

SPECIAL ISSUE: The Dynamics and Value of Ecosystem Services: Integrating
Economic and Ecological Perspectives

Modeling the dynamics of the integrated earth system and the value of global ecosystem services using the GUMBO model

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Abstract

A global unified metamodel of the biosphere (GUMBO) was developed to simulate the integrated earth system and assess the dynamics and values of ecosystem services. It is a ‘metamodel’ in that it represents a synthesis and a simplification of several existing dynamic global models in both the natural and social sciences at an intermediate level of complexity. The current version of the model contains 234 state variables, 930 variables total, and 1715 parameters. GUMBO is the first global model to include the dynamic feedbacks among human technology, economic production and welfare, and ecosystem goods and services within the dynamic earth system. GUMBO includes modules to simulate carbon, water, and nutrient fluxes through the *Atmosphere*, *Lithosphere*, *Hydrosphere*, and *Biosphere* of the global system. Social and economic dynamics are simulated within the *Anthroposphere*. GUMBO links these five spheres across eleven biomes, which together encompass the entire surface of the planet. The dynamics of eleven major ecosystem goods and services for each of the biomes are simulated and evaluated. Historical calibrations from 1900 to 2000 for 14 key variables for which quantitative time-series data was available produced an average R^2 of 0.922. A range of future scenarios representing different assumptions about future technological change, investment strategies and other factors have been simulated. The relative value of ecosystem services in terms of their contribution to supporting both conventional economic production and human well-being more broadly defined were estimated under each scenario, and preliminary conclusions drawn. The value of global ecosystem services was estimated to be about 4.5 times the value of Gross World Product (GWP) in the year 2000 using this approach. The model can be downloaded and run on the average PC to allow users to explore for themselves the complex dynamics of the system and the full range of policy assumptions and scenarios. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

There is now a relatively long history of global computer simulation modeling, starting in the 1970s with the World2 (Forrester, 1971) and World3 models (Meadows et al., 1972; Meadows and Meadows, 1975). Since then the field has expanded greatly, owing partly to the increasing availability and speed of computers and to the rapidly expanding global data base that has been created in response to increased interest in global climate change issues (Meadows, 1985; Meadows et al., 1992; Nordhaus, 1994; Rotmans and de Vries, 1997; IPCC, 1992, 1995, 2001). Collectively, global models constitute a relatively well focused and coherent discussion about our collective future. As Meadows (1985) has pointed out:

“Global models are not meant to predict, do not include every possible aspect of the world, and do not support either pure optimism or pure pessimism about the future. They represent mathematical assumptions about the interrelationships among global concerns such as population, industrial output, natural resources, and pollution. Global modelers investigate what *might* happen if policies continue along present lines, or if specific changes are instituted” (Meadows 1985, p. 55; Italics added).

The global unified metamodel of the biosphere (GUMBO), which we describe in this paper, builds on the long tradition of global modeling and the rapidly expanding global data base.

GUMBO addresses the following key objectives:

1. To model the complex, dynamic interlinkages between social, economic and biophysical systems on a global scale, focusing on ecosystem goods and services and their contribution to sustaining human welfare.
2. To create a computational framework and data base that is simple enough to be distributed and run on a desktop PC by a broad range of users. GUMBO was constructed in STELLA, a popular icon-based dynamic simulation modeling language (<http://www.hps-inc.com>), and the full model can be downloaded and run using the free run-time only version of STELLA.

In designing GUMBO we sought to provide a flexible computational platform for the simulation of alternative global pasts and futures envisioned by diverse end-users. GUMBO limits historical parameter values to those which produce historical behavior consistent with historical data. It then allows one to make explicit assumptions about future parameter or policy changes, or to determine what assumptions are required to achieve a specific future. It is then possible to assess how plausible those assumptions are, and to consider policy options that might make the assumptions required for a desired future more likely to occur. By allowing the user to change specified parameters within GUMBO and generate alternative images of the future we hope to provide a tool that will both stimulate dialogue about global change and generate a more complete understanding of the complex interrelationships among social and economic factors, ecosystem services, and the biophysical earth system. This dialogue is needed in order to achieve sustainable development on a global scale.

GUMBO is unique among global models in three important ways:

1. ecosystem services are a focus of GUMBO and explicitly affect both economic production and social welfare. This allows the model to calculate dynamically changing values for ecosystem services based on their marginal contributions relative to other inputs into the production and welfare functions.
2. both ecological and socioeconomic changes are endogenous to the model, with a pronounced emphasis on interactions and feedbacks between the two—all other global models to date limit either ecological or socioeconomic change to exogenously determined scenarios (c.f. Meadows et al., 1992; Rotmans and de Vries, 1997; IPCC, 2001);
3. the model includes natural capital, human capital, social capital and built capital as state variables and factors of production, and distinguishes between material factors and factors

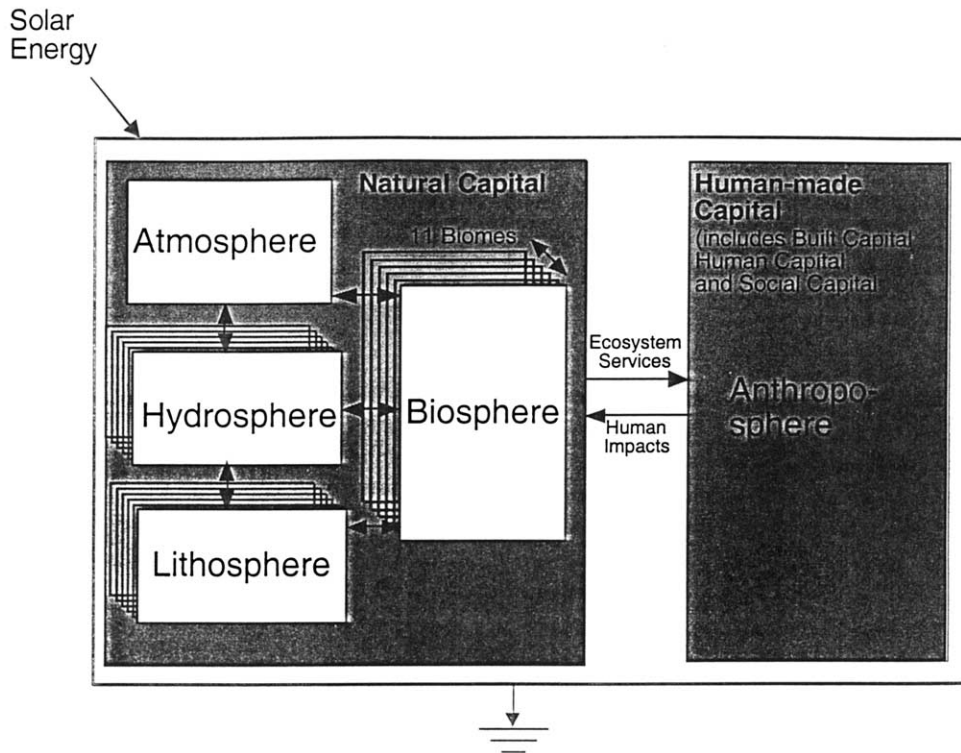


Fig. 1. Basic structure of GUMBO. The hydrosphere, lithosphere, and biosphere are reproduced for each of 11 biomes. STELLA diagrams to indicate the general complexity of the structure of each sphere are given in Figs. 2–9. The full model and equations are available for download at: <http://iee.umces.edu/GUMBO>.

of transformation (material cause and efficient cause, in Aristotelian terms). Thus, the model allows limited substitution between factors of production at the margin, but also imposes strong sustainability constraints for the system as a whole.²

This paper first describes the general structure and behavior of GUMBO, along with limitations and caveats (the full model and documentation can be downloaded from: <http://iee.umces.edu/GUMBO>). It then presents results from a few

² Weak sustainability requires that the future be left a constant amount of capital, but assumes more of one type of capital can always substitute for less of another. Strong sustainability, on the other hand, requires that the future be left constant amounts of natural capital (the material means of production), while allowing substitution among social capital, built capital and human capital (the efficient means of production, or agents of transformation).

alternative scenarios developed using contrasting assumptions about technology, the resilience of the global environmental system and the ability of economic production to cope with future changes in sinks and sources of natural capital. For each scenario, we examine the dynamics of the values of ecosystem services to assess which ecological variables impose the tightest constraints on production and welfare. We also discuss the plausibility of the assumptions necessary to bring about each scenario, and the level of risk implied in planning futures around each scenario.

2. Model development

GUMBO consists of five distinct modules or 'spheres': the Atmosphere, the Lithosphere, the Hydrosphere, the Biosphere, and the Anthropo-

sphere (Fig. 1). It is further divided into 11 biomes or ecosystem types which encompass the entire surface area of the planet: *Open Ocean*, *Coastal Ocean*, *Forests*, *Grasslands*, *Wetlands*, *Lakes/Rivers*, *Deserts*, *Tundra*, *Ice/rock*, *Crop-lands*, and *Urban* (see Fig. 1). These 11 biomes represent an aggregation of the sixteen biomes used in Costanza et al. (1997a). Their relative areas change in response to urban and rural population growth, Gross World Product (GWP), and changes in global temperature. Among the spheres and biomes, there are exchanges of energy, carbon, nutrients, water and mineral matter.

GUMBO is the first global model to explicitly account for ecosystem goods and services and factor them directly into the process of global economic production and human welfare development. Ecosystem services contribute to human quality of life in numerous ways. First, such services provide critical life-support systems for humans and all other species. Second, all sustainable production processes require renewable resource inputs. By creating the conditions essential for the reproduction of all forms of life, ecosystem services also provide the material means for sustainable economic production. Third, ecosystem services create the conditions necessary for cultivated natural capital, such as agriculture, aquaculture and silviculture. Ecosystem services also contribute directly to human well-being (Daily, 1997; Costanza et al., 1997a). In GUMBO, ecosystem services are aggregated to seven major types, while ecosystem goods are aggregated into four major types. Ecosystem services, in contrast to ecosystem goods, cannot accumulate or be used at a specified rate of depletion. Ecosystem services include: soil formation, gas regulation, climate regulation, nutrient cycling, disturbance regulation, recreation and culture, and waste assimilation. Ecosystem goods include: water, harvested organic matter, mined ores, and extracted fossil fuel. These 11 goods and services represent the output from natural capital, which combines with built capital, human capital and social capital to produce economic goods and services and social welfare.

Below we briefly describe the major 'sectors' in the GUMBO model. The atmosphere and anthro-

posphere are considered to be globally homogeneous in this version. The other sectors (lithosphere, hydrosphere, and biosphere) are divided into 11 biomes and the structure described is replicated for each biome. In addition, there are sectors in the model for ecosystem services, land use, and the model's data base. In what follows, we briefly describe the important processes and structure in each sector and display the STELLA diagram for the sector to indicate how the elements are connected. In these diagrams, boxes represent state variables, double arrows represent fluxes in and out of state variables, single arrows represent information flows or other functional connections, and circles represent auxiliary variables. The full model with equations and documentation is available for download at: <http://iee.umces.edu/GUMBO>.

2.1. The atmosphere

The atmosphere module in GUMBO (Fig. 2) facilitates exchanges of carbon, water, and nutrients across biomes. The atmosphere also accounts for global energy balances. Atmospheric dynamics are calibrated against two important global indicators: atmospheric carbon and global temperature.

Source and sink functions of atmospheric carbon are linked to all other spheres. For example, carbon exchange with the biosphere depends on the rates at which carbon is lost to the atmosphere from burning and decaying plant material as well as the rates of carbon removal from the atmosphere through vegetation growth (Houghton et al., 1987). Carbon exchange with the lithosphere occurs through degassing from volcanic activity, and the accumulation and oxidation of organic soil matter (Houghton et al., 1987). The net carbon flux between the atmosphere and the hydrosphere results from partial pressure differences between air and water. Carbon input from the anthroposphere to the atmosphere is primarily the result of fossil fuel combustion and cement production.

Sources and sinks of atmospheric water are evaporation and precipitation in the hydrosphere and transpiration within the biosphere. Sources of

atmospheric nutrients, primarily various types of nitrogen oxides, are introduced from biomass oxidation in the biosphere and fossil fuel combustion within the anthroposphere. Atmospheric nutrient sinks are ocean sea spray and wet precipitation in the hydrosphere and dry deposition in the lithosphere.

Global energy accounting was adapted from a

model created by Few (<ftp.usra.edu/pub/esse/DROP/outgoing/stella/few/energymod3.stm>) in order to simulate energy budgets for each biome at 1-year time steps. We introduced spatial energy diffusion fluxes to account for heat exchanges across biomes. Incoming solar energy is proportional to a solar radiation constant and a biome-specific albedo. Energy radiation into space is proportional to biome-specific properties for heat retention and imperfect emissivity. Energy exchanges between biomes take into account temperature differences and time constraints for energy transport.

Atmosphere

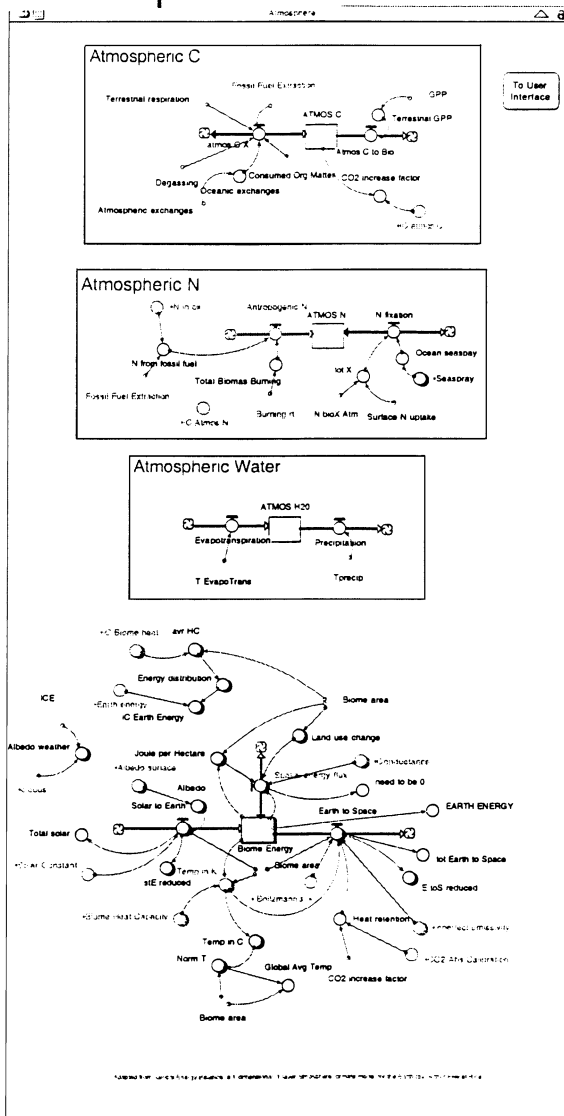


Fig. 2. STELLA diagram of the Atmosphere sector.

2.2. The lithosphere

The GUMBO lithosphere (Fig. 3) represents the solid uppermost shell of the earth, which includes soils and deposited sediments. Lithosphere stocks are represented by silicate rocks, carbon reserves, and ore and fossil fuel deposits in rock and soil. Fluxes between rocks and soils are from weathering and sedimentary deposition (burial). New silicate rock is formed and lost by the slow rates of ocean spreading and seafloor subduction. Weathering causes an overall decay of carbon, silicate rocks and ore deposits and forms soils through interaction with the biosphere. A specified ‘burial rate’ converts carbon, silicates and ores back into sedimentary rocks and accounts for biome-specific recycling rates.

2.3. The hydrosphere

The GUMBO hydrosphere (Fig. 4) accounts for biome-specific stocks of water, carbon, and ‘generic nutrients’ in surface and subsurface water bodies. Surface storage occurs in ice and surface water, subsurface storage occurs in deep water, fossil water and unsaturated water (soil moisture). Storage of carbon and nutrients in the hydrosphere occur in surface water, terrestrial groundwater and oceanic surface and deep water. Average biome temperature determines the nature of precipitation. Fluctuating biome temperatures from the atmospheric energy module regulate the water exchange between ice and surface waters. Surface water exchanges between continental and

Lithosphere

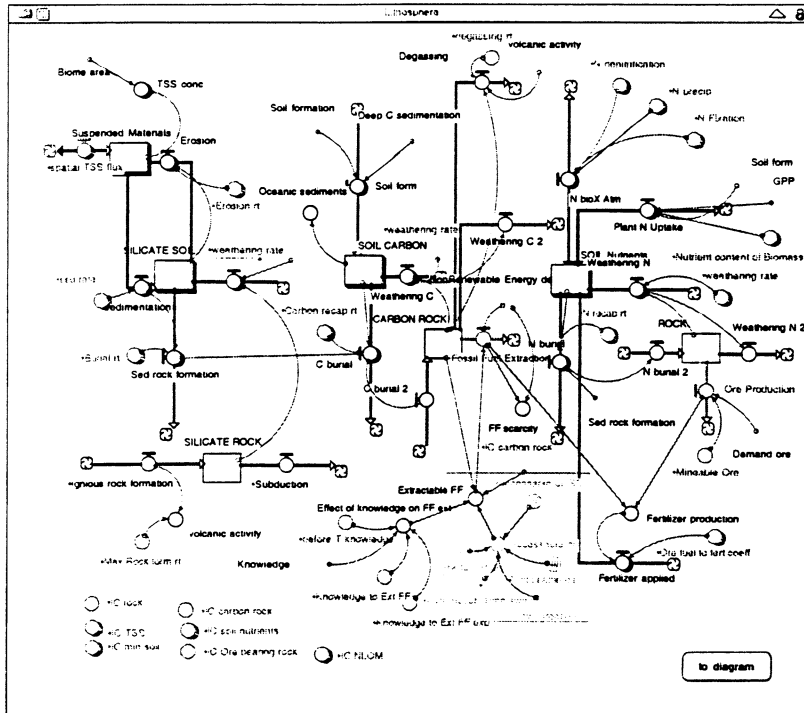


Fig. 3. STELLA diagram of the Lithosphere sector.

oceanic biomes are calculated to compensate for uneven distributions among biome-specific evapotranspiration. Additional fresh water is available as 'fossil water' stored in geological deposits and does not normally have free exchange with surface waters. GUMBO allows the mining of fossil water as a reaction to shortages in surface water due to the demand for water generated in the anthroposphere. Biome-specific stocks of nutrients are exchanged with the atmosphere (e.g. nitrogen fixation and denitrification), the lithosphere (e.g. erosion and sedimentary processes), and the biosphere (e.g. mineralization and plant uptake).

2.4. The biosphere

The biosphere is a self-regulating system sustained by large-scale cycles of energy and materials such as carbon, oxygen, nitrogen, certain minerals, and water. The fundamental processes

are photosynthesis, respiration, and the fixing of nitrogen by certain bacteria. Sources of carbon to the GUMBO biosphere (Fig. 5) are atmospheric and hydrospheric carbon fixed by autotrophs through photosynthesis. Autotrophic carbon is partially fluxed into consumers and partially into dead organic matter. Consumer carbon continues its course into dead organic matter, which is further cycled through a decomposer stock. Biospheric carbon is released into the atmosphere or hydrosphere through respiration from the autotrophs, consumer and decomposer stocks. Accelerated carbon flux from the biosphere to the atmosphere is moderated by forces within the anthroposphere and occurs when autotrophs and consumers are harvested and consumed by humans. Harvested carbon is immediately released back into the atmosphere as waste, stored into built capital like roads or homes, or reapplied towards reforestation. A small fraction of the

Hydrosphere

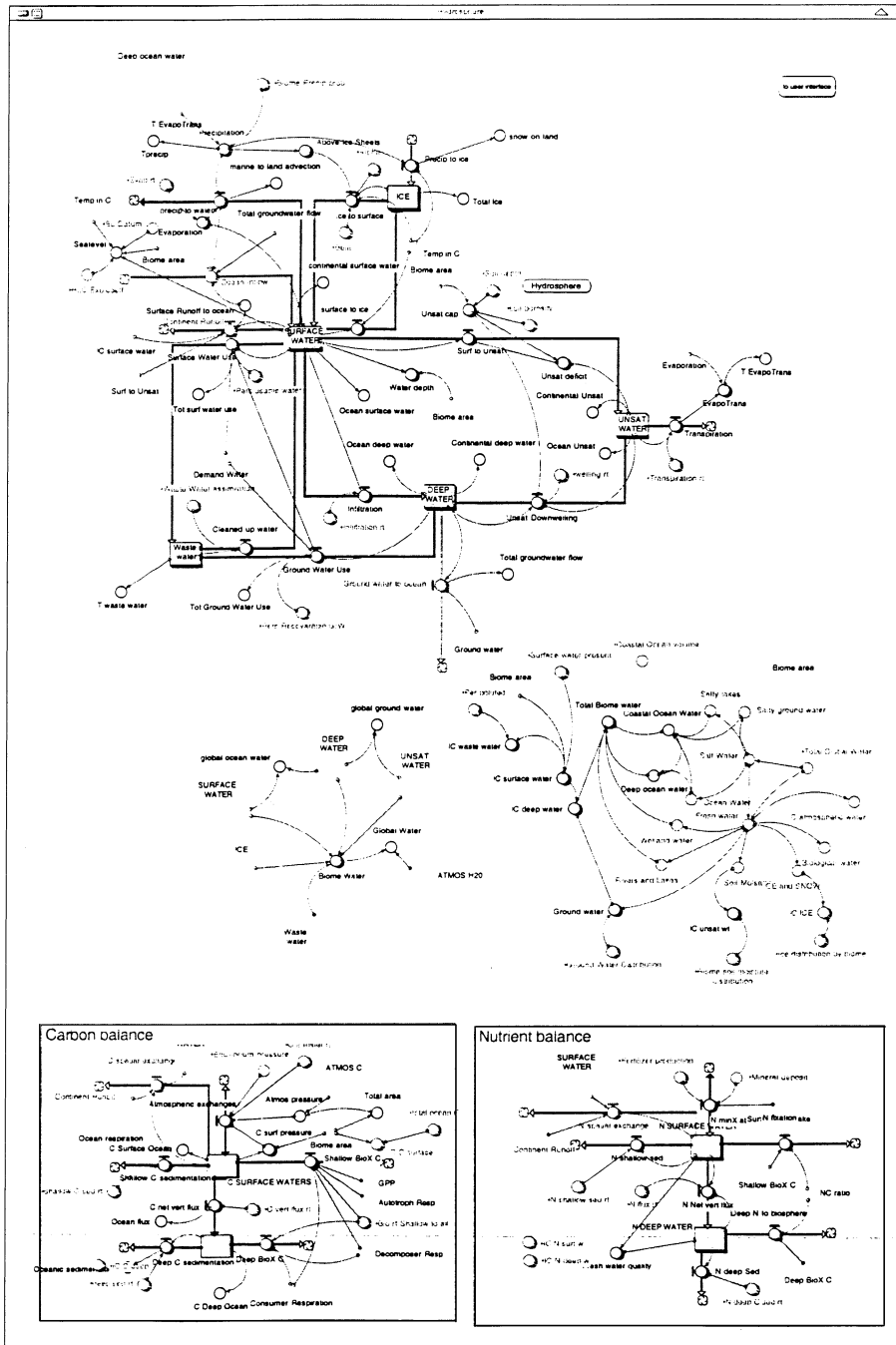


Fig. 4. STELLA diagram of the Hydrosphere sector.

Biosphere

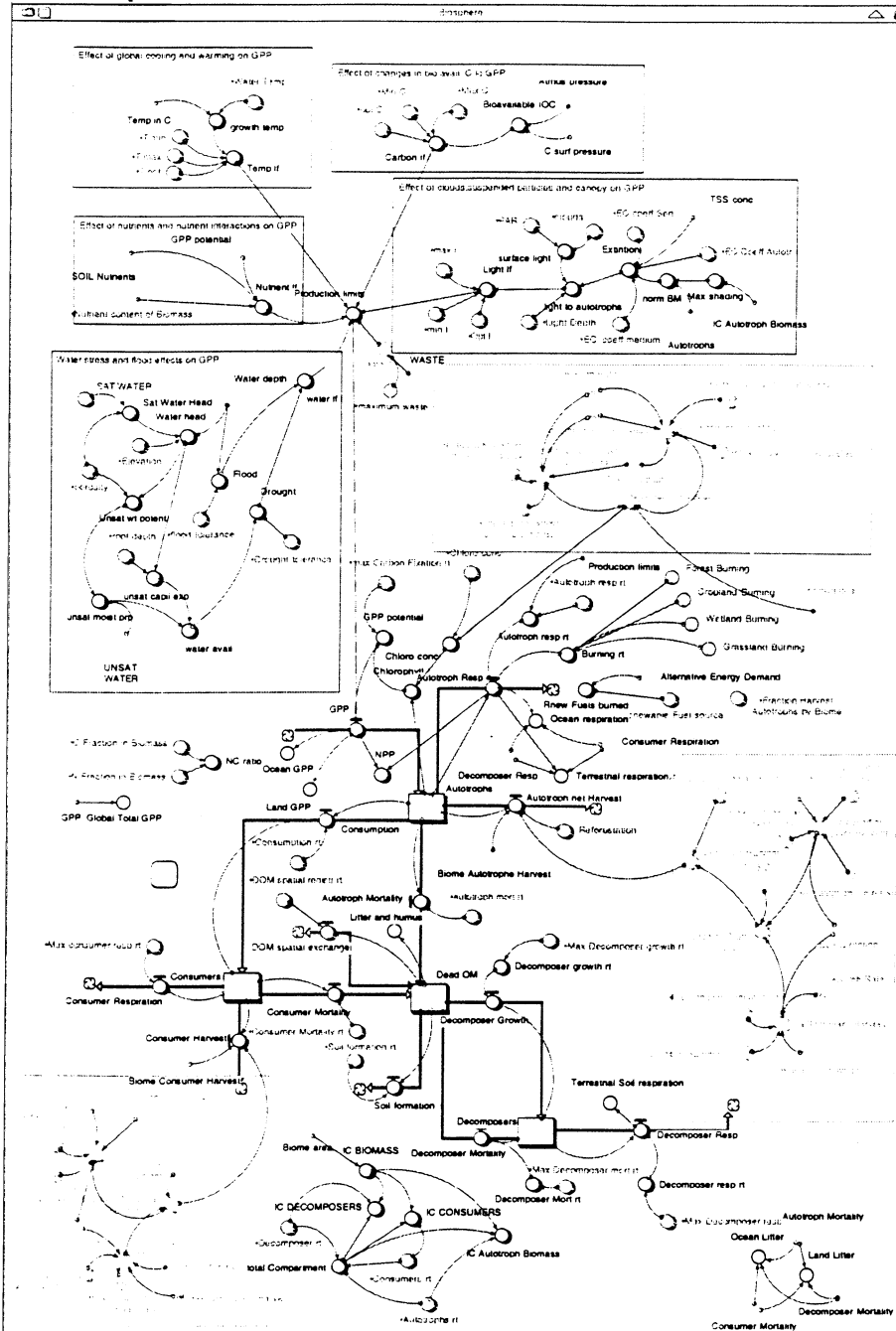


Fig. 5. STELLA diagram of the Biosphere sector.

carbon in the biosphere that resides in the dead organic matter is fluxed towards soil formation and ultimately towards the formation of carbon deposits in rock.

Many of the ecosystem services provided by the biosphere are associated with the rate of photosynthesis or productivity of autotrophs. Important factors for achieving optimum productivity are the nutrient availability in the lithosphere, temperature, light levels, and carbon pressure in the atmosphere, soil moisture in the hydrosphere and waste levels generated within the anthroposphere.

2.5. The anthroposphere

The anthroposphere in GUMBO (Fig. 6) represents human social and economic systems. The anthroposphere harvests large amounts of material and energy from the larger system and discards waste at each phase along a production chain. In contrast to the larger biosphere, only a very small portion of materials are internally recycled within the anthroposphere. Human population, knowledge and social institutions (rules and norms) drive the rate of this material and energy flux.

The anthroposphere is the nexus of valuation in GUMBO. The anthroposphere brings together the numerous elements within the other spheres that affect human well-being, links them to human activities that affect well-being, and assesses the impacts of human activity on those elements. There are two distinct types of value estimated in GUMBO. First, GUMBO calculates the contribution of the elements, activities and impacts to the production of conventional economic goods and services (GWP). Second, GUMBO calculates the contribution of the elements, activities and impacts to our sustainable social welfare (SSW) function or quality of life. Both economic production and human welfare are modeled with a Cobb–Douglas function, as follows:

$$\text{GWP} = \text{HK}^{\alpha_1} \cdot \text{SK}^{\alpha_2} \cdot \text{BK}^{\alpha_3} \cdot \text{W}^{\alpha_4} \cdot \prod_{i=1}^{10} \text{NK}_i^{\alpha_i+4}$$

and

$$\text{SSW} = \text{BK}^{\beta_1} \cdot \text{C}^{\beta_2} \cdot \prod_{i=1}^7 \text{NK}_i^{\beta_i+2} \cdot \text{HK}^{\beta_{10}} \cdot \text{SK}^{\beta_{11}} \cdot \text{W}^{\beta_{12}} \cdot \text{M}^{\beta_{13}}$$

where

α_n and β_n are the percentage increases in levels of output (GWP or SSW, respectively) arising from a 1% increase in the corresponding input. Inputs are: HK = human capital (technology and labor), SK = social capital (social networks and institutions), BK = built capital (buildings, roads, etc.), W = waste (waste products of depreciated capitals and consumption), C = consumption (non-invested GWP), NK = natural capital (disaggregated into the 11 ecosystem goods and services), and M = mortality. The coefficients on waste, α_4 and β_4 , and Mortality β_{13} are negative, while all others are positive. The α_i and β_i parameters are different for the production and welfare function. Differences between the production and welfare functions are that the welfare function: (1) includes only ecosystem services (not ecosystem goods like fossil fuel); and (2) it also includes C (which is a percentage of the production function), and M (average human death rate as an indicator of human health). Thus the welfare function includes the welfare derived from production (via consumption) plus the welfare derived directly from the non-marketed ecosystem services, social capital, built capital, and human capital, and the negative influences on welfare of waste and mortality. Distribution effects on welfare are included through the influence of social capital (Putnam, 2000).

While the α_i parameters in the production function can be calibrated to fit GWP data, values of the β_i parameters in the welfare function are, of course, matters of aggregate individual preferences, which are themselves moderated through culture and world view. In GUMBO we allow the user to experiment with these weights and/or to change them to better reflect their own preferences. In the results we report later, we have used the weights shown in Table 1, which divides the global population into technological ‘optimists’ and ‘skeptics’ (Costanza, 2000). The world is then made up of some (potentially time varying) percentage of each type. In the current run, we

assume 20% optimists (mainly populating the developed world) and 80% skeptics. The optimists give more weight to built capital, consumption, and individual knowledge, and less to natural capital and waste. Both weigh social capital and mortality equally.

The Cobb–Douglas function adopted here is among the most widely used functions in economic modeling for a number of reasons. First the marginal product of each input is positive and decreasing. That is, more of any input will always lead to more output, but each additional unit of input produces less additional output than the preceding one, if other inputs are held constant. Second, it allows for substitution between inputs. Third, and probably most importantly, it is mathematically tractable and log linear, leading to ease of estimation and manipulation (Bairam, 1994).

A limitation of the Cobb–Douglas function in some models is that it allows a virtually infinite substitution of inputs. As long as no input goes to zero, more of any input can always substitute for less of another. This is equivalent to the notion of weak sustainability, which assumes that more built (or social or human) capital can always substitute for less natural capital. However, there are powerful arguments for assuming strong sustainability (i.e. beyond some threshold built, human or social capital cannot substitute for natural capital). For example, no number of fishing boats

can substitute for drastically depleted fish stocks. But the GUMBO model is a *systems* model that captures the feedbacks between the use of capital stocks in the production function and the production of the capital stocks themselves. In GUMBO the notion of strong sustainability is thus explicitly built in because natural capital is an essential input to all other forms of capital. There is no economic ‘production’ in the model, only transformation. Natural capital is the material transformed, while built, social and human capital are the agents of transformation. Thus, while more built capital, social capital or human capital can substitute for less natural capital in the production of GWP or SSW at the margin in the production function, these capitals themselves cannot be produced without natural capital. Thus natural capital is fundamentally a complement to the other capitals in the production process. Further, if natural capital falls below a certain level, or if waste emissions reach excessive levels, natural capital loses the ability to regenerate in the model, and begins a spontaneous decline. Once such a threshold is passed, natural capital can fall to zero, at which point production could fall to zero regardless of the level of other inputs. This approach effectively models the principles of strong sustainability.

The GUMBO framework permits the quantitative aggregation of ‘factors of production’ contributing to both GWP and SSW into four distinct types of capital stocks: *natural capital*, *social capital*, *human capital* and *built capital* (see Berkes and Folke, 1994; Serageldin, 1996; Costanza et al., 1997b, 2001).

Table 1

β_i parameters in the SSW function for this run for technological optimists and skeptics

SSW function parameters (β_i)	Optimist	Skeptic
1. Built capital	0.25	0.01
2. Consumption	0.25	0.01
3. Gas regulation	0.01	0.05
4. Climate regulation	0.01	0.05
5. Disturbance regulation	0.01	0.05
6. Soil formation	0.01	0.05
7. Nutrient cycling	0.01	0.05
8. Waste treatment	0.01	0.05
9. Recreational and cultural	0.04	0.10
10. Knowledge	0.35	0.10
11. Social capital	2.00	2.00
12. Waste	−0.01	−0.50
13. Mortality	−0.20	−0.20

2.6. Natural capital

Natural capital aggregates all the biophysical stocks which produce both ecosystem goods (raw materials and mineral resources) and ecosystem services. Both ecosystem goods and services contribute to both GWP and SSW. Ecosystem goods are the only source of material means, and hence are essential inputs into all production processes, human or natural, but also contribute directly to our quality of life independent of their contribution to production. Unlike the other forms of

capital, natural capital is capable of reproduction on its own with no human intervention. Thanks to the steady inflow of solar energy, it is possible to invest in renewable natural capital simply by using it up slower than it replenishes itself. It is also possible to actively invest in natural capital through ecological restoration, or to cultivate natural capital with inputs of human, social and built capital. Within GUMBO, we invest goods and services in natural capital by reducing consumption and/or direct investment via ecosystem protection and restoration efforts.

2.7. *Social capital*

Social capital refers to the institutions, relationships, and norms that shape the quality and quantity of a society's social interactions. Social capital is not just the sum of the institutions that underpin human society; it is the glue that holds them together (<http://www.worldbank.org/poverty/scapital/whatsc.htm>). Social capital reduces transaction costs via cooperation and makes social and economic interactions possible (Costanza et al., 2001). It is thus an essential element in virtually all economic production, but that is only a part of the benefit it provides as it contributes directly to SSW. Humans are innately social creatures, and human relationships, trust and community are essential components of our SSW. While social capital can depreciate, it does not wear out through use. Indeed, it would seem that using social capital probably increases it, while neglecting it leads to its decay. However, it is also likely that building excess social capital within a group (bonding) can make it more difficult to establish social capital between groups (bridging) (Putnam, 2000). While seemingly immaterial, social capital cannot, of course, exist without people, human contact, and appropriate infrastructure, all of which require material inputs.

2.8. *Human capital*

Human capital consists of both quantity and quality of technology, knowledge and labor. As a

critical factor in the quality of labor, health is also a component of human capital. Production of any sort is impossible without labor and knowledge. Human capital in the form of acquired knowledge, skills and physical health further contributes to our SSW. An education, it has been said, makes your mind a better place to spend your leisure time. Skills and knowledge instill pride and status, and offer greater opportunities for less dangerous, more fulfilling employment. And few would deny that health plays an important role in SSW.

In GUMBO, human technology is represented simply as the overall stock of human knowledge. As such, human capital can depreciate if not used, or it can be stored in various formats. Each of these formats, of course, requires material and energy to create and maintain, and hence requires continual investment in order not to depreciate. Future generations must also be trained in how to access and use this stored information. In addition, as new knowledge accumulates, older knowledge often becomes obsolete, which is also a form of depreciation.

2.9. *Built capital*

Built capital and labor have traditionally received the greatest attention in economic analysis. No explanation is necessary concerning how built capital contributes to GWP and how it requires resources for creation and maintenance. While built capital also contributes directly to SSW (the sole purpose of any aesthetic architectural embellishments, for example), it may play a less important role than is often assumed (Frank, 1999). Built capital continues to play a major role, however, in the depletion of resources, and in the current economic system, ownership of built capital strongly influences the distribution of wealth. Of all the capitals, investment in built capital places the most demands on natural resources. Built capital depreciates by physically falling apart, or else as the result of new technologies making existing infrastructure obsolete.

All four types of capital, as well as energy, are required for the production of GWP and SSW

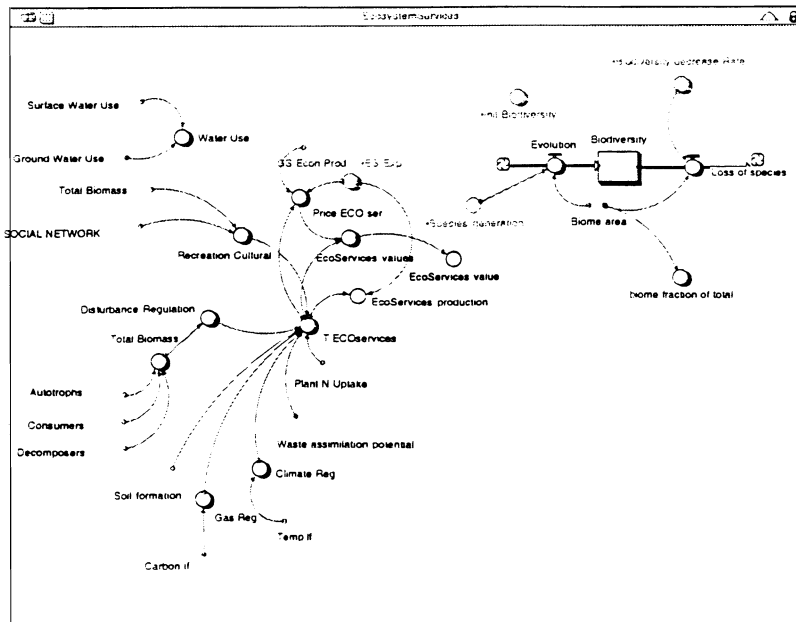


Fig. 7. STELLA diagram of the Ecosystems services sector.

within the anthroposphere even though they make different contributions to each. In GUMBO, accumulated waste reduces the output of both GWP and SSW. Consumption contributes to SSW. Human, social and built capital stocks spontaneously depreciate, while natural capital is renewable and has the potential for self-maintenance. Aggregated economic goods and services (GWP) can be invested in maintaining or creating any of the four capitals, or can be consumed. Investment in human, social or built capital requires a fixed amount of GWP and of raw materials, though it is possible to allow raw material demands to change with changing technology. Rates of investment in each type of capital are control variables in the model. Consumption depreciates instantly into waste, and social, human and built capital become waste as they depreciate over time. Waste absorption capacity is an ecosystem service, and if the flow of waste is greater than the absorption capacity, waste accumulates. Waste accumulation (i.e. pollution) directly affects the ability of natural capital to spontaneously reproduce, and can even cause it to spontaneously degrade. It also decreases production of GWP and SSW.

2.10. Ecosystem services

The 17 ecosystem services listed in Costanza et al. (1997a) have been aggregated somewhat in GUMBO and some were not included. Seven classes of ecosystem services are included in GUMBO (Fig. 7) and are briefly described below. A more complete classification and description of ecosystem services and functions is available in de Groot et al. (this volume). In what follows we briefly describe how each class of service is included in GUMBO.

2.10.1. Gas regulation

Gas regulation refers to the regulation of atmospheric chemical composition (Costanza et al., 1997a). In GUMBO, this ecosystem service is primarily associated with the changes in the global C cycle—exchanges of carbon within the biosphere and primary productivity of the biosphere terrestrial and ocean biomes. The exchange of C is simulated as processes such as terrestrial respiration, fossil fuel extraction, degassing, oceanic exchanges and consumption of organic matter. Together, these promote carbon inflow or outflow within the atmospheric C pool.

2.10.2. *Climate regulation*

This service is defined as the regulation of global temperature, precipitation, and other biologically mediated climatic processes at global or local levels (Costanza et al., 1997a). In GUMBO, climate regulation is associated with variations in global temperature from year to year. A global biome energy pool determines global average temperature. An inflow of solar radiation to the Earth and an outflow of radiation from the Earth to space controls this energy pool, and the energy pool is in turn affected by the extent of biome area, their albedo capacity and by the atmospheric C pool.

2.10.3. *Disturbance regulation*

This service is described as an ecosystem's capacitance, damping and resilience in response to environmental fluctuations (Costanza et al., 1997a). In the GUMBO model, it is measured as the biome's yearly change of total biomass (autotrophs, consumers and decomposers). The lower the variability in biomass, the greater the systems' disturbance regulation service.

2.10.4. *Soil formation*

Soil formation results from the weathering of rock material and of the accumulation of organic matter (de Groot et al., 2002). In GUMBO, the process of soil formation is closely related to rates of decomposition (Schlesinger, 1997), thereby accounting for different rates of organic matter accumulation in different biomes. As autotrophs and consumers die, a pool of dead organic matter accumulates, and from this pool a flux of soil formation is generated in each biome.

2.10.5. *Nutrient cycling*

This service refers to the storage, cycling, processing and acquisition of nutrients within the global system (Costanza et al., 1997a). In GUMBO, Nitrogen is used as a proxy for all other nutrients, and plant uptake of N serves as a proxy for nutrient cycling. Plant N uptake is represented as an inflow of nutrients into the soil nutrient pool associated with each biome's gross primary production, soil formation and biomass nutrient content. The soil nutrient pool also is influenced by atmospheric exchanges, weathering of rock material and fertilizer application.

2.10.6. *Waste assimilation*

This service refers to nature's ability to recover mobile nutrients, and remove or breakdown excess xenic nutrients and compounds (Costanza et al., 1997a). In GUMBO, this is modeled as the product of waste stock and either waste assimilation rate or waste assimilation potential—the model chooses the lowest value from the two. In each time step assimilation potential is represented as total assimilation capacity relative to the current amount of waste.

2.10.7. *Recreational and cultural*

These services hinge on an ecosystem's ability to provide for recreational activities such as ecotourism and sport fishing as well as cultural activities like worship and aesthetic appreciation (Costanza et al., 1997a). In the GUMBO model, recreational and cultural activities are positively related to total biomass amounts and the density of the social network, and negatively related to human population stocks. Hence, while the recreational and cultural activities service increases with increasing social network density and biomass, it decreases with increasing population.

2.11. *'Prices' of ecosystem services: marginal products as a measure of value*

While future versions of the GUMBO model will include a variety of methodologies for calculating ecosystem values,³ the current version cal-

³ For example, the 'simplest' approach to pricing ecosystem services in the model is to estimate prices externally and assume that they are constant over a model run. We can use the methods described in Costanza et al. (1997a), updated with new data and with user-controlled ranges on each of the prices. This allows users to see the implications of various constant ecosystem service prices on the value (price times quantity) of these services over time. A second method of pricing ecosystem services is based on ecological production input-output matrices as described in Patterson (2002) (this volume). At each time step in a run of the GUMBO model we export a production flow matrix and calculate the ecological production-based prices. The time series of these prices can then be compared with constant prices and with various policy scenarios in the model. Methods based on intertemporal optimization and shadow prices are discussed in the paper's conclusion.

culates the marginal product of ecosystem services in both the model's production and welfare functions. The rationale is simple. We calculate the impact of an incremental change in an ecosystem service on total output (either production of goods and services or of welfare). For example, if an additional unit of 'climate stability' (measured as reduced variability around a mean temperature) increases global output by \$3 million, then climate stability must be worth \$3 million per unit at the margin under current conditions. We will refer to these estimates of marginal product as ecosystem service prices. Conditions for calculating 'theoretically correct' prices using this approach include optimal allocation of all resources, no externalities, and no public goods. However, we are not interested in theoretical prices in some fictitious 'optimal' world, but rather in what the world would be willing to pay for an extra unit of that service under actual conditions in the current time period, given the existing allocation of other resources—and this is precisely what the marginal contribution of an ecosystem service to global production or social welfare tells us. In addition, GUMBO is a global model in which externalities and property rights (and hence the public good issue) are irrelevant with respect to prices. Further, within the model, we know resource stocks, and deterministic model equations are equivalent to complete knowledge concerning system-wide impacts of resource use. Hence, while the assumptions necessary for the marginal analysis approach to pricing rarely hold in the real world, they do approximately hold in the world of the GUMBO model (which is one of the main reasons for constructing the model in the first place).

Another important point is that the appropriate price for ecosystem services is the current time marginal product of the service, not including the value of the given service in future time periods. We make an important distinction between environmental goods that are produced from ecosystem structure and ecosystem services that result from ecosystem function. Without ecosystem structure there is, of course, no

ecosystem function, but the two components of natural capital have quite different physical and economic properties and must be treated separately. Ecosystem goods are in the form of stocks and flows: a stock of trees generates a flow of wood products, a stock of fish generates a flow of fish protein, and a stock of grass generates a flow of fodder. These goods are in general both rival (if one person benefits from the good, another cannot) and excludable (it is possible to exclude people from benefiting from them), and in the absence of negative externalities from their use, could be suitably allocated by market forces. Ecosystem services are in the form of funds and services: the stocks found in a forest (ecosystem structure) interact to generate the services of climate regulation, gas regulation and water regulation (ecosystem function). Services cannot accumulate into stocks or funds, so in calculating the price for a service, it would be a mistake to consider costs or benefits derived from that service in future periods. In the future we will use GUMBO to value both natural capital stocks and funds, and in this case will need to account for flows and services in future periods. Note also that most ecosystem services are both non-rival and non-excludable and hence they cannot be efficiently allocated by unregulated market forces. Waste absorption capacity is an important exception, as it is rival, and can be made excludable.

There are at least two specific ways of using the GUMBO model to calculate the marginal productivity of ecosystem services. The obvious approach is to take total first derivatives of the GWP and the SSW production functions with respect to the ecosystem service in question, which is the equivalent to the marginal product of the service. However, this constrains us to using continuously differentiable functions to model ecosystem processes, which may not be the best representation of reality. Instead, we prefer that state-of-the-art understanding of ecosystem processes, and not a specific methodology, drive the model. As an alternative, we can 'empirically' estimate the marginal product of each ecosystem service. We simply take the model output for each time step, freeze all variables but the one we wish

to price, and change this one by a small increment.⁴ The measured change in the value of the output will be equal to the price of the increment of the variable in question. With the latter approach, we are free to use the most appropriate function to model a particular process. In the current version of the model, we have taken the simpler approach of mathematically approximating first derivatives.

2.12. Land use

Eleven land (and water) use/cover types (or biomes) are included in GUMBO (Open Ocean, Coastal Ocean, Forests, Grasslands, Wetlands, Lakes/Rivers, Deserts, Tundra, Ice/rock, Croplands, and Urban). Land use changes in GUMBO (Fig. 8) are driven by human population and GWP changes (from the anthroposphere), constrained by the remaining area of each biome. Population is partitioned into urban and rural components.

2.13. Data base

A separate sector is included in GUMBO to store the calibration data for the model, convert units as necessary, and do other miscellaneous conversions (Fig. 9). Global data includes: average temperature, atmospheric CO₂ concentration, anthropogenic CO₂ production, average sea level, GWP, human population, oil production, fish harvest, food production, forest production, metals and minerals production, and land use for each of the 11 biomes. Our plan is to ultimately link the model to an integrated on-line data base that we are creating (see Villa et al., this volume), which will allow continuing recalibration and testing of the model.

2.14. Limitations and caveats

Like any model, GUMBO only represents a simplified description of the world and has the

⁴To do this efficiently, we would feed the output of the GUMBO model into another program designed specifically to carry out these calculations.

same general limitations shared by all global models. Because ‘simplification is the essence of model building’, there will always be issues that remain outside the purview of the model (Meadows and Meadows, 1975, p. 17). For example, we remain largely ignorant of precisely how ecosystem structure generates ecosystem services, and must instead rely on the best accepted and most plausible explanations present in the literature to model these complex relationships (see de Groot et al., this volume). Some of the changes important to GUMBO are characterized by pure uncertainty—we are ignorant not only of the probabilities of various outcomes, but we do not even know what outcomes are possible. This is particularly true for ecosystem evolution and for the invention of new

Data Base

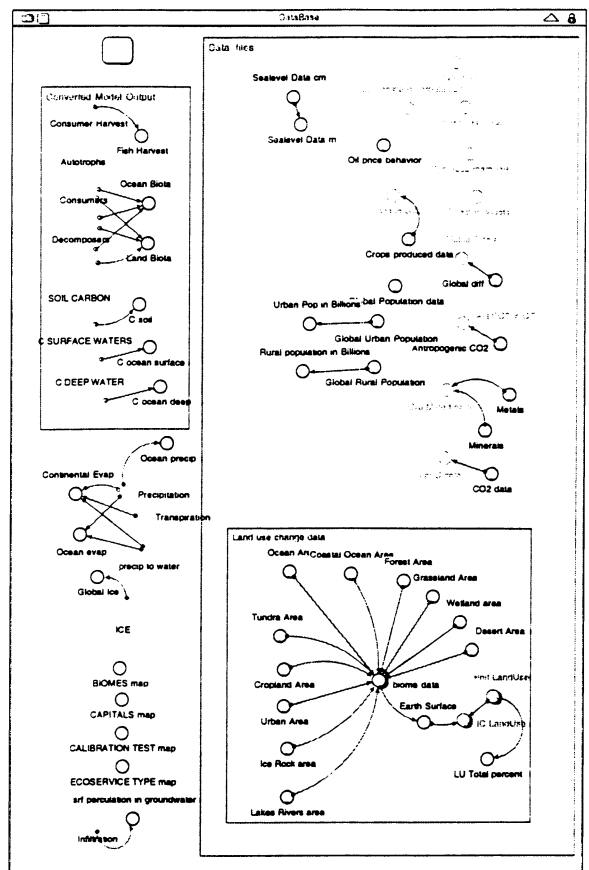


Fig. 9. STELLA diagram of the Data Base sector.

human technologies, both of which are critical factors determining the impact of human action on ecosystem services. As we describe later, these uncertainties are handled using alternative future scenarios that allow the implications of alternative assumptions to be explored. Another serious challenge involves investments in productive capacity within the economic sub-system. Most global models have greatly simplified economic production within the model by either leaving out price-investment feedback loops (Meadows et al., 1972, 1992), or by treating economic production as exogenous to the system (Rotmans and de Vries, 1997). In GUMBO, relative rates of investment are currently treated as exogenous control variables manipulated by the model user. In addition, the functional forms we have chosen for both the GWP and SSW functions (see Section 2.5) are relatively simplistic and the variable coefficients are somewhat subjective. However, a major strength of the GUMBO model is that users can readily manipulate these functions and variables and observe the resulting impacts on the model output.

3. Results

In this section, we describe both the preliminary calibration results for the model and the results of a series of scenarios. These results are summarized in Figs. 10–15. The model was run starting in 1900 for 200 years at a time step of 1 year. Each figure shows a selection of related variables over the historical period from 1900 to 2000, and continuing over the future period from 2000 to 2100. Time series of available calibration data are plotted on the appropriate figures for direct visual comparison with the model results. One can see from inspection of these figures that the model has been calibrated to agree quite well with the full range of available historical data, including land use, global temperature, atmospheric CO₂, sea level, fossil fuel extraction, human population, and GWP. It should be noted that these results are not ‘forced’ in any way by exogenous variables, but are the results of the internal dynamics of the model. Because it is an integrated global

model, all the variables are endogenous except solar energy inputs, which are assumed in this version to be constant over time.

Table 2 shows the results of some statistical tests of the fit between the model and the data. We had quantitative time-series data on a total of 14 variables. For each variable, Table 2 shows the results of a linear regression with the GUMBO model as the independent variable and data series as the dependent variable. Table 2 shows the R^2 , F value for the regression equation, degree of freedom (model, data), intercept (\pm S.D.) and slope (\pm S.D.). The R^2 values for all 14 variables are very high, ranging from 0.64 for global temperature to 0.98 for human population, GWP, and forest area. The average R^2 over the 14 variables was 0.922. All F values for the regressions were highly significant ($P < 0.0001$), indicating that the model explained a significant amount of the variation in the data. But the regression equations do not check that the relative magnitudes of the model and data match. In terms of the regression equations, the slope should be equal to 1 and the intercept equal to 0. We used the method suggested by Dent and Blackie (DBK, Dent and Blackie, 1979) to test the joint hypothesis that the regression’s slope is statistically indistinguishable from 1 and the intercept is statistically indistinguishable from zero. Table 2 reports the F values, respective significance levels (***) indicates $P < 0.0001$) and associated degrees of freedom (model, data) for this test. Eight of the 14 variables passed this rather severe test of the model’s fit with the data, and one can see from inspection of Table 2 that the other six variables have slopes and intercepts that, while not statistically indistinguishable from 1 and zero, are still rather close.

Overall, we can conclude that the model fits the (limited) available quantitative time-series data extremely well. But what about the variables for which we do not have quantitative time-series data? We used more qualitative assessments of these variables, insuring that their behavior was at least consistent with any limited quantitative data we had, along with our best guesses of the real behavior. Also, since GUMBO is a systems model, rather than a statistical model, all the

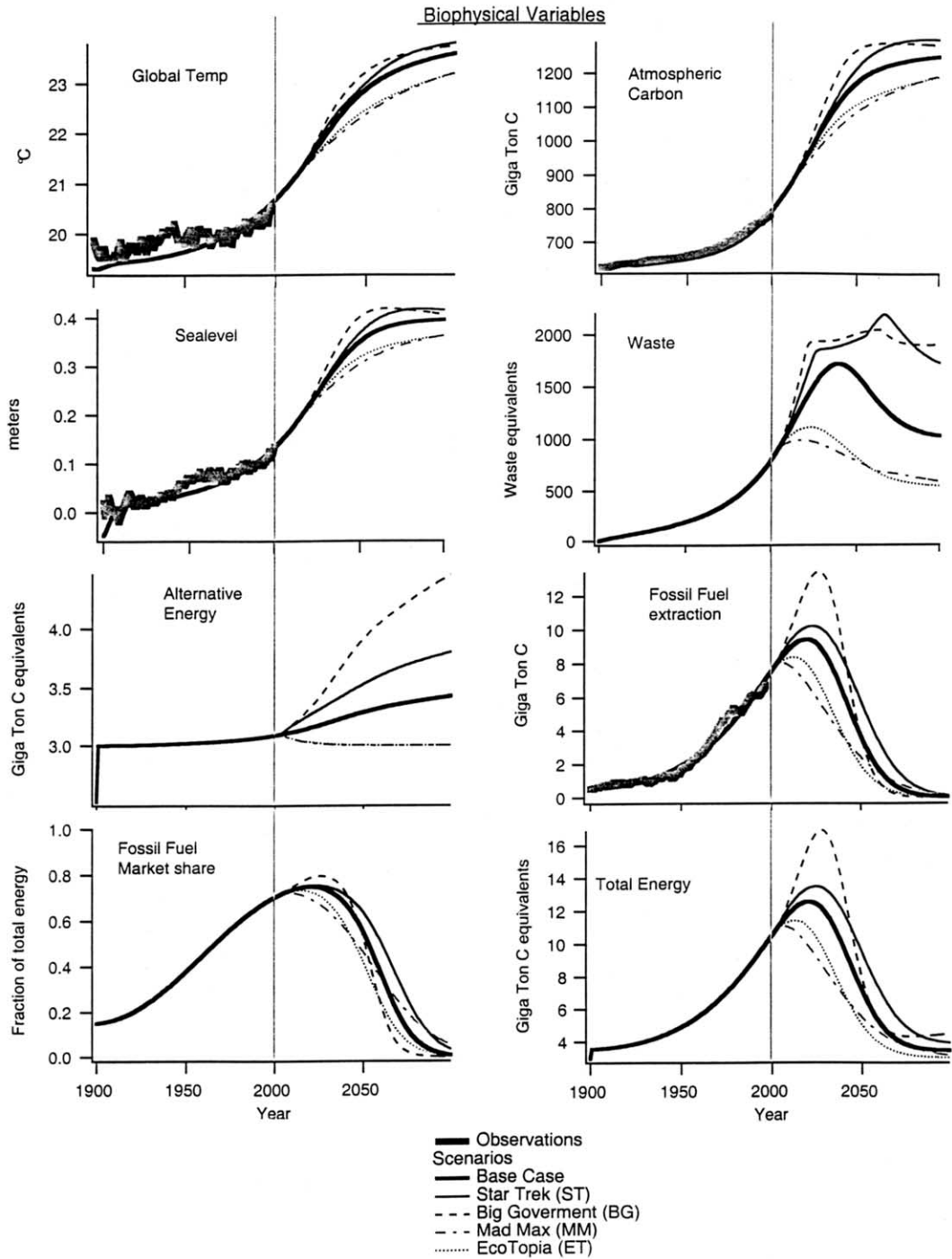


Fig. 10. Selected biophysical variables in GUMBO. All plots show the base case calibration and observations (if available) from 1900 to 2000, and the five scenarios listed in the legend for 2000–2100.

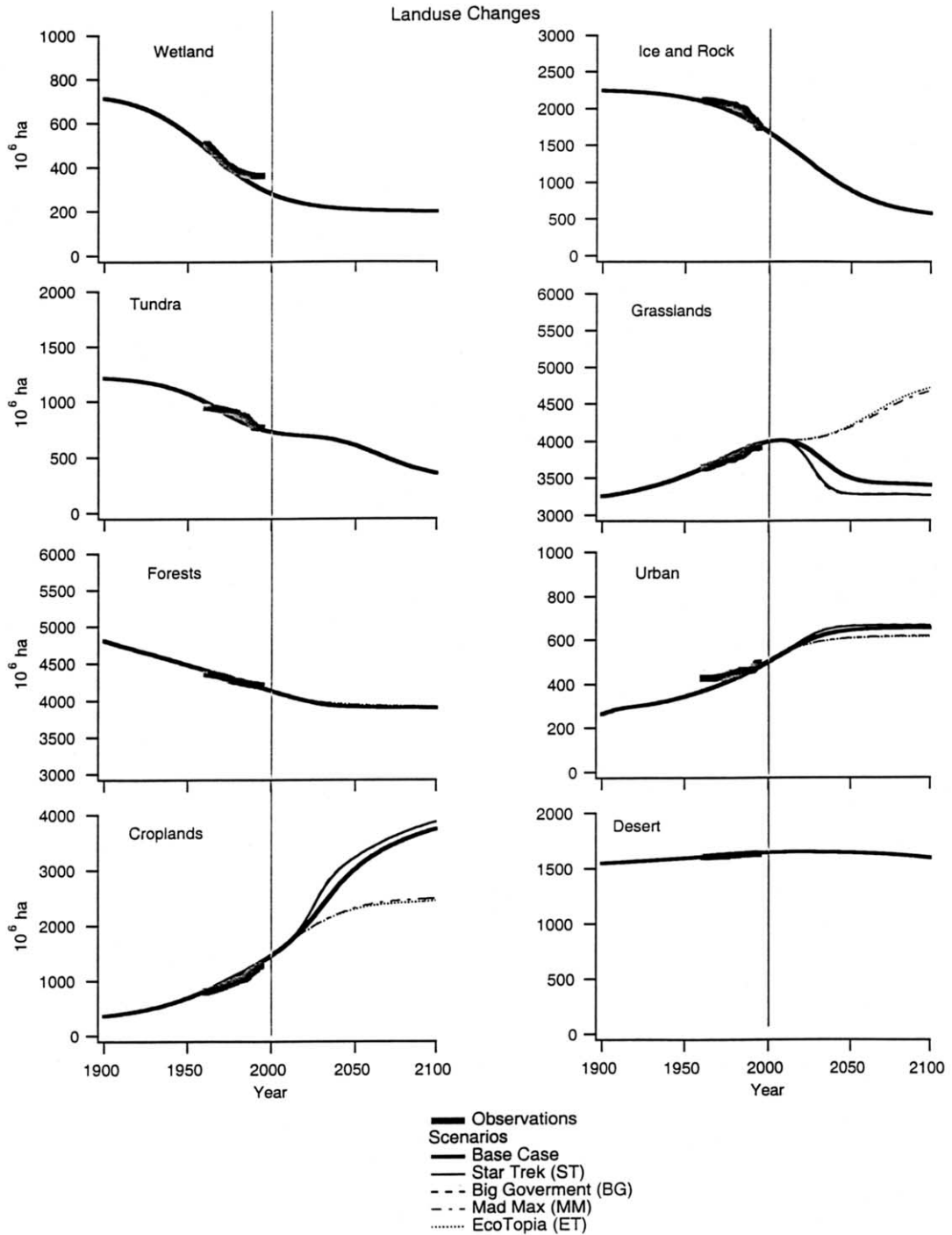


Fig. 11. Selected land use variables in GUMBO. All plots show the base case calibration and observations (if available) from 1900 to 2000, and the five scenarios listed in the legend for 2000–2100.

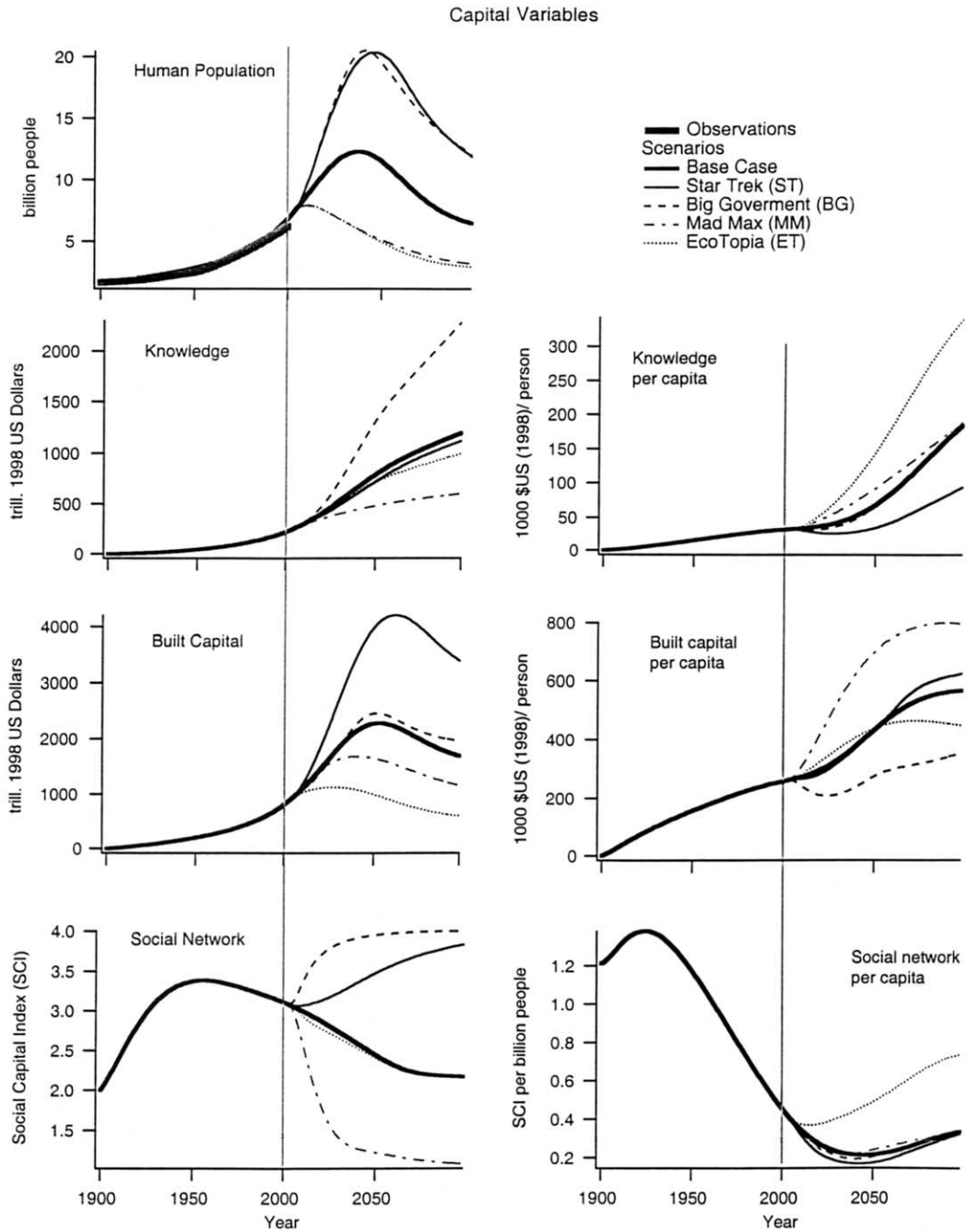


Fig. 12. Selected capital variables in GUMBO. All plots show the base case calibration and observations (if available) from 1900 to 2000, and the five scenarios listed in the legend for 2000–2100.

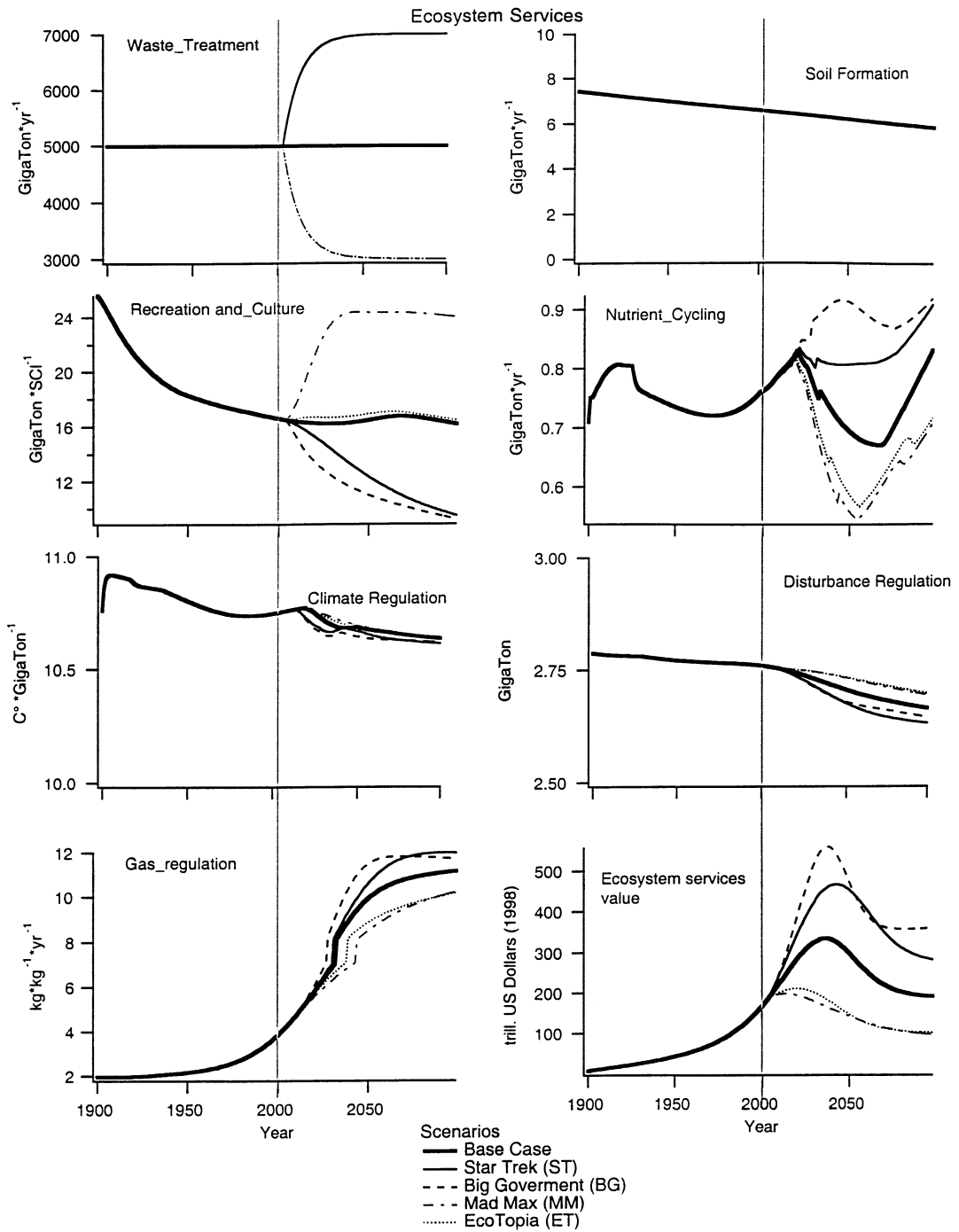


Fig. 13. Selected ecosystem services variables in GUMBO. All plots show the base case from 1900 to 2000, and the five scenarios listed in the legend for 2000–2100. All plots are physical measures except ecosystem services value, which is the sum of the physical measures multiplied by prices in Fig. 14.

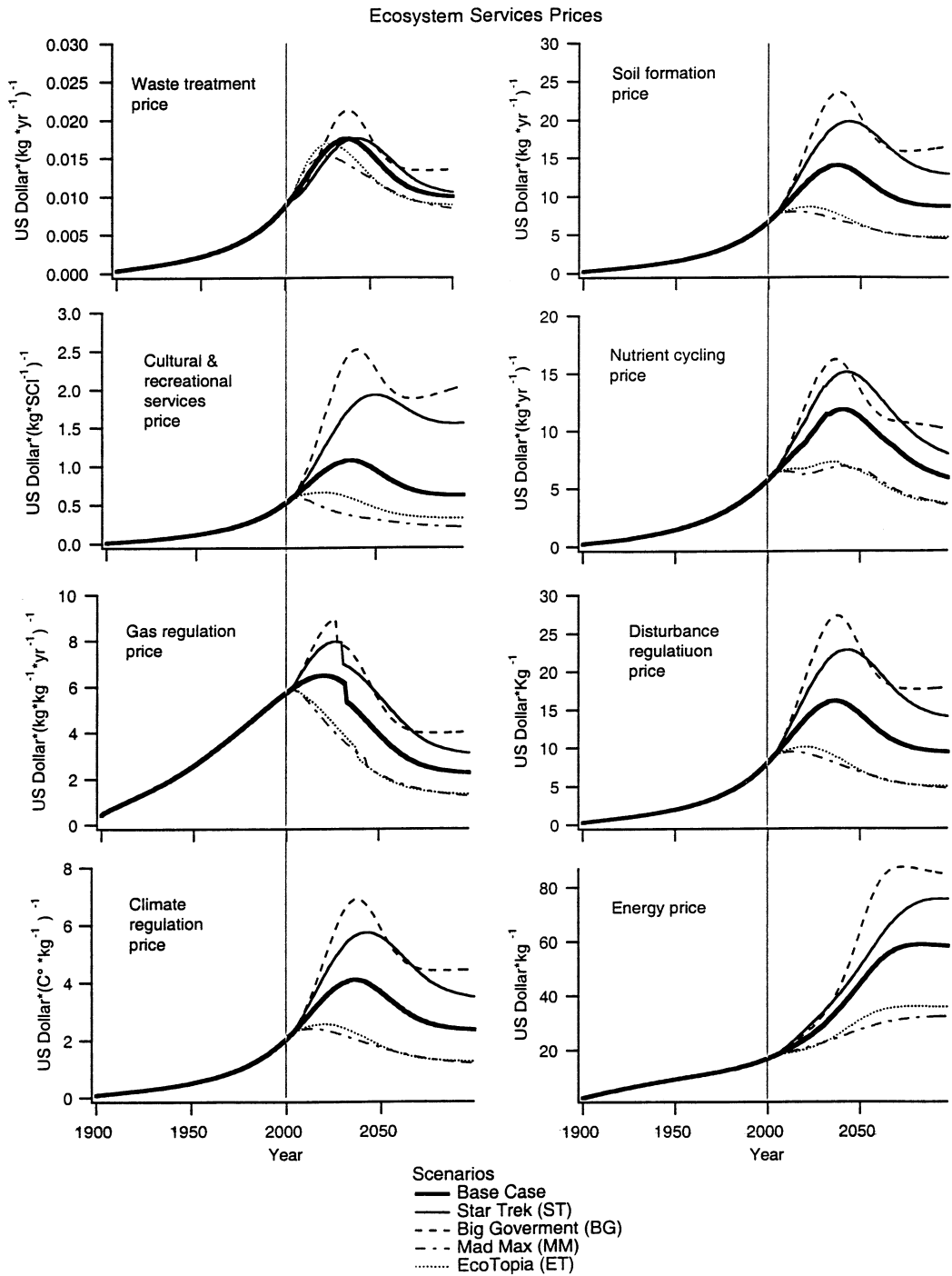


Fig. 14. Ecosystem services prices in GUMBO. All plots show the base case from 1900 to 2000, and the five scenarios listed in the legend for 2000–2100.

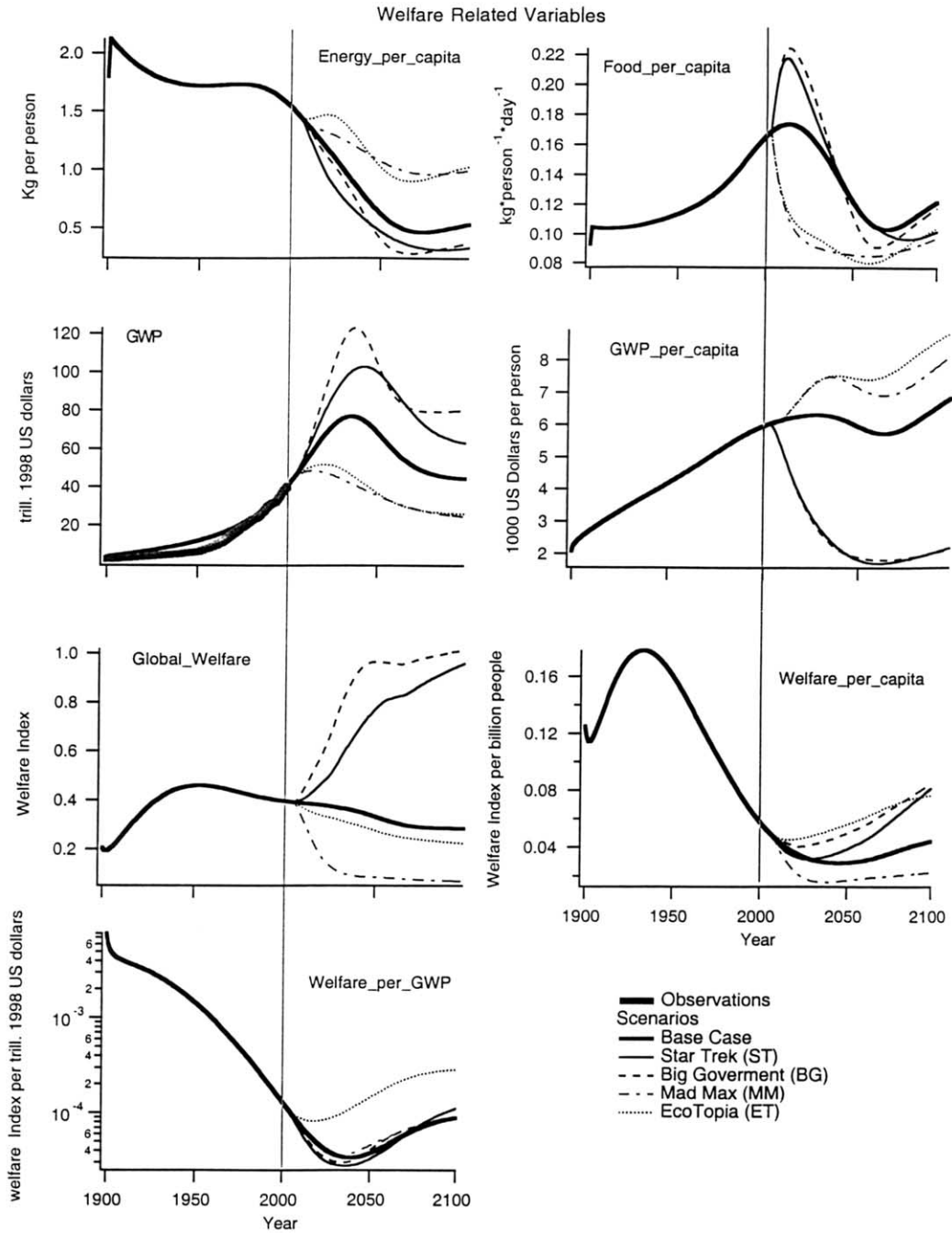


Fig. 15. Selected welfare related variables in GUMBO. All plots show the base case calibration and observations (if available) from 1900 to 2000, and the five scenarios listed in the legend for 2000–2100.

Table 2

Results of regression and Dent and Blackie (DBK) tests for the 14 model variables for which historical data were available

Fitted variable	R^2	Regression				DBK test	
		F (regression)	DOF	Intercept \pm S.D.	Slope \pm S.D.	F (DBK)	DOF
1. Forest area	0.98	2061.2	1,33	-988 ± 116	1.2 ± 0.03	1.851	2,32
2. Grassland area	0.97	1035.1	1,33	-216 ± 125	1.1 ± 0.03	0.984	2,32
3. Wetland area	0.93	437.7	1,33	-92 ± 23	1.2 ± 0.06	0.978	2,32
4. Desert area	0.95	6022.1	1,33	-148 ± 72	1.1 ± 0.04	26.239***	2,32
5. Tundra area	0.88	236.7	1,33	-106 ± 63	1.1 ± 0.07	0.036	2,32
6. Ice rock area	0.92	365.1	1,33	182 ± 92	0.9 ± 0.05	0.051	2,32
7. Cropland area	0.97	1085.0	1,33	8.8 ± 33	1.1 ± 0.03	0.230	2,32
8. Urban area	0.92	413.1	1,33	-297 ± 35	1.6 ± 0.08	19.251***	2,32
9. Atmospheric carbon	0.98	6873.0	1,99	5 ± 8	1.0 ± 0.01	5.583***	2,98
10. Fossil fuel prod.	0.98	4319.9	1,97	0.045 ± 0.048	1.0 ± 0.01	105 401.000***	2,96
11. Global temperature	0.64	179.7	1,98	-5.3 ± 1.9	1.2 ± 0.09	8092.000***	2,97
12. Sea level	0.83	488.7	1,100	-0.01 ± 0.003	1.0 ± 0.04	151 686.000***	2,99
13. Human population	0.98	126597.6	1,100	0.14 ± 0.03	1.0 ± 0.01	7827.550***	2,99
14. Gross World Product	0.98	5459.2	1,100	4.09 ± 0.20	0.9 ± 0.01	109.041***	2,99

For each variable, the regression results are reported first: R^2 , F value for the regression, degrees of freedom (model, data), intercept, and slope (\pm S.D.). All F values for the regressions were highly significant. For the DBK test, the F value (***) indicates highly significant), followed by the degrees of freedom (model, data) are given. See text for more details.

variables are interdependent. Calibrations for any variable affect all the other variables, and this imposes an overall consistency check on the model.

As far as model ‘validation’ is concerned, we plan to assemble additional time-series data for variables in the model other than the 14 reported in Table 2. We can then test the fit of the model to these variables before any additional calibration is performed as a validity check.

3.1. Scenarios

A series of five scenarios are also plotted on Figs. 10–15. These scenarios include a base case (using the ‘best fit’ values of the model parameters over the historical period) and four alternative scenarios. These four alternatives are the result of two variations (a technologically optimistic and a skeptical set) concerning assumptions about key parameters in the model, arrayed against two variations (a technologically optimistic and a skeptical set) of policy settings concerning the rates of investment in the four types of capital (natural, social, human, and built). They correspond to the four scenarios laid out in Costanza (2000). These

assumptions and policies are laid out in Table 3. If one pursues a set of technologically optimistic policies (higher rates of consumption and investment in built capital, lower investment in human, social and natural capital) and the real state of the world corresponds to the optimistic parameter assumption set (new alternative energy comes on line, etc.) then one ends up in the ‘Star Trek’ (ST) scenario. If one pursues technologically optimistic policies and the real state of the world corresponds to the skeptical parameter assumption set (no new energy forms come on line, etc.) then one ends up in the ‘Mad Max’ (MM) scenario. If one pursues a set of technologically skeptical policies (lower rates of consumption and investment in built capital, higher rates of investment in human, social and natural capital) and the real state of the world corresponds to the optimistic parameter assumption set then one ends up in the ‘Big Government’ (BG) scenario. Finally, if one pursues technologically skeptical policies and the real state of the world corresponds to the skeptical parameter assumption set then one ends up in the ‘EcoTopia’ (ET) scenario.

In the model, the new parameter sets are brought on line gradually (at a user determined rate) start-

Table 3
Parameters reflecting assumptions about how the world works and investment policies for the baseline (neutral) and four alternative scenarios

State of the world assumptions: Parameter name	Neutral		Optimistic		Skeptical		Optimistic		Description
	Baseline	Big Government	Eco-Topia	Mad Max	Star Trek				
<i>Ecosystem health and human population</i>									
Healthcare factor	0.002	0.003	0.001	0.001	0.003	0.001	0.001	0.003	Effect of developments in medical science on mortality
Max healthcare effect	0.01	0.003	-0.01	-0.01	0.03	-0.01	-0.01	0.03	Maximum that can be achieved in reduction of mortality
Waste carrying capacity	80 000	100 000	60 000	60 000	10 0000	60 000	60 000	10 0000	Threshold amount of waste that will be fatal to all human beings
Knowledge vs. fertility	0.001	0.002	0	0	0.002	0	0	0.002	Effect that knowledge has on the human fertility rate
Fertility know. max	0.03	0.04	0.02	0.02	0.04	0.02	0.02	0.04	Maximum effect of knowledge on the fertility rate
<i>Waste treatment Params</i>									
Assimilation capacity	5000	7000	3000	3000	7000	3000	3000	7000	Amount of waste that will surpass the earth's waste assimilation capacity
Effect of NCF on waste	0.5	0.1	0.9	0.9	0.1	0.9	0.9	0.1	Effect of natural capital formation on waste assimilation effectiveness
<i>Unknowns about our energy reserves</i>									
Time switch	2100	2003	2003	2003	2003	2003	2003	2003	Time when new energy sources will start to come on line
Accessible oil	700	800	600	600	800	600	600	800	Ultimately recoverable fossil fuel
Max unknown alt energy	2	4	0	0	4	0	0	4	Maximum of new (currently unknown) energy available
Energy switch rate	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	Rate of change to new alternative energy source
<i>Did technology cause a decline in social capital</i>									
Knowledge SC effect	0.0002	0	0.0004	0.0004	0	0.0004	0.0004	0	Effect of new knowledge on social capital
<i>Developments in meat and fish production</i>									
<i>Ocean</i>									
Max energy effect on con harvest	0.04	0.06	0.02	0.02	0.06	0.02	0.02	0.06	Maximum percentage of fish that can be harvested from the ocean
Energy effect on con harvest	0.003	0.006	0	0	0.006	0	0	0.006	Effect of energy on the efficiency with which fish can be harvested from the ocean
<i>Coastal ocean</i>									
Max energy effect on con harvest	0.04	0.06	0.02	0.02	0.06	0.02	0.02	0.06	Maximum percentage of fish that can be harvested from the coastal ocean
Energy effect on con harvest	0.003	0.006	0	0	0.006	0	0	0.006	Effect of energy on the efficiency with which fish can be harvested from the coastal ocean
<i>Grasslands</i>									
Max energy effect on con harvest	0.02	0.025	0.015	0.015	0.025	0.015	0.015	0.025	Maximum percentage of animals that can be harvested from the grasslands
Energy effect on con harvest	0.04	0.07	0.01	0.01	0.07	0.01	0.01	0.07	Effect of energy on the efficiency with which animals can be harvested from the grasslands

Table 3 (continued)

State of the world assumptions: Parameter name	Neutral Baseline	Optimistic Big Government	Skeptical Eco-Topia	Skeptical Mad Max	Optimistic Star Trek	Description
<i>Agricultural developments in croplands</i>						
Energy effect on plant harvest [Cr]	0.25	0.3	0.2			Effect of energy on the efficiency with which crops can be harvested
Max energy effect on plant harvest [Cr]	0.7	0.9	0.5			Maximum potential percentage of crops that can be harvested
Effect of know-how on Chlo conc [Cr]	0.03	0.04	0.02			Ability of the agricultural sciences to increase crop production per acre
Max know on Chl effect [Cr]	0.02	0.03	0.01			Maximum achievable crop production per unit area
<i>Policies</i>						
Parameter name	Neutral Baseline	Skeptical Big Government	Skeptical EcoTopia	Optimistic Mad Max	Optimistic Star Trek	
<i>Savings rates</i>						
Human capital	0.016	0.022	0.022	0.01	0.01	
Social capital	0.16	0.18	0.46	0.05	0.02	Social capital savings rate is dependent on human population densities
Built capital	0.15	0.1	0.1	0.2	0.2	
Natural capital	0.15	0.3	0.3	0	0	
Consumption	0.52	0.40	0.12	0.74	0.77	

Each alternative scenario represents a combination of either optimistic or skeptical assumptions about how the world works, with either optimistic or skeptical patterns of investment in the four types of capital. For example, the ‘Big Government’ scenario combines optimistic state of the world assumptions with skeptical investment policies, while ‘Star Trek’ combines optimistic state of the world assumptions with optimistic investment policies.

ing at a user determined date. For this set of scenario runs, the start date was 2003 and the rate of introduction was 10% per year.

The GUMBO model contains 234 state variables, 930 variables total, and 1715 parameters. Figs. 10–15 show a small subset of some of the more interesting and relevant output. Fig. 10 shows some of the key biophysical variables, including average global temperature, atmospheric carbon, sea level, and fossil fuel extraction. All of these reproduce historical behavior extremely well. The base case projection for global temperature in 2100 is about 3.5 °C above the current temperature, consistent with the latest IPCC projections. In general, the ST and BG scenarios lead to higher global temperatures, CO₂, sea level, waste, and fossil fuel extraction than the base case, while ET and MM are generally lower than the base case in these same variables. The alternative energy plot is a key one. Alternative energy includes all alternatives to fossil fuel, including renewable energy sources such as solar, wind, and biomass, but also any as yet undiscovered or unperfected energy sources such as nuclear fusion (hot or cold) or very advanced solar collectors. The ST and BG scenarios assume that alternative energy is a huge new resource that comes on line fairly quickly after 2003, while the ET and BG scenarios assume that alternative energy is limited to the currently known renewable alternatives and that their supply is ultimately somewhat limited. Total energy is the sum of fossil and alternative energy. The BG scenario assumes higher rates of investment in knowledge creation (i.e. through research and development) and thus leads to higher alternative and total energy than the ST scenario.

Fig. 11 shows land use for eight of the 11 biomes (lakes/streams, open ocean, and coastal ocean areas do not change significantly). Data sets are from FAO for the period from 1961 to 1994. The model calibrates quite well to historical land use changes at the global level, with only grasslands, croplands, and urban showing significant differences between the five scenarios. Grasslands are highest in MM and ET because they are converted to croplands at a much lower rate. Croplands are correspondingly higher in BG and ST and lower in ET and MM than the base case. Urban is slightly higher than the base

case in BG and ST, and slightly lower in ET and MM.

Fig. 12 shows types of human-made capital, including human population and knowledge (together forming human capital), built capital, and social capital (as measured by the strength of social networks). The human population is significantly higher in both ST and BG, peaking at about 20 billion. Population declines in all scenarios are a result of decreasing human fertility which is linked to increased knowledge, not to increasing mortality (Lutz et al., 2001). ST and MM peak at about 7 billion, while the base case peaks at about 12 billion. Knowledge is highest in BG (due to increased investment in government supported R&D) and lowest in MM. But knowledge per capita is highest in ET and lowest in ST, due to the relative rates of change in population and knowledge in these scenarios. Built capital is highest in ST and lowest in ET, but built capital per capita is highest in MM, intermediate in ET, and lowest in BG. Social capital is highest in BG and lowest in MM, with ET not very different than the base case. But social capital per capita is significantly higher in ET than in the other scenarios due to increased investment in social capital and lower population.

Fig. 13 shows the seven ecosystem services included in the model in physical units, and the total value of all ecosystem services (prices times quantities). The value of global ecosystem services based on this approach are shown to be about 180 Trillion \$US in the year 2000. This compares to a GWP of about 40 Trillion \$US in the year 2000 (Fig. 15), indicating that ecosystem services are about 4.5 times as valuable as GWP in the model in the year 2000. This compares to a factor of about 1.8 estimated using static, partial, analysis in Costanza et al. (1997a). In all of the future scenarios, the value of ecosystem services and GWP roughly parallel each other. Ecosystem services are estimated to be most valuable in ST and BG, due to larger populations and greater relative scarcity, as is evident from the increased prices of the services (as measured by their marginal products), which are shown in Fig. 14.

Fig. 15 shows welfare-related variables. GWP is highest for ST and BG and lowest for ET and MM. But GWP per capita is highest for ET and lowest for ST. The situation for total welfare and welfare

per capita is similar, but in these cases MM is significantly lower than the other scenarios in both total welfare and welfare per capita. An interesting measure of economic efficiency we have calculated in the model is welfare per GWP, based on the idea that a really efficient economy would produce the maximum amount of welfare for the minimum GWP, rather than simple maximizing GWP. According to this measure, ET performs much better than any of the other scenarios or the base case.

4. Discussion and conclusions

As stated earlier, our main objective in creating the GUMBO model was not to accurately predict the future, but to provide simulation capabilities and a knowledge base to facilitate integrated participation in modeling. We created a computational and data base framework to aid in the discussion and design of a sustainable future that includes the dynamics of human well-being. It should be noted that this is ‘version 1.0’ of the model. It will undergo substantial changes and improvements as we continue to develop it, and the conclusions offered here can only be thought of as ‘preliminary’. Nevertheless, we can reach some important conclusions from the work so far, including:

- To our knowledge, no other global models have yet achieved the level of dynamic integration between the biophysical earth system and the human socioeconomic system incorporated in GUMBO. This is an important first step.
- Preliminary calibration results across a broad range of variables show very good agreement with historical data. This builds confidence in the model and also constrains future scenarios. We produced a range of scenarios that represent what we thought were reasonable rates of change of key parameters and investment policies, and these bracketed a range of future possibilities that can serve as a basis for further discussions, assessments, and improvements. Users are free to change these parameters further and observe the results.
- Assessing global sustainability can only be done using a dynamic integrated model of the

type we have created in GUMBO. But one is still left with decisions about *what* to sustain (i.e. GWP, welfare, welfare per capita, etc.) GUMBO allows these decisions to be made explicitly and in the context of the complex world system. It allows both desirable and sustainable futures to be examined.

- Ecosystem services are highly integrated into the model, both in terms of the biophysical functioning of the earth system and in the provision of human welfare. Both their physical and value dynamics are shown to be quite complex.
- The overall value of ecosystem services, in terms of their relative contribution to both the production and welfare functions, is shown to be significantly higher than GWP (4.5 times in this preliminary version of the model).
- ‘Technologically skeptical’ investment policies are shown to have the best chance (given uncertainty about key parameters) of achieving high and sustainable welfare per capita. This means increased relative rates of investment in knowledge, social capital, and natural capital, and reduced relative rates of consumption and investment in built capital.

5. Future work

In future iterations, we will use GUMBO to calculate the ‘shadow prices’ of ecological resources based on ‘optimal’ (rather than ‘actual’) levels of resource use. Shadow prices account for the future goods and services generated by an additional increment of capital today. In contrast to ecosystem services, which cannot accumulate over time, the value of a natural capital stock is determined by the value of the flows of ecosystem goods and services it generates through time. The same is obviously true for the other forms of capital: for example, the value of a factory is equal to the value of the widgets it will produce through time, discounted by the opportunity cost of financial capital. Natural capital generates both market and non-market goods, but in the GUMBO model these contribute to human welfare just as concretely as widgets, albeit through more numerous paths. Renewable natural

capital is unique in that its capacity to regenerate is determined in part by the current stock, so the marginal value of the stock must also account for the additional stock that will regenerate from the additional incremental unit. In the GUMBO model and in reality, if renewable natural capital stocks fall below a certain level, they risk hitting an ecological threshold of spontaneous decline. Ideally, the value of an incremental unit of forest stock should include the reduced risk of reaching this threshold (see Limburg et al., 2002, this volume). In the real world, of course, we do not know where such thresholds lie.

The basic problem in this case is to maximize the equation

$$ISW = \int_0^{\infty} SSW(HK(t), SK(t), BK(t), NK(t)) e^{-\delta t} dt$$

where ISW is intergenerational sustainable welfare, (SSW(\cdot)) is the sustainable social welfare function from the GUMBO model, and δ is the discount rate, which will be discussed in greater detail below. An analogous equation applies to the production of goods and services. In both cases, of course, the maximization must be done subject to the laws of motion for all arguments of SSW(\cdot). The solution to this problem provides us with the time path for optimal resource use, from which it would be quite simple to calculate marginal productivity of ecological resources and hence values.

The enormous number of variables in the GUMBO model (and in the real world) make it impractical, if not impossible, to use analytical techniques to solve for an optimum. In addition, with so many variables it is virtually certain that there are many local optima for the model, and seeking a global optimum would probably be both futile and pointless. We are in the process of developing programs that will be able to find a number of optima in the GUMBO model for very long time horizons, and calculate shadow prices for each of these optima. Obviously, different local optima are likely to produce different prices and values for ecological resources, so we will present prices as a range, not as an exact number.

Dynamic optimization problems with infinite time horizons are notoriously sensitive to the choice of a discount rate, yet there is little consensus on a ‘correct’ rate, or even whether discounting is appropriate for intergenerational analysis. For example, in analyses of global warming, Cline (1992) argues for a rate in the region of 1.5%, while a study by Nordhaus (1994) uses 6%⁵ Solow admits that discount rates may not be appropriate for intergenerational issues (Solow, 1974). Indeed, a commonly heard justification for positive discount rates is that they are a ‘mathematical necessity’ (e.g. Arrow et al., 2000, p. 1402; citing Koopmans). This is a case of the methodology determining the problem instead of vice versa.

The typical justification for intertemporal discounting is the marginal opportunity cost of capital. While this certainly makes sense at the scale of a businessman considering a 20-year investment, scaling issues arise when extrapolating this rationale to a global, infinite time horizon model. For a small-scale investment the relevant discount rate is the marginal opportunity cost of capital. Presumably, however, the opportunity cost of money changes depending on the level of investment. In the GUMBO model, we are looking at all investments. Therefore, we are concerned with the average opportunity cost of capital, not simply the marginal opportunity cost. Further, we are examining all capital types and not just financial capital. Thus, the relevant discount rate for a given year relative to the previous year should be the average opportunity cost of total capital, which is essentially the rate of growth of the entire system.

It certainly makes sense that growth rates form the basis for intertemporal discounting. Financial capital only provides returns because it can be invested to generate more production in the future. Financial capital has no value itself, but simply entitles someone to a share of the real wealth. If financial capital received positive returns, but there was no growth in production of goods and services, then there would simply be more money chasing the same amount of goods

⁵ Though in the Nordhaus model the rate drops to 3% in the future.

(i.e. inflation) or else there would have to a redistribution of real wealth towards the holders of financial capital. In fact, a richer future combined with the diminishing marginal value of wealth is another frequent justification for discounting.

What happens then when we look at an infinite time horizon? The appropriate discount rate over time is the average rate of growth of total capital over time. The GUMBO model is based on a finite planet in which infinite material growth is impossible. Eventually, therefore, we must either approach some sort of steady state, in which the growth rate becomes zero, or else experience negative growth. Unless we experience negative growth rates in the future, the average rate of growth will only asymptotically approach zero as time approaches infinity. If we allow δ to change through time and set it equal to the average growth rate of the system, as long as a future generation is better off than the present one, values in that generation will be appropriately discounted. If the growth in the future becomes negative for long enough that the future is worse off than the present, then this approach would allow future generations to receive a greater weight than the present one.

This is a radical departure from traditional approaches to discounting, and is not compatible with typical dynamic optimization models. However, this approach is driven by theory and the sense of ethical obligations to future generations, and not by the demands of a particular methodology. An appropriate discount rate outlined here will not impose such unacceptable costs. The GUMBO model specifically includes investment and output (of both goods and services and welfare) and thus allows us to calculate the actual average opportunity cost for total capital, both within and between time periods. Thus, we can endogenously calculate the appropriate discount rate in the GUMBO model. We will use GUMBO to test the hypothesis that an intertemporal discount rate based on the average rate of growth of the system guarantees sustain-

ability, and that discount rates higher than that will cause the system to crash.

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