The COSMOPAD modelling framework: Conceptual System Dynamics Model of Planetary Agricultural & Biomass Development*

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1. Abstract

COSMOPAD is a conceptual system dynamic model of planetary agricultural and biomass development. Originally intended to be the “agriculture and food module” of a conceptual integrated world model created to be the successor of WORLD III, the model has been worked out as a stand alone module or holon. The aim of the modelling effort was to create a model for generating insight in human induced worldwide biomass production and its effects, mainly from a sustainable development point of view, without cluttering the model’s users with to much detail. This line of reasoning led to the development of a strongly aggregated model. The resulting simplicity of COSMOPAD allows for relatively straightforward collection of and integration with data, easier interpretation of results and offers a lot of possibilities for functioning within other models. As a matter of fact COSMOPAD still fits seamlessly within the Insight for TERRA model. A disadvantage of this high level approach is that the only policies that can be evaluated are conceptual “meta-policies”.

In the first section of this paper the structure of COSMOPAD is discussed along with the issues for and the context in which it was originally meant to be applied.

In a second section the data used to populate the model variables and equations are extensively elaborated upon.

A third section shows some simulation results for different future scenarios in which the impact of different agricultural policies are assessed. The time horizon for these simulations is 2030.

In the next section the simulation results, their validity as well as that of the model are discussed and based on those simulation results some early ideas for alternative more sustainable agricultural meta-policies formulated.

The fifth and final section of this paper is concerned with further applications of the model as it exists and possibilities for its extension. An initial roadmap leading to the construction of a regionalized model is set up, as well as blueprints for some additional modules for COSMOPAD dealing with fisheries, aquaculture and forest-management more specifically.

2. **Content**

3. Introduction

The origins of the COSMOPAD modelling framework lie within the EU funded TERRA project. The TERRA projects goals included assessing the impact on all aspects of society of ISTs[1] and – more generally speaking – of the roll-out of the GNKS[2]. COSMOPAD was initially intended to function as a sub-model of the integrated Insight for TERRA model[3], the sub-model was however developed using a holonic approach and can therefore function as a stand alone model. The COSMOPAD model is intended to help analyse the impact on the requirements for sustaining the agricultural sector and on global land usage, by the meshed effects of population growth, ICT induced productivity growth, economic development, and trends in the demand for cultivated biomass for industrial and food consumption purposes. At this point fisheries have been omitted from the considerations of this model[4].

COSMOPAD is a System Dynamics model developed using the VENSIM 4.2a System Dynamics modelling platform. It is a multi-view model that spans more than 200 variables and equations which are available by the authors.

COSMOPAD is a conceptual model in the sense that it helps to understand how the systemic properties of the global agricultural system, combined with a selected set of parameters reflecting policy orientations, affect the general sustainability of the agricultural sector. In other terms, the aim of the model is not to do exact predictions about the future, but rather to gain insight in the relationships between different aspects of interest of the system. This approach has the advantage that a limited set of precise data is needed to calibrate the initial values of the model-variables. Reasonable assumptions about the actual values of essential model variables, and data-based insights in the current trends, are sufficient to proceed into meaningful simulation runs.

Using the model and the initial data a number of scenarios covering the 2000 to 2030 time span will be developed. The aims of these activities can be split up into a number of concrete issues:

1. Checking the consistency of a number of assumptions about evolutions by integrating them in one model
2. Formulating a set of visions about the future
3. Identifying data needed for the more quantitative policy model
4. A first exploration of possible (meta-)policy options.

[1] Information Society Technologies
[2] Global Networked Knowledge Society
[3] See “The Insight for TERRA modelling framework” and “The Insight for TERRA model” by Tom Tesch, Raoul Weiler, et al. (2003).
[4] Fisheries are currently still considered within the eco-system sub-model, reflecting the idea that the fishery-induced problems are mostly related to the loss of biodiversity.

4. Structure of the COSMOPAD Model

In this chapter the overall structure of the model is discussed from a general perspective, without digging deeper into the equations themselves, which are fully listed in appendix.

a. Overall structure

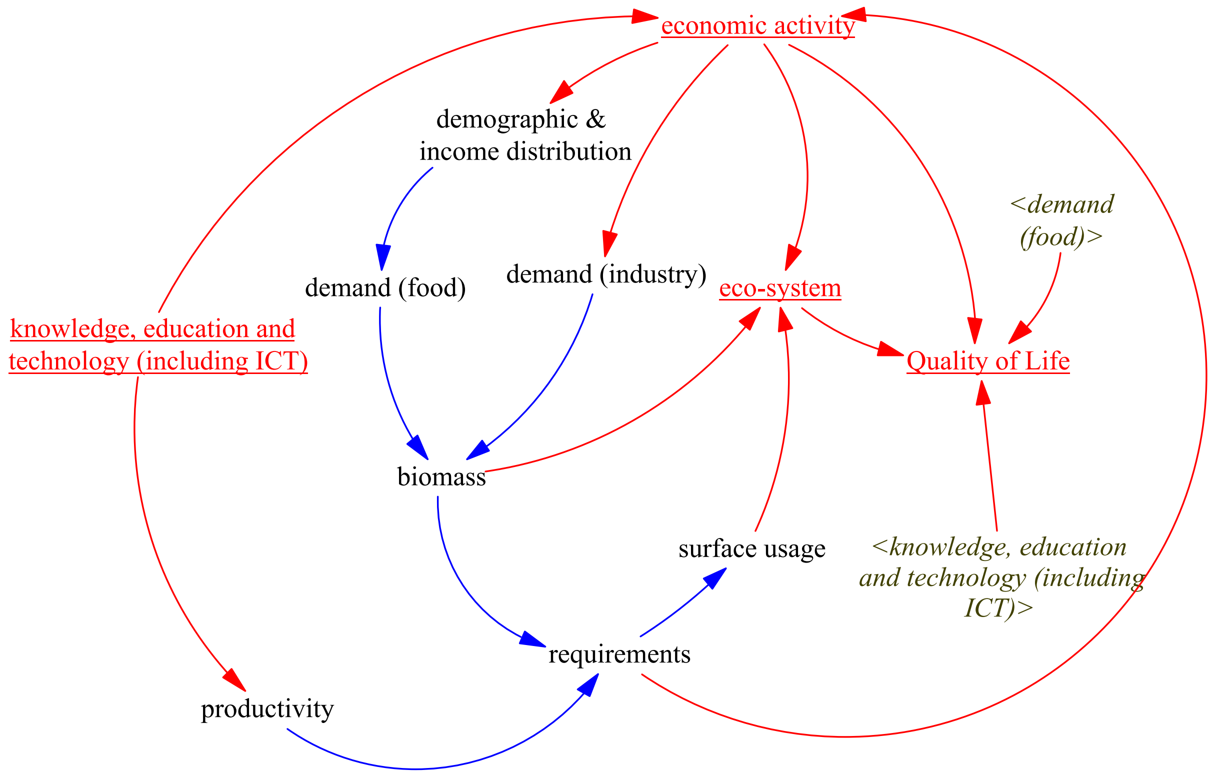

Figure 1: Overall schematic view of COSMOPAD within Insight for TERRA

This first model-view shows how COSMOPAD fits within the TERRA work (the Insight for TERRA model). Not all the sub-models of Insight for TERRA are represented here. Some sub-models and linkages (which do not have a dominant impact on model behavior), like the values and social fabric sub-models and their linkages have been omitted to enhance the clarity of the representation. The sub-models indicated in underlined script are Insight sub-models, those in plain text are COSMOPAD sub-models. Those represented are dominant in determining the behaviour of COSMOPAD, and the arrows indicate dominant causal relations. The full arrows indicate dynamics modeled within COSMOPAD, the dashed arrows show linkage amongst other Insight modules and COSMOPAD itself. Text in italics represents a "variable ghost", the repetition of a variable elsewhere in the model, in order to simplify representation (generally by avoiding crossing arrows).

b. Demography sub-model

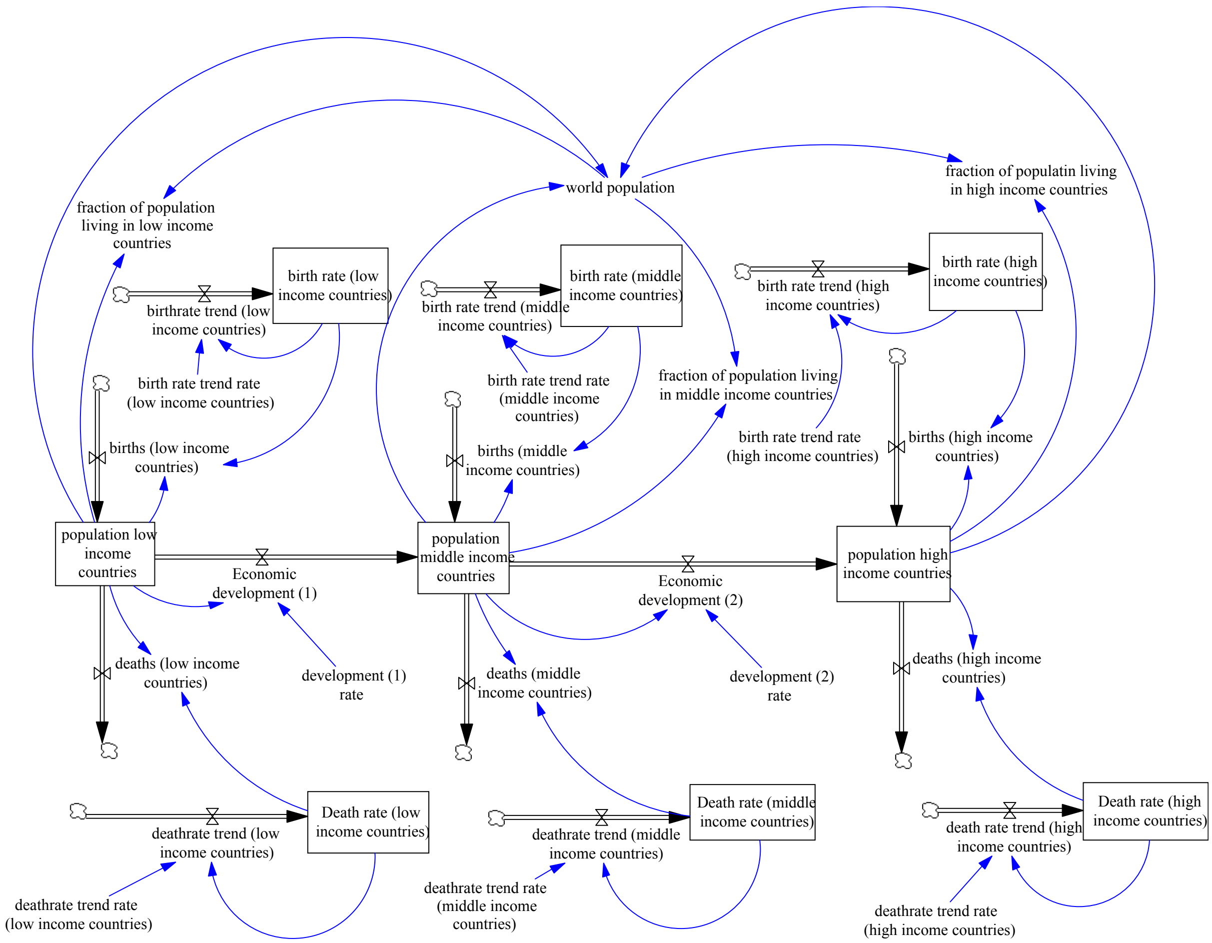

Figure 2: Graphical representation of the demographic sub-model of COSMOPAD

We have created a demographic representation of the world that differentiates amongst three standard income categories (for a full listing of the countries in each category, refer to chapter 5). Each of these groups has its own growth dynamic (the model allows for separate trends in birth-rate and death-rate). The linkages between the three income groups are called "Economic development (1)" and "Economic development (2)". As such the model allows for some representation of increasing worldwide prosperity and the phenomenon often referred to as "the middleclass explosion".

c. Biomass sub-model

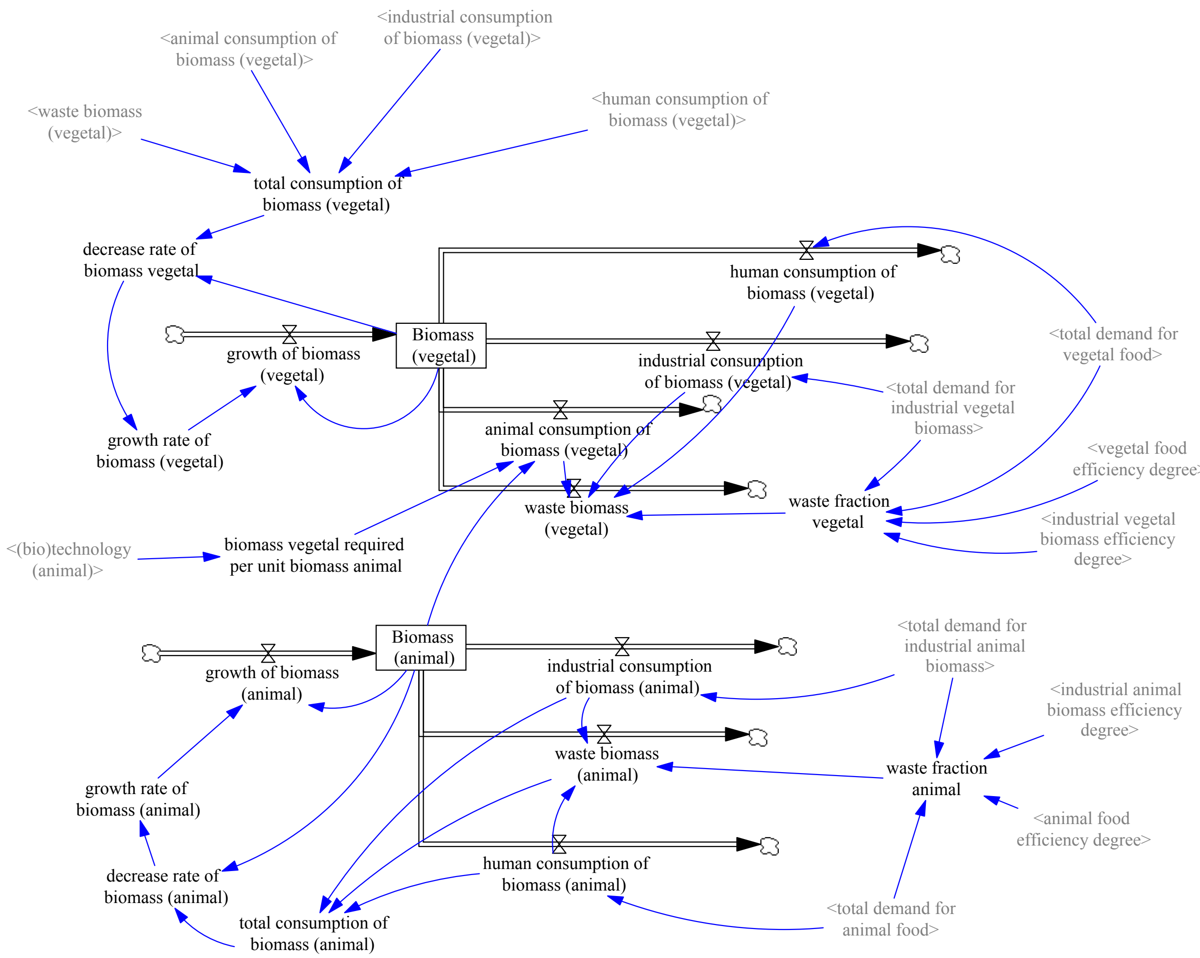

Figure 3: Graphical representation of the biomass sub-model

This sub-model represents the core of the COSMOPAD model. The total agricultural output is aggregated into two variables representing cultivated vegetal and animal biomass. The growth of both these levels is driven by demand and the outflows by human consumption, animal consumption of vegetal biomass, industrial consumption and resulting waste streams.

In a further elaboration these waste streams will need to be represented as (mostly disrupting) inputs into the ecosystem. A des-aggregation into the compounds - natural ones like CO_2, nitrates, NH_3, phosphates, methane, etc. on the one hand and biocide residues on the other - will have to be represented.

d. Food demand sub-model

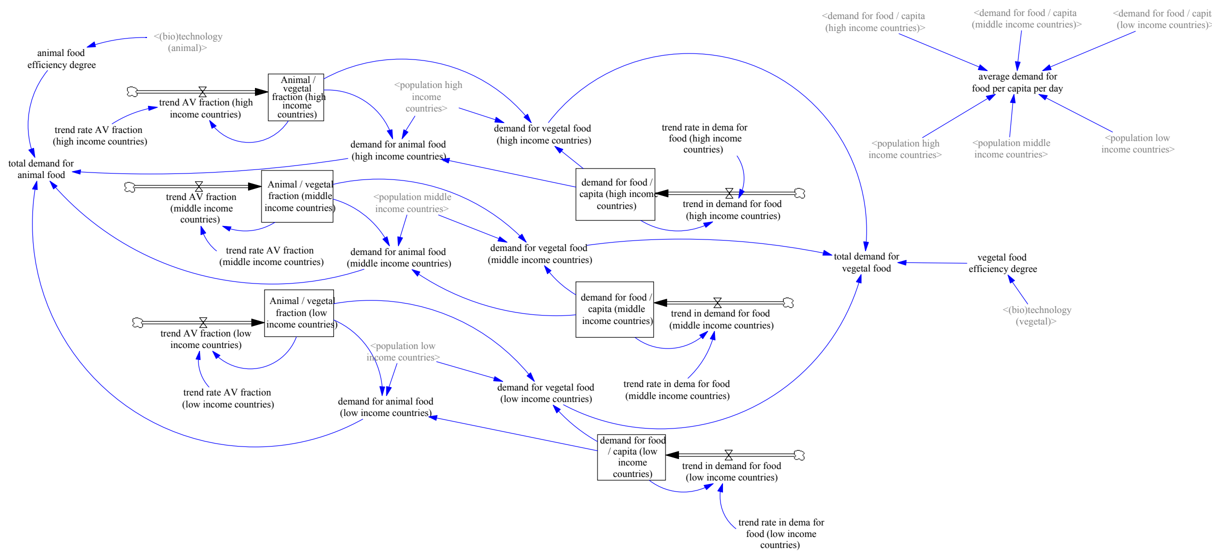

Figure 4: Graphical representation of the food demand sub-model

In this sub-model a closer look is taken at the fraction of yearly human energetic intake that originates from vegetal or animal sources. This sub-model allows the representation of the fraction of food intake from vegetal and animal sources for each of the income categories defined earlier, providing with the possibility of giving each of these a trend (e.g. recently there has been an increasing group of vegetarians growing in the richer countries). The output of this sub-model is the net demand for vegetal and animal biomass. So far the changes are driven by some trend-rates affecting a level. The COSMOPAD holon can be added to the integrated Insight for TERRA model, and these simple structures replaced with links to the social-fabric / culture / values sub-model.

As a verification point for the correct functioning of the model, an indicator of the worldwide daily energetic intake per capita per day (expressed in Kcal) has been included. As will be demonstrated in the simulation section, the growth of calorie intake per capita per day matches FAO[5] forecasts remarkably well.

[5] Ref. 24

e. Industrial demand sub-model

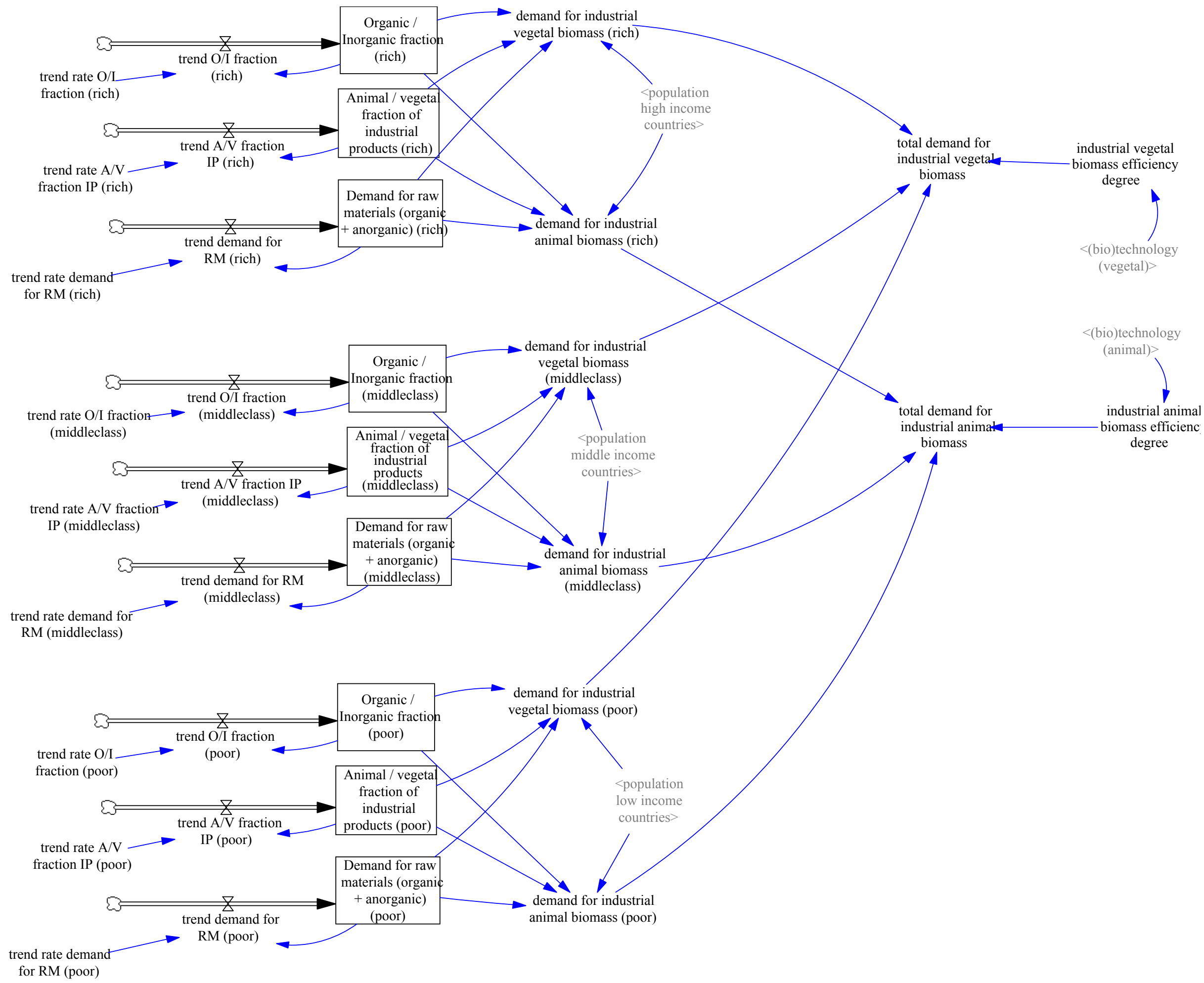

Figure 5: Graphical representation of the industrial demand for biomass sub-model

This sub-model is analogous to the previous one. Instead of considering the demand for biomass for food purposes, the demand for industrial application is represented. The dynamic sub-system representing the aggregated demand for raw materials in the three income classes is a simplified one. This representation serves as a place holder until new trends (like the production bio-diesel) really impact on the agricultural sector.

The demand for raw materials is split out into two fractions an organic and an inorganic one. The organic one is then further split up into an animal and a vegetal fraction.

f. Requirements for biomass level sub-model

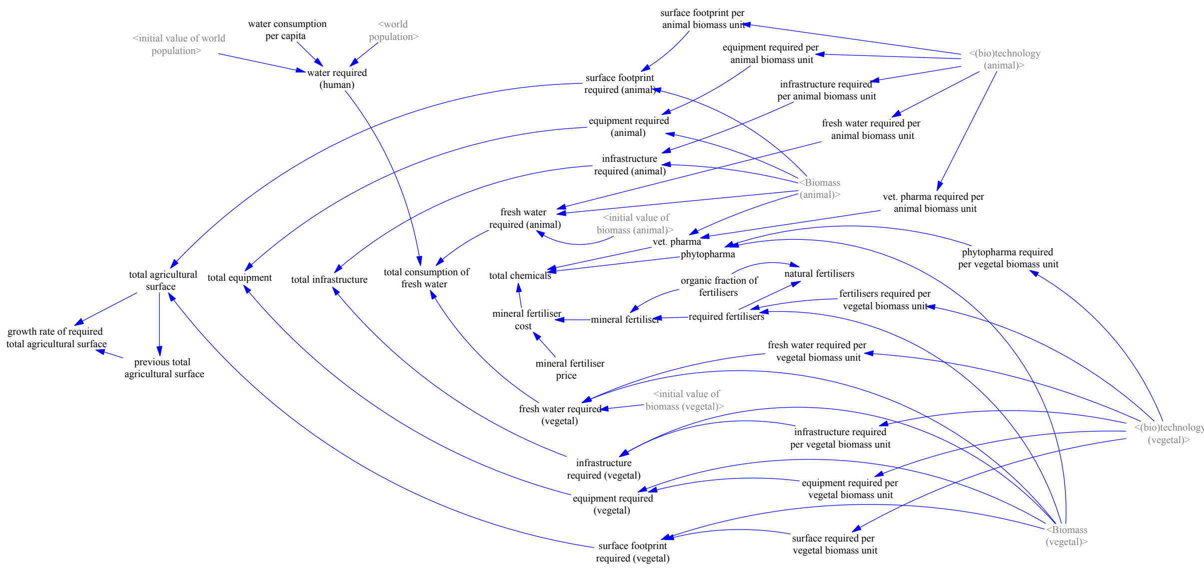

Figure 6: Graphical representation of the requirements for the level of biomass sub-model

In this sub-model, the impact of the agricultural activities is expressed in terms of required raw materials and goods for maintaining the quantity biomass at the current level. One of the dominant internal linkages is the required agricultural surface that drives the surface usage sub-model discussed further. Another set of strong internal linkages is the one connecting this sub-model to the productivity sub-model. This connection is based on the assumption that technological progress will affect the requirements per produced unit of biomass.

g. Requirements for biomass dynamics sub-model

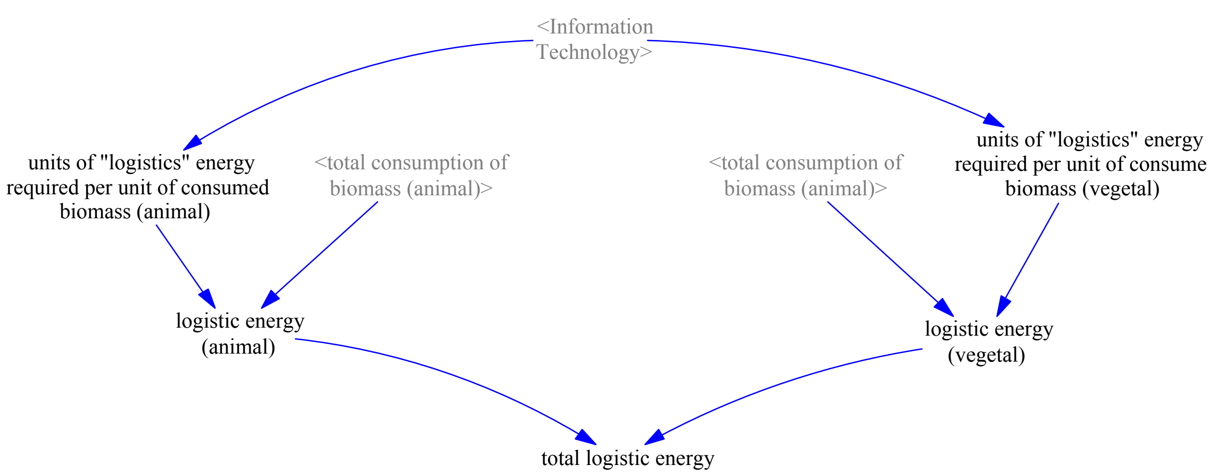

Figure 7: Graphical representation of the requirements for the biomass dynamics sub-model

For the sake of completeness, a sub-model representing the energy required to harvest and distribute biomass is added. The usage of this sub-model is mainly indicative[6]. It is assumed that information technology contributes to the rationalisation and optimisation of distribution logistics and in this manner reduces the amount of "logistic energy" required per unit of biomass consumed.

[6] The Insight for TERRA model contains a separate "distribution & logistics" module.

h. Surface usage sub-model

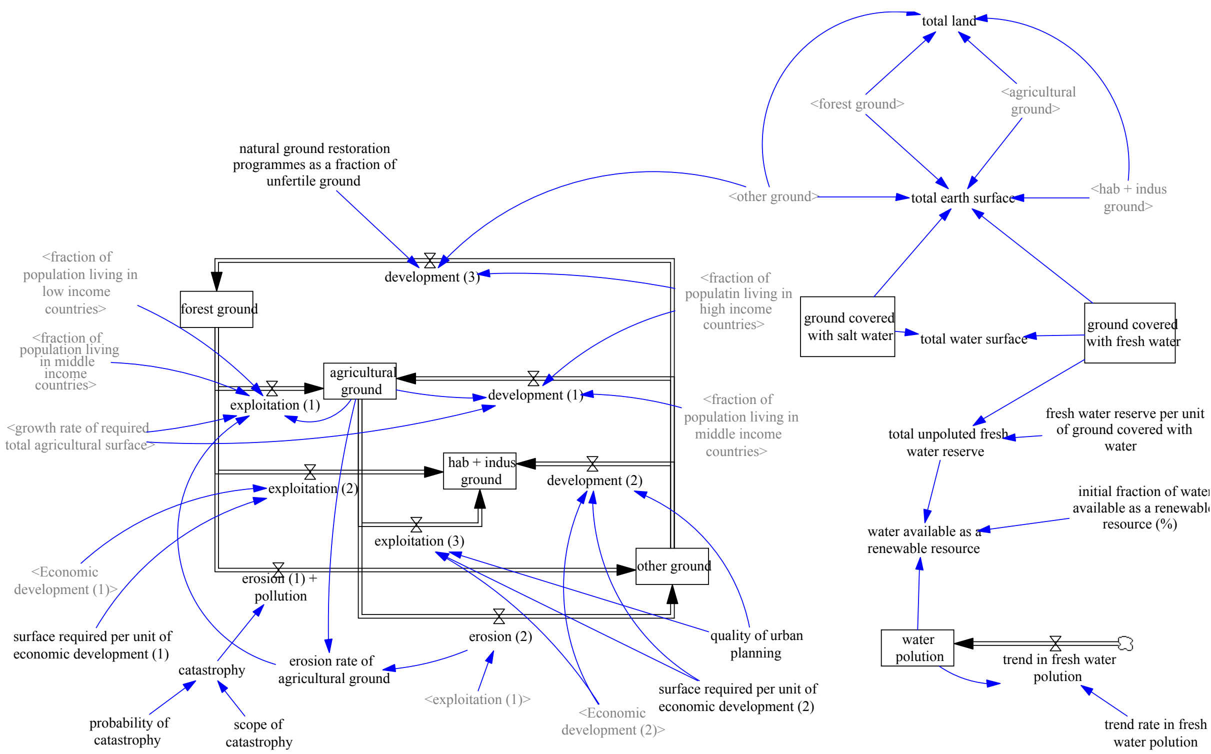

Figure 8: Graphical representation of the surface usage sub-model

This sub-model represents the global usage of the earth's soil surface. A distinction is made between natural ground (representing surfaces not exploited for human activities, excluding ground covered with water, e.g. tropical forests, plains, etc…), agricultural soil, built up ground, unfertile ground (not suited for agricultural purposes, heavily eroded and/or polluted soils), ground covered with fresh and salt water.

The demand for arable surface drives the transformation of natural ground into agricultural ground. In this version of the sub-model, a considerable fraction (affected by the size of the population in the poor income category) of this newly exploited soil turns into unfertile ground after a relatively short period of time, a process of overuse and erosion is assumed.

This sub-model also has a placeholder for representing the available fresh water reserves; further work should include the linkage of this variable to the eco-system variables (including water pollution).

i. Productivity sub-model

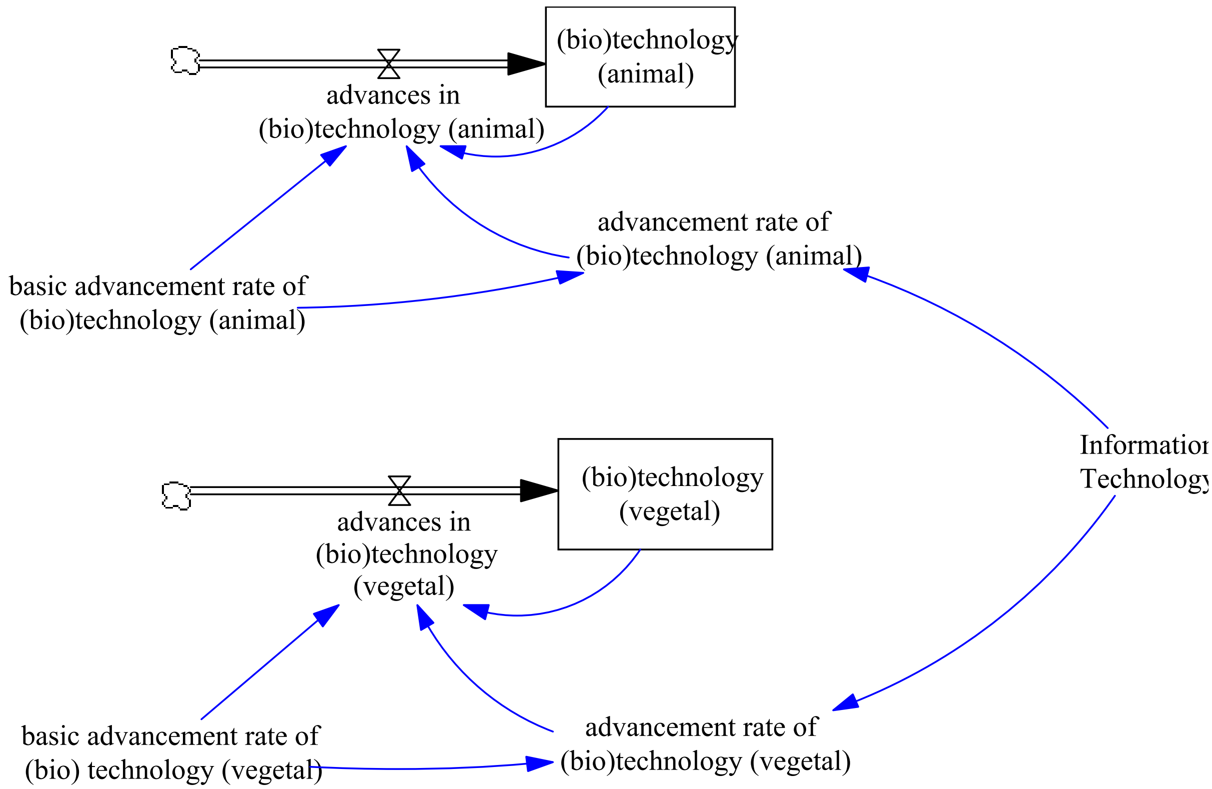

Figure 9: Graphical representation of the productivity sub-model

This sub-model is a conceptual representation of the overall technological innovation process in the agricultural sector and the effect of ICT on the advancement rate hereof. Information technology is represented as a multiplier on the progress rates of (bio) technology[7]. The model is set up in such a way as to allow setting different advancement rates for bio-technology geared towards the vegetal aspects of agricultural and for bio-technology geared towards the animal aspects thereof.

This is a simple representation ignoring aspects of progress like saturation effects and new technologies. This representation allows exploring quickly scenarios, while keeping the model relatively simple. Additionally in our long term vision there was no need for a more advanced productivity growth model, since this is explicitly addressed as a sub-model within Insight for TERRA.

This sub-model represents "additional" technological progress due to increased efforts in R&D. For instance, the historical trends of productivity increases leading to a faster relative growth of production than of the usage of agricultural grounds is endogenously present in the equations driving the usage of soil.

[7] By (bio)technology is meant any technology that is applied within an agricultural context.

j. Indicator sub-model

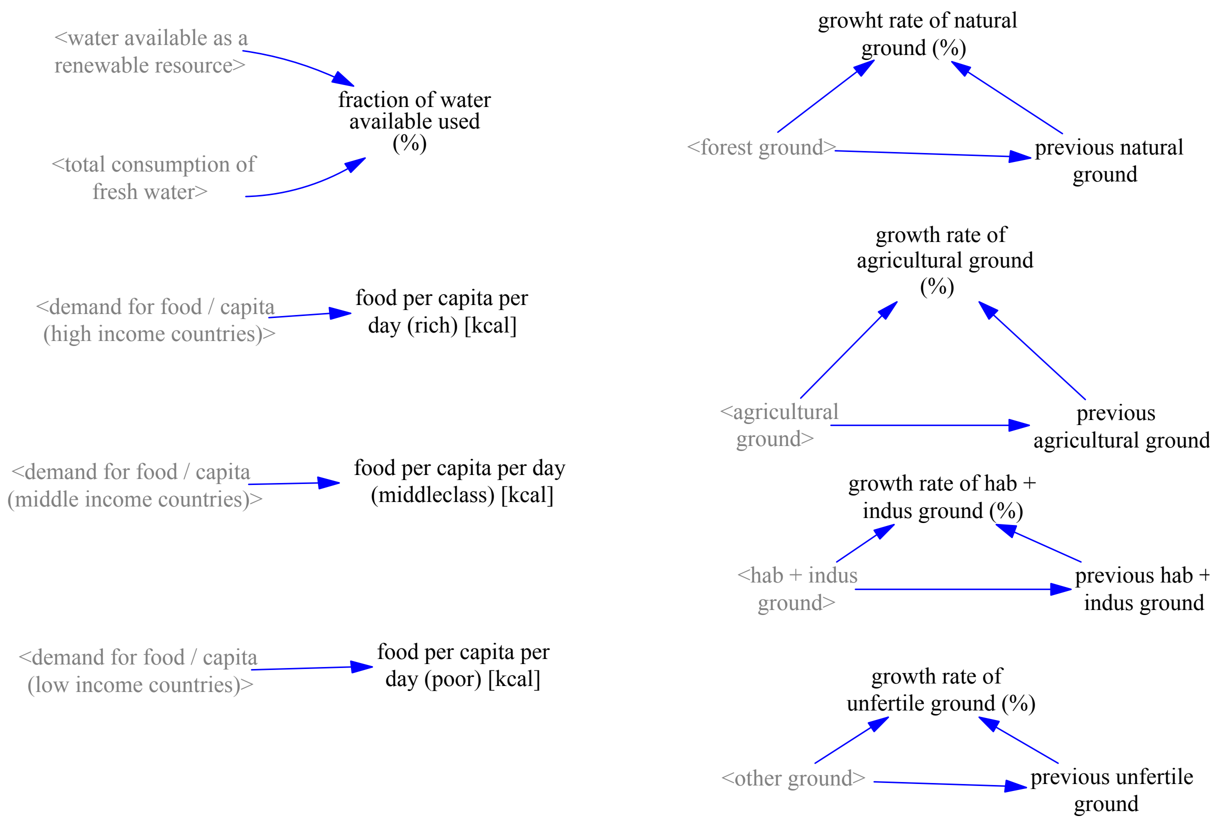

Figure 10: Graphical representation of the indicator sub-model

The purpose of this sub-model is mainly to provide simulated output graphs which can easily be compared with data and projections from other sources. This sub-model in COSMOPAD appears to produce a number of curves and forecast in accordance with the results of other research efforts (ref. Chapter 6: simulation results). This is an indication of the validity of applicability of the COSMOPAD approach to this type of sustainability issues.

5. **Variables and Data Sources**

The purpose of this effort was to set up a modelling framework for modelling agricultural trends. This is why at this stage the effort that was put into the calibration of the equations and variable-values of the model has been restricted to a bare minimum in order to prove that the model can work.

The model for instance provides with the capability of estimating the demand for biomass for industrial purposes, clearly this is an important sink for cultivated material (cotton, leather, …) even now, but as research and discussion concerning bio-fuel advances, this will be of increasing importance. At this stage however data to calibrate this part of COSMOPAD has been difficult to get our hands. This is why in the simulations that are represented in the next chapter, the demand for biomass for industrial purposes is kept zero.

Our main sources of data were:

- FAO (Ref 24)
- Wirsenius PHD thesis (Ref 23)
- WWF Living Planet 2000 (Ref 27)
- CIA World Fact Book 2002
- IFs (International Futures) v1.15

Where needed, data was estimated in accordance with experts in the field. As an indication of validity of the assumption made, Table 1 provides an overview of some simulation results compared with data found in literature.

Topic	Literature		COSMOPAD	
	2000	2030	2000	2030
1. Population (in Billion)*	6	7.89**-8.27	6	7.53
2. Average Food Demand (in kcal/day/ca)*				
2.1 World	2,806	3,050	2,845	3,168
2.2 Income Class				
Rich	3,380	3,500	3,390	3,490
Medium	2,910	3,180	3,030	3,360
Poor	2,680	2,980	2,350	2,680
3. Earth surface use*				
3.1 Total Agriculture Surface (mio ha)	1,506	1,708	1,600	1,772
3.2 Surface growth rates				
Forest	-0.22	-	-0.18	-0.31
Agriculture	0.34	-	0.28	0.36
Industrial	1.6	-	1.66	1.29
4. World Water Withdrawal (in km3)°	3,940°	-	3,940°	6,921°

* CIA
** FAO
° WWF

Table 1: Comparison Data – Model

6. Simulation Results

In this chapter we will briefly show some results from the runs with the COSMOPAD model, populated with the data as it stands. Two scenario's are compared, one called "current" representing a business-as-usual or base case scenario, representing the likely evolutions if no specific policies are implemented. The second scenario called the "technology scenario" is one where more effort is put into research for biotechnology and ICT.

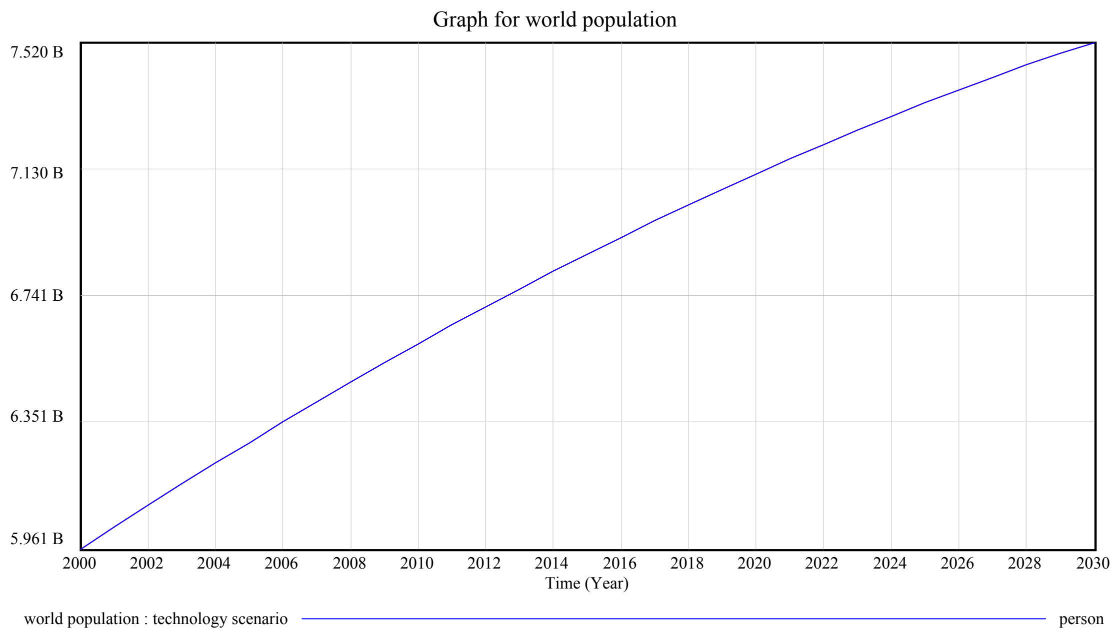

Figure 11: Graph for world population

The graph for world population shows a quite conservative growth of population over the next 30 years. The demographics of the model are not affected in our technology scenario.

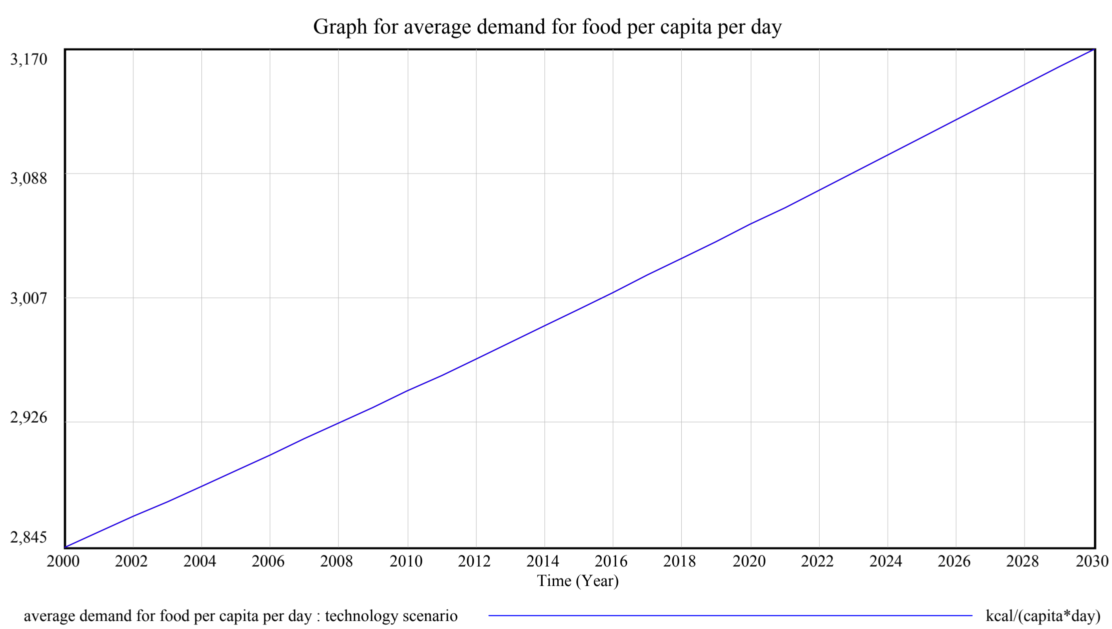

Figure 12: Graph for average demand for food per capita per day

The next graph (on the previous page) shows the trend in average calorie intake per capita per day. Combined with the previous graph, this leads to an increased demand in agricultural grounds (underneath).

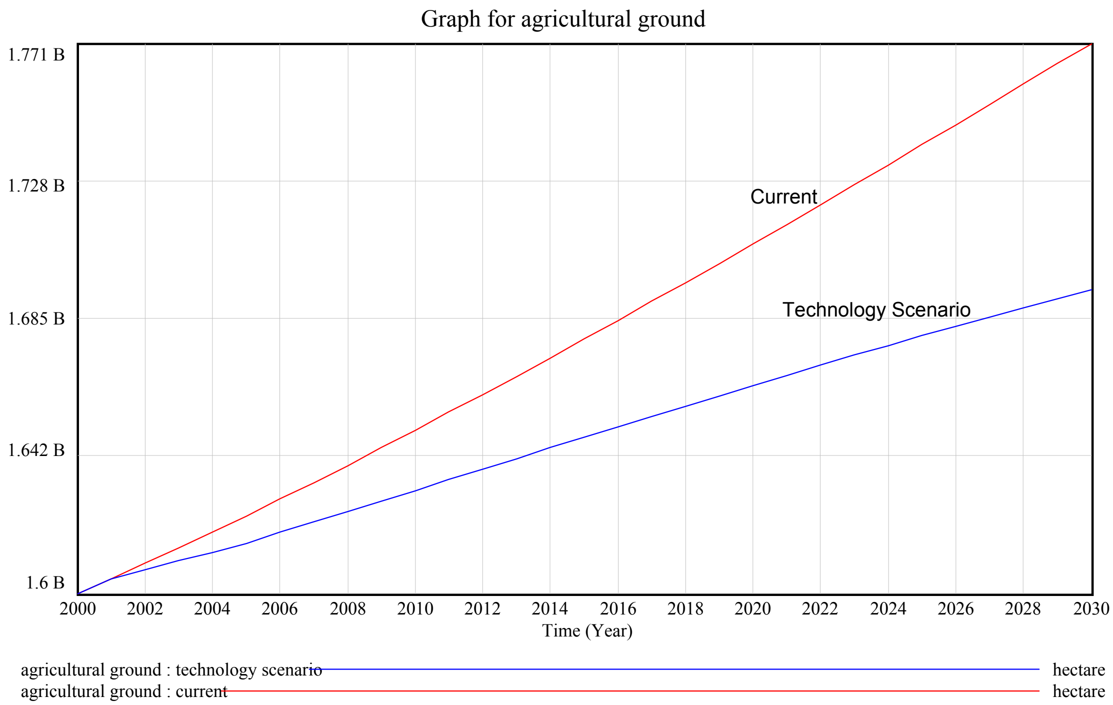

Figure 13: Graph for agricultural ground

In the case of the technology scenario we see a lesser need for new arable land. This translates into the following graph, representing the size of worldwide forest land…

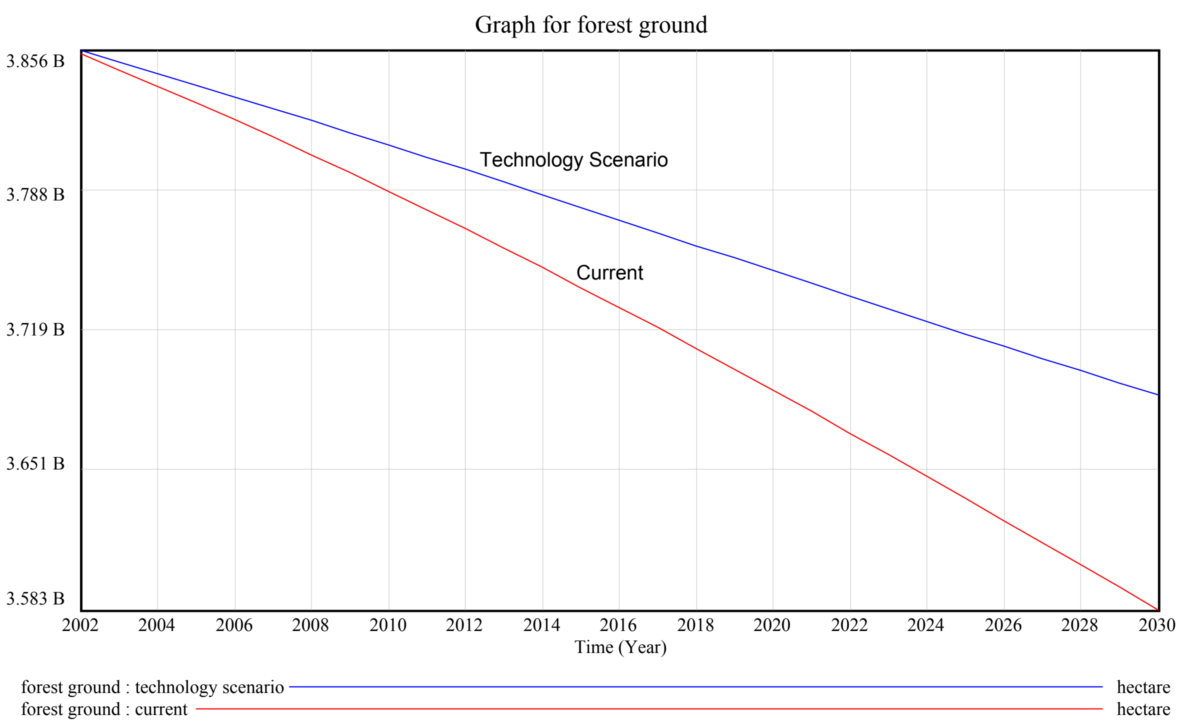

Figure 14: Graph for forest ground

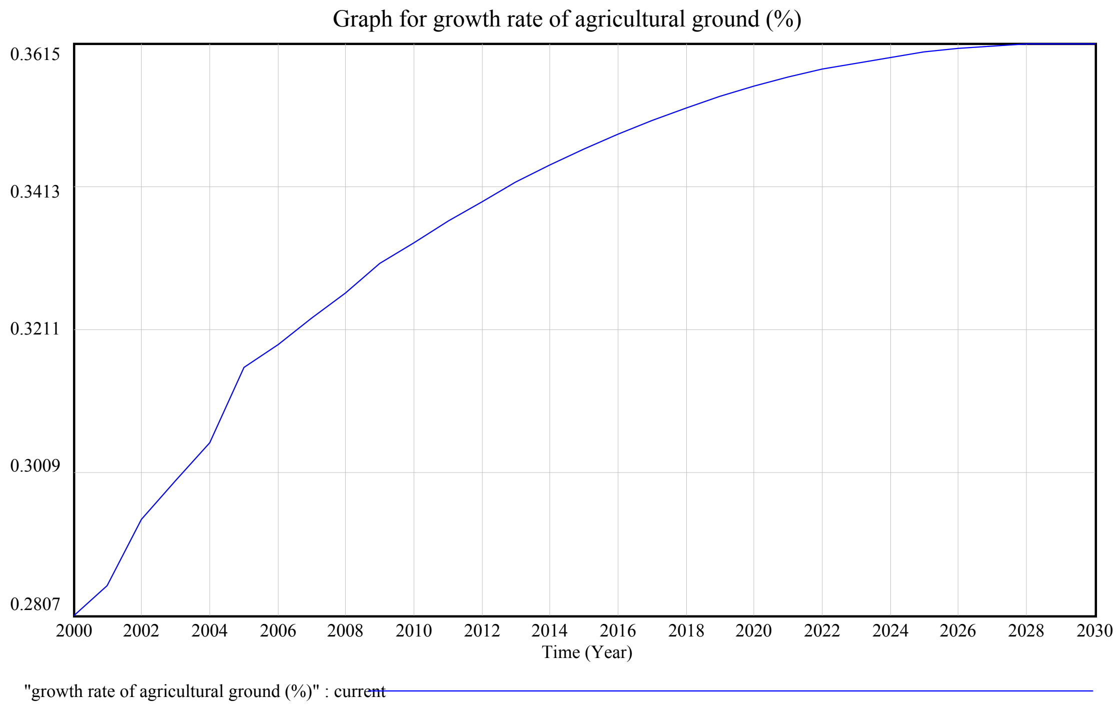

Figure 15: Graph for growth rate of agricultural ground

The growth rate of agricultural ground, shows that if nothing is done, it will stabilise around 0.36%, which is of course unacceptable (permanent growth of the surface required for agriculture is certainly unacceptable), but we believe a regionalised version of the model would prove that there is plenty of room for dramatic agricultural productivity increases in the developing world.

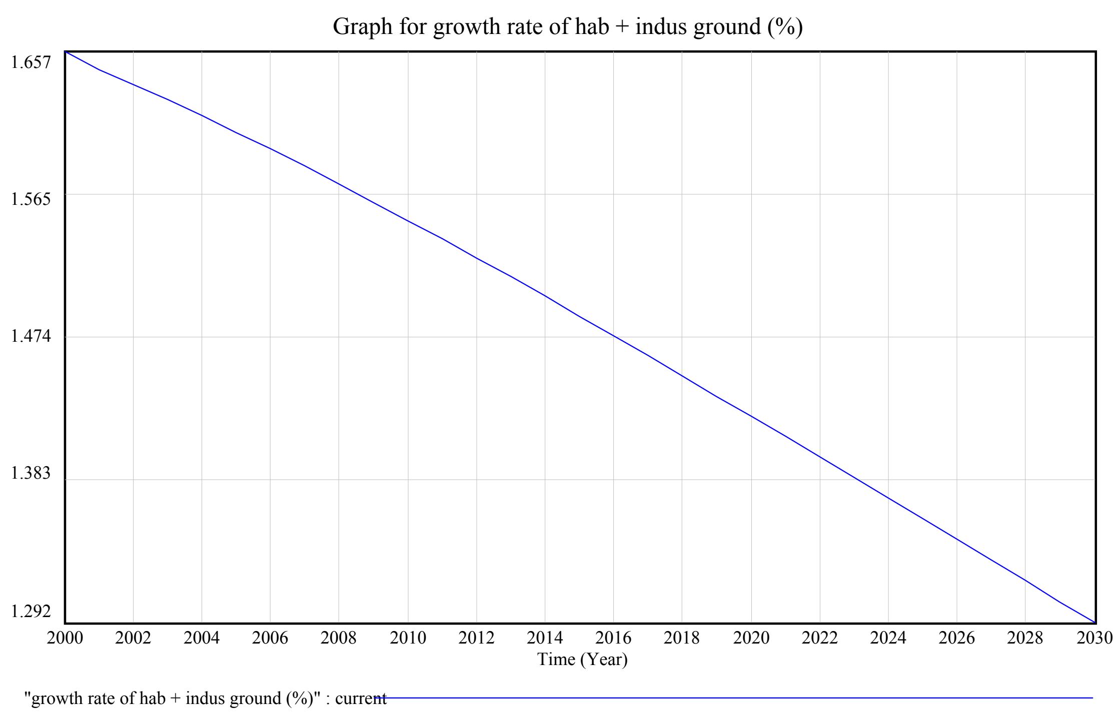

Figure 16: Graph for growth rate of built up land

Interestingly, the model also shows a decreasing trend in the growth rate of built up land, which could be a measure for the slow dematerialisation of our economy and the increasing urbanisation that concentrates more people on smaller surfaces.

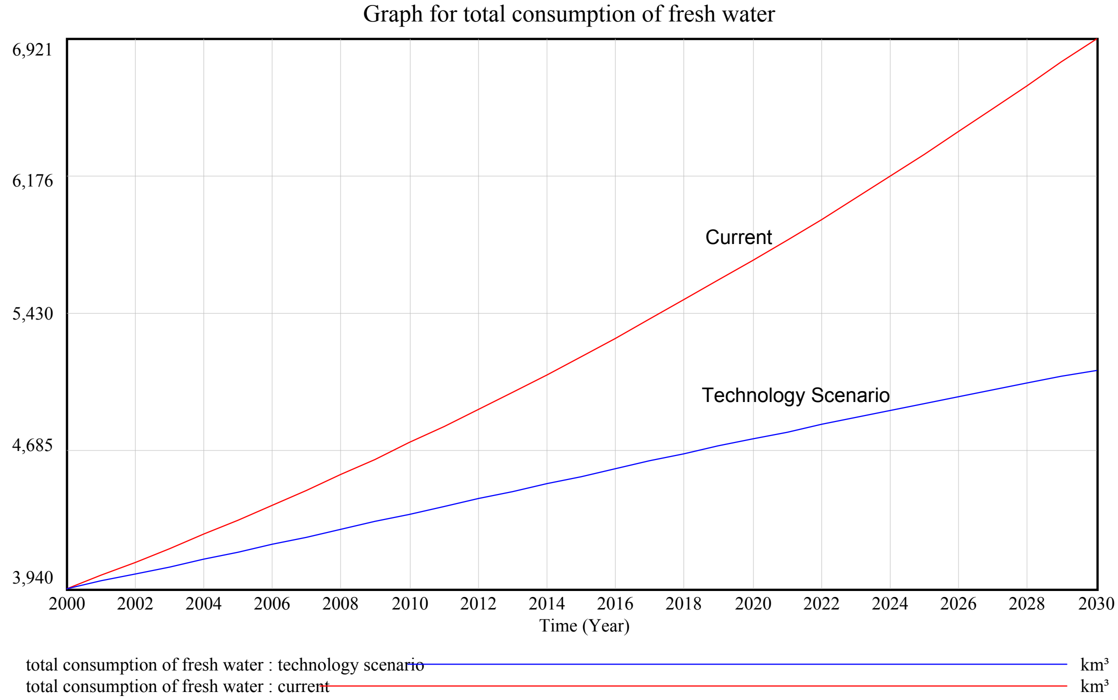

Figure 17: Graph for total consumption of fresh water

A last graph where the dramatic effects of technology can be seen is the total consumption of fresh water. It is clear that there is no worldwide water-shortage, however there are local problems leading to desertification that if not taken care of might lead to the emergence of a worldwide water-problématique.

7. **Conclusions and Recommendations**

a. Conclusions

The COSMOPAD framework has proven to be an applicable method for modelling agriculture. In this document we have shown that the model can be run and calibrated with data. For the dynamic simulation runs up until now, some real data have been used. We have found that most data required to fully populate the model with real numbers are available, and an effort to exploit the data with the model is well under way.

Even without "hard" data a number of general global trends and a number of problems soon become apparent. The growth of the middleclass is well represented and the effects are quite dramatic. The mere fact that a lot of poor are moving into the middleclass income category with its less efficient feeding habits (more meat in the daily diet) is driving the exploitation of new agricultural grounds, which in turn drives the deforestation process.

So far, technological progress (mechanization, irrigation, fertilizer, ICT-monitoring, GMO, etc), appears to be the only way out of this dilemma, since it allows for greater overall efficiency and can reduce the use of fresh water and size of the waste streams released into the eco-system. As a thought experiment we have run a scenario in which all technological advancement was stopped. It turned out that in this scenario, humanity would run out of agricultural soil before 2030. Of course this has not been checked with more precise data, and an integrated model would probably demonstrate that stopping technological progress would have an impact on economic growth, which in turn would affect economic development and would slow down the transition of a large part of the poor into middleclass population, slowing the agricultural surface exhaustion phenomenon down, without avoiding it.

b. Sustainability Criteria

It is clear from our preliminary simulations that agricultural development as it has been unfolding up until now is far from being sustainable. Based on the basic agriculture related sustainability issues represented in the model, we propose the following indicators as a measure for increasing sustainability (please note that these are not measures for sustainability, but for the improvement of in sustainability)

First of all humanity should aim at feeding the population without increasing the required amount of biomass. This could be achieved by increasing the efficient use of biomass (e.g. switching from meat to vegetable diets).

(1) $$\frac{dBiomass}{dt} \leq 0$$

Secondly the anthropogenic waste flows into the eco-system should be kept at current levels at least, and better yet should be reduced, by reducing the waste produced per unit of biomass, resulting in equation (2).

(2) $$\frac{d\frac{Waste}{Biomass}}{dt} \leq 0$$

Thirdly the surface used for agricultural purposes should be kept at a minimum per unit of biomass, resulting in equation 3.

(3) $$\frac{d\frac{SurfaceUse}{Biomass}}{dt} \leq 0$$

Finally the usage of fresh water should be kept as low as possible, especially when considering the size of the current water reserves that are under constant pressure due to overuse and pollution. The resulting indicator equation is represented in equations (4a,b).

$$WaterUse = -\frac{dWaterreserve}{dt}$$

(4a, b)
$$\frac{d\dfrac{Wateruse}{Waterreserve}}{dt} \leq 0$$

c. Recommendations

I. Model elaboration

A first step in further validating the model is the full integration with more data collected elsewhere. As far as the structure of the model itself is concerned a number of additions could be made.

Most important to truly catch the worldwide agriculture development dynamic we believe is a further regionalization of the model into a small number of large COIs[8]. Of course the agricultural model then also needs to be fitted within the regionalized insight world model in order to catch the broader range of socio-economic and ecologic impacts related to agricultural policy.

At a later stage we believe it will be important to include sub-models into the present model for assessing fisheries, aquaculture and forest-management. Additionally the aggregated waste streams represented in the model will have to be specified into a number of chemicals and compounds in order to facilitate the integration of outputs from COSMOPAD into the eco-system module of Insight for TERRA.

The modelling of fisheries is a typical system dynamics exercises that is nearly as popular as the population and rabbits & foxes textbook examples. The fisheries sub-model should take into account sweet and salt water fishing, each with their own and interrelated dynamics. The number of fish should be a level with natural reproduction of fish as a inflow and fisheries as an outflow. This model would be sufficient to show how trade-offs between fish and meat diets are best made to promote worldwide sustainability. (For instance the significant flows of fish into meat, through animal fodder need to be modelled)

In our view aquaculture should be represented as a separate, extremely efficient (as far as the early data we have found shows) method of generating biomass.

In the long term, the model should also provide some possibilities for analysing the impact of global warming and flooding, turning different types of surface into grounds covered with salt water for a period of time.

II. Agricultural policies

The model developed, the data collected and the simulation results obtained from the different runs, all seem to point at the same set of policies.

1. Great care should be taken in the exploitation of agricultural surface in such manner as to avoid the deterioration of the soil through pollution or erosion.
2. Strict policies and regulations concerning the use (and pollution) of fresh water need to be implemented to avoid dramatic local water shortages in the long run.
3. Waste streams from agricultural sources need to be monitored closely, limited to a minimum, recycled as much as possible and the impacts on the eco-system carefully assessed. ICT has great potential to be useful in implementing this policy.
4. By monitoring the entire food chain, inefficiencies and waste should be kept at the lowest levels possible. This would again require a shift from the rather traditional agricultural sector into an ICT intensive sector.

[8] Communities Of Interest

5. In order to reach earlier goals, research to improve the efficiency of agriculture should be strongly encouraged. This research should not be limited to the agriculture related science per se, but should also be concerned with the novel application of new technologies (like ISTs) for the traditional agricultural business.

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