy, Land, Technology, and a GEOSS sector. The SBAs are inherently embedded into the FeliX model structure. Some of them are part of a specific module, e.g. Population sector covers health issues. Other SBAs are addressed across various modules, for instance disasters are investigated in Land, Population and Energy modules of the FeliX model.

It is worth mentioning that if an SBA is explicitly embedded into one specific model module it does not mean that the impact of GEO in that area is constrained only to this particular module. All modules are interrelated and the outcomes of GEOSS can spread across the whole system as it is happening in the real world.

The high-level view of the modules constituting the FeliX model is presented in Figure 3. For better understanding of relations, processes and policies captured in the FeliX model, each module is shortly described.

Figure 3: Overview of the FeliX model structure



Economy Module

The economy module is based on neo-classical growth theory. Capital is an accumulation of investments whereby in FeliX investments in the Energy sector are separately accounted. Growth of Gross World Product is driven by increases in the labor force, which is modeled explicitly in the population module, capital accumulation and technological change.

The economy module contains a representation of the climate system and takes into account impacts associated with global average temperature change according to the DICE model by Nordhaus (1992, 1994). In addition to the climate mitigation measures i.e. reduction of greenhouse gas (GHG) emissions contained in the DICE model the FeliX model accounts for climate adaptation activities following rising intensity of storms, forest fires, droughts, flooding and heat waves and also prevention/adaptation activities to new climate conditions. However, as the range of the impact from the greenhouse warming is uncertain the assumed model parameters will need to be revised with the advances of research in that area. The DICE model is known to potentially underestimate climate impacts (e.g. Stern, 2007).

Carbon Emission and Carbon Cycle Module

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 with regards to carbon intensity of production. The model accounts for CO_2 emission from oil, gas, coal, biomass, solar and wind power energy technologies in terms of end-to-end lifecycle impacts.

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 mixed layer and the deep ocean.

Climate and Environment Module

Increasing the atmospheric concentration of CO_2, or any other greenhouse gas, is forcing the global climate to warm. With more molecules of CO_2 in the atmosphere, a higher proportion of the outgoing long-wave radiation is absorbed, reducing the net emission to space. The FeliX model takes into account this effect and following Nordhaus (1994) and Fiddaman (2002) captures the additional surface warming from accumulation of CO_2. Positive forcing increases the atmospheric and upper ocean temperature.

Additionally, heat transfer between atmospheric and upper ocean and deep ocean is modeled. This disturbance of the climate system measured by changes in temperature lead to climate impacts, accounted for in various sectors of the model. Thus, the impact of the climate change is spread out across the whole model structure, affecting inter alia land quality parameters and population growth.

Population Module

World population is modeled as an aging chain (Sterman, 2000) and accounts for potential labor and non-labor population. There are three population cohorts – Population 0 to 14, Population 15 to 64 and Population 65+. The population birth rate is determined by average reproductive lifetime and total fertility, which in turn is influenced by the degree of economic development measured in GDP per Capita terms modeled in economy module.

Each population cohort differs with regards to mortality. The greatest impact on mortality has a life expectancy determined by health services, food availability and pollution. A wealthy society can invest more in health services and thus extend life expectancy. Furthermore, there we define a minimum food intake condition in order to mimic successful food security policies. Pollution has a negative impact on life expectancy.

Energy Module

The FeliX model structure encompasses various sources of energy – oil, gas, coal, solar, wind and biomass. The 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 market share for each production technology.

The mechanism of price-based competition is an abstraction from the complex and higher frequency patterns of the energy market. As the model is a purposeful simplification of reality, the FeliX model introduces weights for each source of energy. As the model calibration period is one century the parameters weights allow for obtaining reasonable simulation results close to the historical data.

The total energy demand and specific energy market share determines the desired production in each specific energy sector. As energy production from oil, coal and gas is constrained by the available non-renewable resources over time, renewable energy generation takes over, which has a great impact on the emissions of GHGs and air pollutants.

The model does not account for some already operational sources of energy, for instance nuclear or geothermal. Also it does not consider the technical and economic issues of power storage or distribution. These are the areas for potential future model developments.

Technology Module

Technological development is explicitly modeled in the energy and land use sectors. R&D investments lead to increased growth of either sector/technology specific or economy wide technological change. Technological change is a major driver of economic growth.

Land Module

In the FeliX model, global land was divided into four categories – agriculture land, forest land, urban and industrial land, and other land (i.e. grassland and woodland). Various social and economic activities as well as natural processes may impact and change the characteristics of a land type and also cause transformation from one land type to another.

Expansion of agriculture has for years been transforming forest land into agriculture land. Deserted farms may become woodland or grassland again. Time-dependency of parameters which are associated with each land transformation flow determine the degree of inertia. Furthermore, there are also certain constrains on land transformation. These take into account national parks, protected areas and also terrain that cannot be transformed.

Growing urbanization creates pressure to transform agriculture or forest land into urban or industrial areas. Similarly, a growing population and changing food preferences to more protein rich diets require sufficient amount of food production, increases the pressure of agricultural land expansion into forests and grasslands.

The model accounts for increased agriculture land fertility due to improvements in land-use (e.g. fertilization, irrigation, improved seeds). Furthermore, Felix accounts for new demands for biomass resources for energy purposes and material use, from both forest biomass as well as biomass from energy crops. The intensification of competition for land between food and energy crops is explicitly modeled. The land module explicitly accounts for water resources, which constrains land fertility due to scarcities of irrigation water.

GEOSS Module

GEOSS scenarios are captured in the FeliX model in two ways. First, GEOSS improvements are modeled by changing values of particular model parameters. The second way is by incorporating new relations between model components or by the introduction of new model components.

Additionally, in order to track the impact of GEOSS the FeliX model does not rely only on economic indicators, but also incorporate non-monetary indicators like the Human Development Index and Total Change in Ecosystem Value.

2.2. Model Calibration and Validation

The FeliX model was calibrated in an iterative process of structure formulation, parameter estimation, analysis of fit and residuals, and model re-formulation. 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 was reached to the historical data. Calibration not only involved goodness of fit criteria, but also the plausibility of the model per se in terms of its capability to explain the observed behavior.

Validation of the model is subject to data availability for validation purposes. Data for calibration and validation came from the research conducted in the GEOBENE project as well as from other sources as such IEA Key World Energy

Statistics[5], BP Statistical Review of World Energy[6], Carbon Dioxide Information Analysis Center[7], or FAOSTAT[8]. The calibration was conducted for a period of one century (ranging from year 1900 up to year 2000). In case 100 years data were not available, the historical data for available period were used.

The model went through a set of standard structure and behavior tests to build confidence in System Dynamics models (see Sterman, 1984; Oliva, 1995). Figure 4 presents results of the calibration effort for a subset of model variables across various modules of the FeliX model whereas Table 1 presents historical fit summary statistics for each of the chosen variables.

Table 1: Historical fit summary statistics (Theil inequality statistics) [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]

	R^2	MAPE	MSE	RMSE	U^M	U^S	U^C
Gross World Product	0.988	0.15	3.99E+24	2.00E+12	0.77	0.00	0.23
GWP per Capita	0.941	0.07	7.51E+04	2.74E+02	0.01	0.00	0.99
Energy Demand	0.973	0.10	1.95E+05	4.41E+02	0.03	0.07	0.90
Oil Production	0.917	0.28	2.17E+05	4.66E+02	0.29	0.15	0.56
CO_2 Emission from Gas	0.987	0.22	2.57E+15	5.07E+07	0.19	0.09	0.72
Total CO_2 Emission	0.977	0.22	2.02E+17	4.49E+08	0.53	0.00	0.47
Agricultural Land	0.987	0.03	6.44E+23	8.02E+11	0.32	0.48	0.20
Forest Land	0.990	0.01	7.17E+23	8.47E+11	0.64	0.33	0.03

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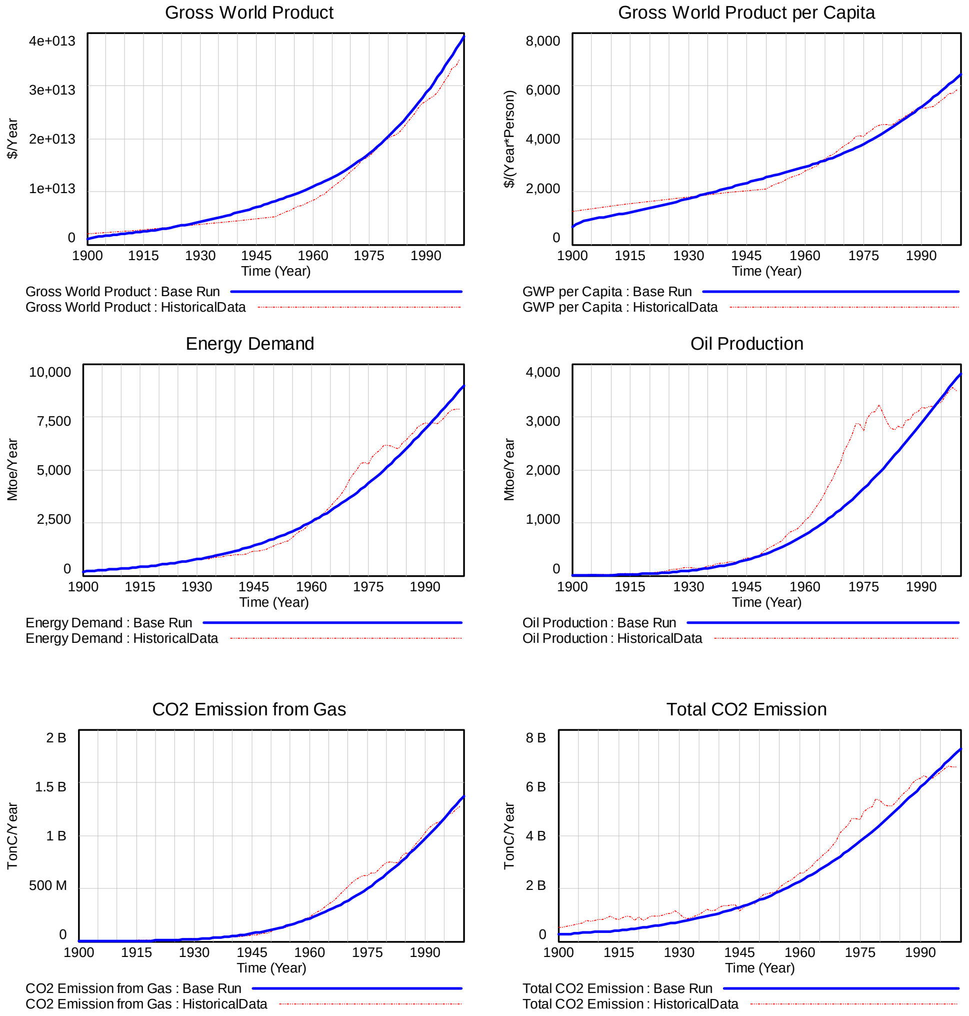
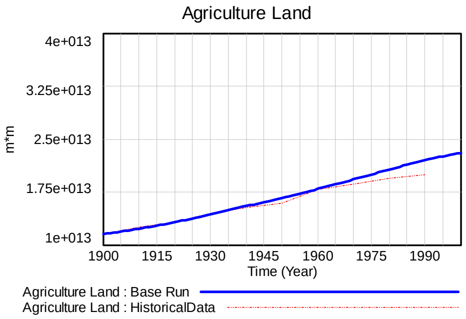
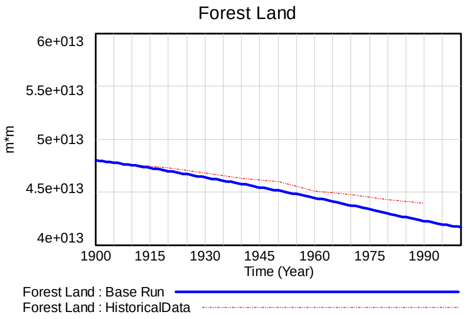
[5] http://www.iea.org/stats/index.asp
[6] http://www.bp.com/productlanding.do?categoryId=6929&contentId=7044622
[7] http://cdiac.ornl.gov/
[8] http://faostat.fao.org/

Figure 4: Overview of the FeliX Model Calibration Outcome (Red, dashed lines are historical data; blue, solid lines are the outcomes of the calibration experiment)







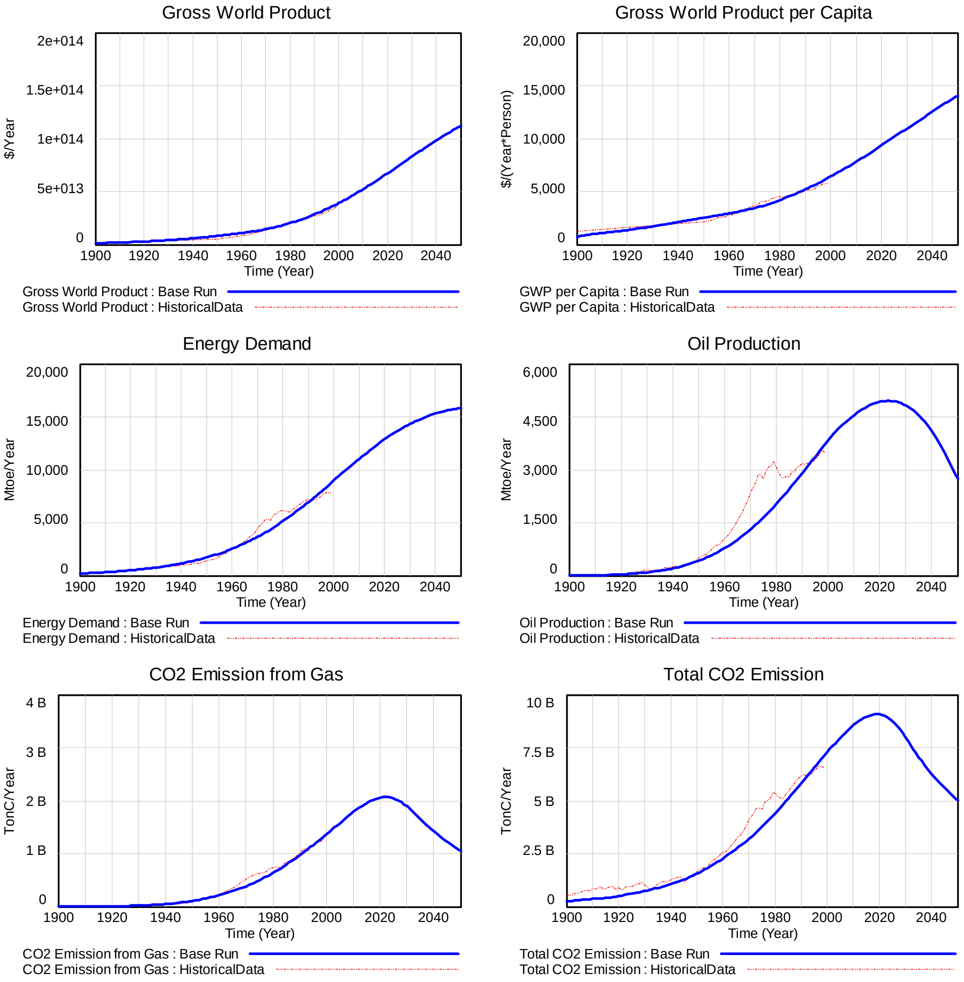
2.3. Baseline Scenario

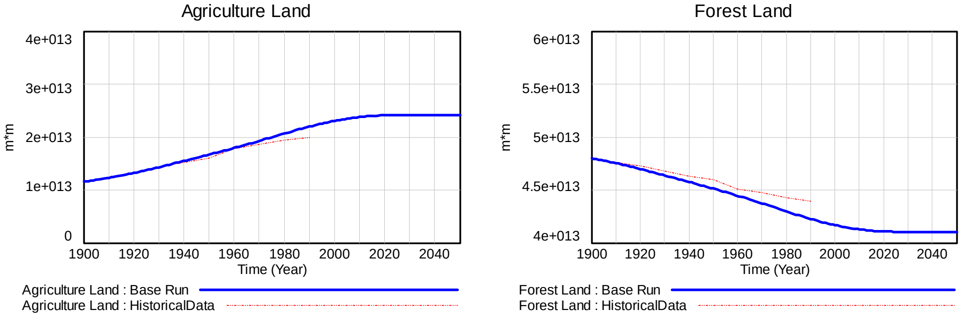
Once the model structure was finalized and the model was calibrated to historical data constituting an acceptable representation of the Earth system the baseline scenario was constructed by extending the model time scale up to 2050. Additional policy assumptions were introduced to the model mimicking consistency with the Millennium development goals. These policies encompass investments in alternative sources of energy including biomass, solar and wind, as well as intensive investments in Carbon Capture and Sequestration.

The inclusion of additional policies for the baseline definition is in the spirit of the 2nd Earth Summit in Johannesburg were the GEO idea was born. Thus, our baseline is more in line with a sustainability scenario rather than a 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 economic, social and environmental policies are in place, but GEOSS related improved data and data policies were not available. Figure 5 presents the baseline runs used for the GEOSS impact assessment.

Figure 5: Overview of the Baseline Scenario (Red, dashed lines are historical data; blue, solid lines are the outcomes of the Baseline scenario experiment)





2.4. GEOSS Scenarios

In order to assess the socio-economic and environmental impacts of GEOSS improvement six SBA storylines were constructed in the energy, disaster health, climate agriculture, and water SBA (weather, ecosystem and biodiversity SBAs are jointly considered under the six scenarios). The storylines were informed by research carried out in the GEOBENE project and from studies published mostly, but not exclusively in the scientific literature. Various story lines were expressed as incremental or more abrupt change and new relations in the FeliX model. The range of parameter changes either was informed by particular studies or was conjectured by the responsible Subject Matter Expert within the GEOBENE project. For illustration, the conjectured storylines for the energy SBA are presented in Table 2.

Each of the six GEOSS scenarios can be considered as an integrated scenario in the sense that the changes it brings to the model affect not only one particular domain of interest but changes propagate through the whole model. Thus, the 'Energy Scenario' or 'Agriculture Scenario' shall not be considered as influencing only the Energy or Agriculture sector respectively. For instance, changes in GHG emissions from the energy sector impact 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 impact of improved earth observations of one observing system can be analyzed from a pure sectorial angle or a full systems view.

In this paper, instead of considering each predefined GEOSS scenario separately, the focus was given to combined scenarios – all six predefined 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 impacts in various model sectors.

Table 2: Example of Story lines Used for Energy Scenario

#	*Story line*
1	GEOSS improves geological surveys as well as modeling of reservoirs. This increases oil discovery and production.
2	Apart from enhanced geological surveys due to use of GEOSS and thus better planning for oil production operations (drilling the production wells, injection wells, horizontal drilling, etc.), better use of GEOSS data improves risk management and process integrity. The examples can be operations standards, procedures and mitigation measures regarding hurricanes or earthquake.
3	GEOSS enables better data mapping of carbon capture and sequestration sites, such as saline aquifers, and better monitoring of leakages from CO_2 sequestration sites. In addition, GEOSS data improve modeling of long-term sequestration effects such as CO_2 absorption by the rock leading to more efficient CCS process.
4	Similarly as in case of oil technologies, GEOSS improves geological surveys as well as modeling of reservoirs. This increases gas discovery and production.
5	Enhanced geological surveys due to use of GEOSS enables better planning for gas production operations. Better use of GEOSS data improves risk management and process integrity.
6	Enhanced planning for solar energy installations due to use of GEOSS data, meaning enhanced locating and commissioning.
7	Improved integration of solar energy installations into electricity grid due to better use of GEOSS data.
8	GEOSS data improve dealing with unit commitment problem of delivery of electricity to the market and therefore it impacts the competitiveness of solar energy technologies (e.g. optimal exploitation of heat storage of concentrating solar power plants).
9	Enhanced planning for wind energy installations due to use of GEOSS data, meaning enhanced locating and commissioning.
10	Improved integration of wind energy installations into electricity grid due to better use of GEOSS data.
11	GEOSS data improve dealing with unit commitment problem of delivery of electricity to the market and therefore it impacts the competitiveness of wind energy technologies (e.g. optimal exploitation of heat storage of concentrating solar power plants).
12	Better use of GEOSS data enhances siting and commissioning of biomass power plants including planning for optimized logistics (BEWHERE model).
13	GEOSS enables better forest management practices including pest and diseases control and silviculture measures such as fertilization, thinning and final harvesting.
14	GEOSS enables better crop and biomass feedstock management practices such as planting and harvesting scheduling, pest and diseases management, plants stress management through irrigation and precision farming. Furthermore, use of GEOSS data improves global coordination of production scheduling (e.g. compensation for expected crop failure in Australia by increased earlier planting in the Northern Hemisphere).

3. IMPACT ASSESSMENT OF GEOSS ACROSS SBAS

The approach used to measure impacts of building 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 is developing over time or in a form of an accumulated value at the end of specified period of time. The starting point for the GEOSS impact assessment is year 2000.

An open architecture of the FeliX model (as opposed to so called "black box" models) allows for further analysis and tracking causes of any difference between GEOSS and baseline scenarios. Model transparency is necessary when dealing with highly interrelated complex systems such as the GEOSS benefit system.

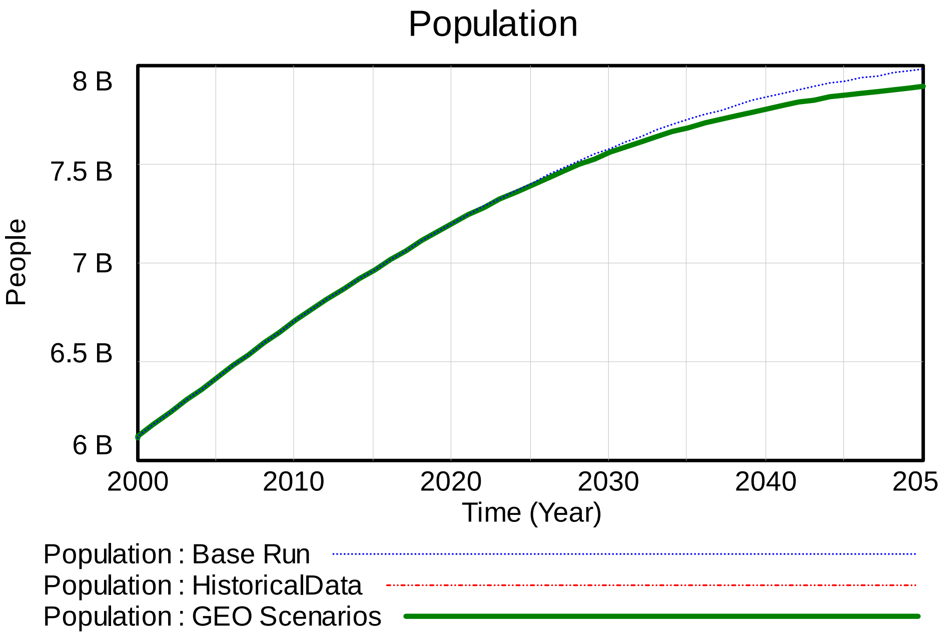
While running the combined scenario (including all six predefined GEOSS scenarios), one of the most interesting examples of GEOSS impact that required more thorough analysis was the deviation in population development. While indicators of global affluence, human wellbeing and state of the environment improved in the GEOSS scenarios we observed an aggregate decline in global population.

The goals to be attained through GEOSS in the various SBAs were defined as follows:

- reducing loss of life and property from natural and human-induced disasters,
- understanding environmental factors affecting human health and well-being,
- improving management of energy resources,
- understanding, assessing, predicting, mitigating, and adapting to climate variability and change,
- - improving water-resource management through better understanding of the water cycle,
- - improving weather information, forecasting, and warning,
- - improving the management and protection of terrestrial, coastal, and marine ecosystems,
- - supporting sustainable agriculture and combating desertification,
- - understanding, monitoring, and conserving biodiversity

GEOSS scenarios revealed improvements on all of these indicators. Despite of reduced mortality associated with these goals, the GEOSS scenarios indicate a decrease of population, which is illustrated in Figure 6. In the GEOSS scenario over a period of 50 years population is expected to be 86.6 million less compared to the reference scenario. These kinds of results seem to be quite controversial in the light of the role attributed to GEO and require some attention.

Figure 6: Population Dynamics for Baseline and GEOSS Scenarios



Population is considered in the System Dynamics notation as a stock – an accumulator in a system analogous to a tank of water (over time a stock accumulates inflows and is reduced by outflows). The level of any stock varies, depending on the values of inflows and outflows. In case of the population, its level depends on birth rate and mortality.

Figure 7 illustrates difference in mortality between the GEOSS and baseline scenario. Since the population death rate in GEOSS scenario is lower than in baseline scenario the difference is indicated as negative. Over a period of 50 years there would be all together 12.3 million life-beings saved due to use of improved data from GEOSS.

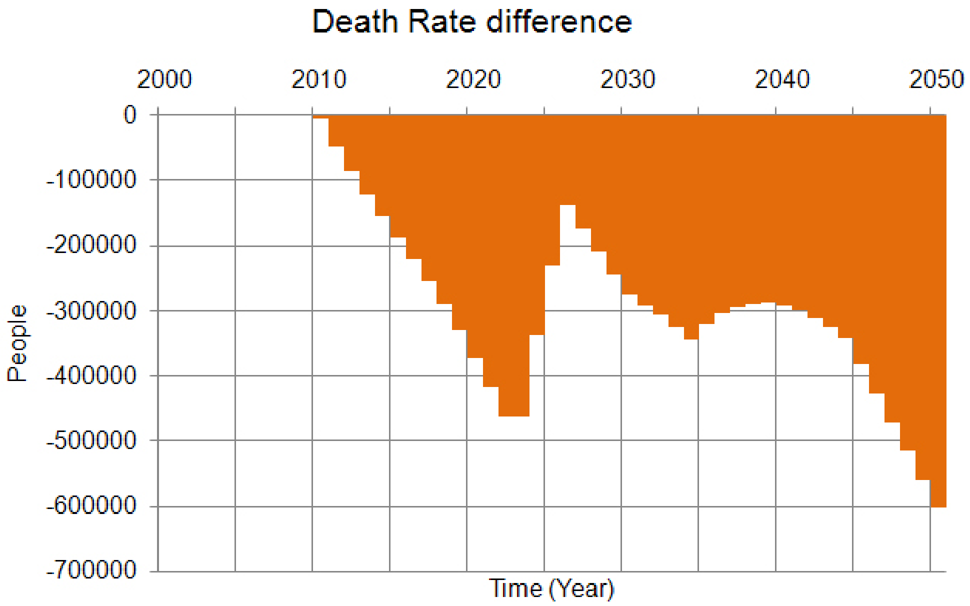
Analysis of the causal relations indicates that the main contributors of the decrease in the death rate are:

- *Increased Food Availability*: GEOSS enables better crops management through improved planting and harvesting scheduling, pest and diseases management, and water and plant nutrition management through irrigation and precision farming. In addition, the use of GEOSS data will enable mid-range agro-meteorological prediction improving the geographic and temporal scheduling of global food production. Furthermore, GEOSS enables more targeted plant breeding according to biophysical indicators such as climate-soil conditions.

- *Improved Warning and Mitigation of Disasters*: The use of GEOSS data enables better information prior to disasters and necessary information to quickly react following a severe event.

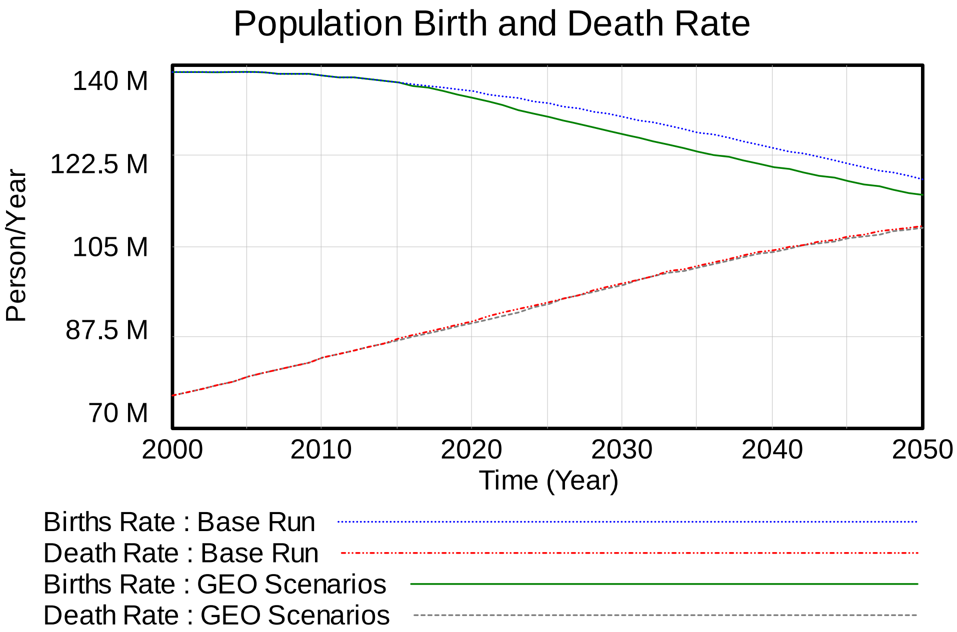
In the light of the above the only reasons of lower population level in case of GEOSS scenario is birth rate.

Figure 7: Difference in Population Death Rate between the GEOSS and Baseline Scenarios



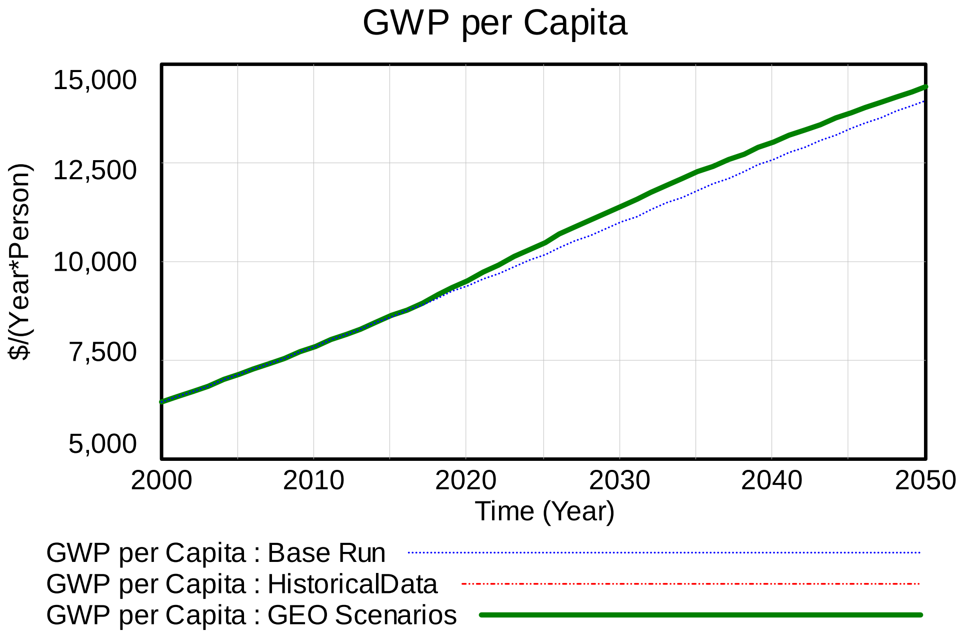
In year 2000 the population birth rate is greater than the population death rate. As presented in Figure 8, over time the birth rate decreases while the death rate increases due to a demographic shift to older age cohort, which in the aggregate leads to slower increase of population. In case of GEOSS scenario even though the death rate increase is not as fast as in case of the baseline the birth rate decreases much faster than in baseline scenario leading to slower population growth.

Figure 8: Birth and Death Rate for Baseline and GEOSS scenarios



The explanation of the stock and flow dynamics of the population might not be satisfactory for those trying to understand even further complex relations within the system. One might ask why the birth rate decline is greater in the GEOSS scenario. Investigating the mechanism in the FeliX model open, we find that the birth rate declined in the GEOSS scenario due to “affluence”. Figure 9 illustrate the average Gross World Product per Capita showing increased GWP per capita by up to $450 in the GEOSS scenario compared to the baseline scenario. This trend is accompanied by greater adoption of “western world life style” of small families and long life as remarkably illustrated by Hans Rosling during his talk at the US State Department[9] and is directly visible in population birth rate decrease (Figure 8).

Figure 9: GWP per Capita for Baseline and GEOSS Scenarios



Another measure of impact we highlight here is the indicator "CO_2 emission". GEOSS provided data enables better data mapping of carbon capture and sequestration sites, such as saline aquifers, and better monitoring of leakages from CO_2 sequestration sites. In addition, GEOSS data improve modeling of long-term sequestration effects such as CO_2 absorption by the rock, leading to more efficient CCS process. The GEO benefit in this area is even more worth noticing taking into consideration all current efforts to mitigate or decrease the scale of climate change. Figure 10 illustrates the difference in CO_2 emission between GEOSS scenario and the Baseline scenario. Thank to use of GEO data, over a period of 50 years the accumulated reduction in CO_2 emission reaches 23.12 billion TonC.

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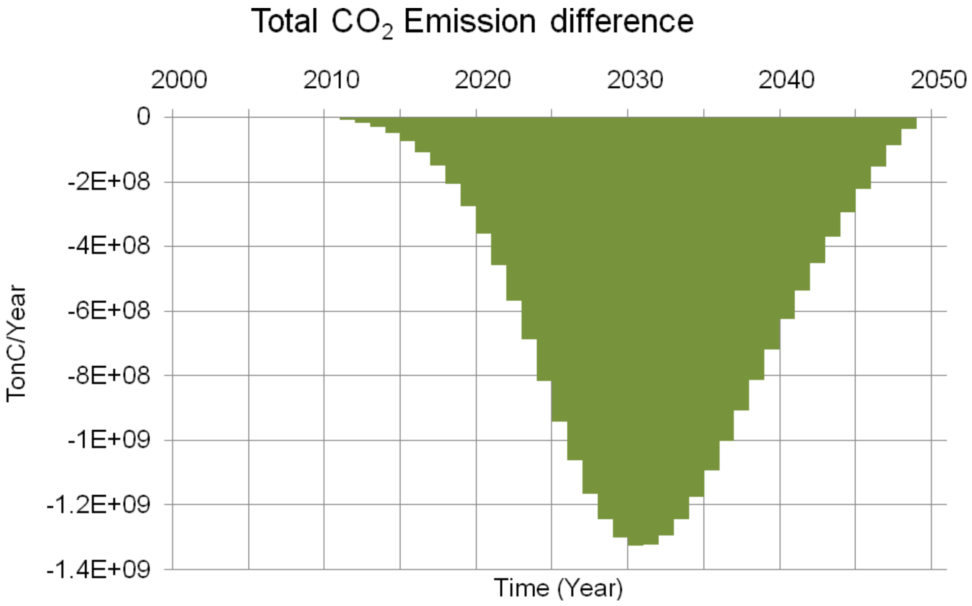
[9] http://blog.ted.com/2009/08/let_my_dataset.php

Figure 10: Total CO_2 Emission Difference between Baseline and GEOSS Scenarios



The outcomes of the simulation scenarios described above constitute only a small portion of the GEOSS impact assessment results across all the GEO defined SBAs obtained via the FeliX model simulation. Over the course of the assessment, it was found out that even though the FeliX model has an open architecture its structure mimicking the society-technology-environment interrelations of the Earth system is complex and requires significant preliminary time investment to gain a better understanding of the model dynamics. From the perspective of the model purpose this level of complexity is necessary. However, the model itself is too complicated as a tool to be directly presented to the higher level decision makers. Still in the authors' view the lessons following the GEOSS assessment are worth bringing to the wider community. For that reason the FeilX model based simulator was constructed. As illustrated in Figure 11 it is equipped with a user friendly interface that allows easy use and navigation through the simulation experiments outcomes.

The users interested in assessing the impact of Global Earth Observations are able to run illustrative GEOSS related scenarios and observe the potential impacts across all model sectors along a number of impact indicators. The simulator is an appropriate tool that enables decision makers to test various GEOSS scenario assumptions, extend their knowledge and understanding about relationships in the system to finally support decision making. The simulator is freely available from the GEOBENE project website[10] together with the whole project research and scientific outcomes.

Figure 11: FeliX Simulator Interface while Running GEOSS Scenarios

4. CONCLUSION

In the times of strained public budgets decision on how to develop a global Earth Observation System of Systems requires international coordination of efficient and effective investments and operations. The FeliX model presented in this paper was developed to serve as an assessment tool for the benefits improvements in Global Earth Observations. The benefit system is defined by Societal Benefits Areas. FeliX's open architecture was designed to support strategic decision processes to develop GEOSS. It identifies the areas where and how GEOSS like initiatives might have significant impacts.

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

Prioritization of coordinating actions and investments to build the joint Global Earth Observation System of Systems necessitates integrated assessment of the prospective economic, social and environmental benefits. In this paper we have developed a methodology and analytical tool and applied it to assess the societal benefits of improving GEOSS across SBAs 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 result in 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 monetary terms but also by social and environmental indicators. Therefore, only impact signals of order-of-magnitude and qualitative understanding of the shape of the cost-benefit relationships derived from the modeling process can support GEOSS decision making processes.

We have assessed two source categories benefit generation. The first relates to benefits from economies of scale of a global or large observing system vis-à-vis the currently prevailing patchwork system of national or regional observing systems. Benefits related to the economies of scale effect we subsume under the term aggregation benefits. The second source of benefit generation from GEOSS relates to economies of scope, which emerge when changes in the observing system impact multiple benefit sectors or benefit dimensions. Economies of scope generating processes we referred to as integration benefits. Quantifying these benefits, which are often of a “public good” nature, proved a significant challenge. Due to the public good nature of the benefits, GEOSS impacts are highly dependent on the type of baseline policy scenario. Apart of the choice of baseline definition there are several other limitations to the model and the use of the FeliX model. Currently there are some subjects that might have been modeled with great detailed while others that might contribute more to the benefit as covered in less detail. This uneven coverage is due to the fact that in some areas data are very sparse, which in other areas we anticipated lower benefit levels ex ante and invested fewer resources in development. As any other model the FeliX model is a purposeful simplification of the reality. There are also some questions regarding existence or strength of 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 soft knowledge of subject matter experts. The latter is a subject of further research and might require revision of the assumed model structure and parameters values. As there is an increasing number of ongoing integrated and systems-oriented studies on relations in the Earth system there is a hope that some of these issues will be soon resolved and the FeliX model structure will be changed accordingly. In the mean time, in order to deal with the uncertainty in the

FeliX model, sensitivity analysis can be conducted, which is a subject for future work with the model.

Relating to the needs in the field as defined by Craglia et al (2008) the systems approach and FeliX model might be a part of engaging, interactive, exploratory, and a laboratory for learning and for multidisciplinary education and science. The first step in that direction has already been made. The constructed simulator being an integral part of the systemic view on the GEO impact analysis brings the outcome of the studies to a broader community. It is freely available on the GEOBENE project website. As for now the simulator user can run one of or combination of six predefined scenarios. However, there is a potential to enable access to the FeliX model structure and developed capability to run user-defined specific scenarios and forecasts. While running the predefined or user-defined scenarios the users will be able to run various 'what-if' scenarios and choose user defined metrics of societal benefit. In this paper, for illustrative purposes, focus was given to socio-economic indicators in terms of population number and gross world product per capita. However, with the idea of an open access to scenarios every user could investigate different metrics. Such an approach can start an open dialog in the community not only on benefits of GEO but also on practical applications and use of GEOSS data in the GEO community. Global Earth Observation has a great potential in shaping a sustainable future of our planet. According to our analysis its positive impact is visible across all social, economic and environmental indicators of the Earth system. Decrease of CO_2 emissions, increased food availability, saving water resources, enabling clean energy technologies are only few examples where improved data on Earth system might be of help.

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