‘Food or Energy?’ Is that the question?

Erik Pruyt* and Gert De Sitter**
*Corresponding author: E. Pruyt, Delft University of Technology,
Faculty of Technology, Policy and Management; Policy Analysis Section
P.O. Box 5015, 2600 GA Delft, The Netherlands – E-mail: e.pruyt@tudelft.nl
** Vrije Universiteit Brussel, Department of Mechanical Engineering, Belgium

July 10, 2008

Abstract

Bioenergy currently draws worldwide attention, both positive and negative. Proponents argue that the large-scale development of bioenergy, more precisely of biofuels, could be part of the solution for diversifying energy sources, enhancing security of energy supply, and meeting environmental and rural development objectives. Opponents argue that it could drive up prices of agricultural products, and hence, threaten agricultural food security, wildlife areas/ecosystems, and international trade flows. A highly-aggregated System Dynamics model of the worldwide food/bioenergy issue is developed in this paper in order to investigate interactional effects between agricultural food production and bioenergy production at the world level[1].

Keywords: Bioenergy, Food Security, System Dynamics

1 Introduction

1.1 Context

Dramatically risen fuel prices, expected future fuel shortages, increasing environmental consciousness and climate change awareness, pressures for energy independence, technological innovations, and a favourable political floor have drawn worldwide attention and investments to renewable energy sources over the last decade.

Bioenergy is renewable energy produced from biomass (from living organisms of biological origin). Bioenergy derived from biological feedstocks[2] can be used –through direct combustion or gasification– for heating and electricity generation, and –through conversion to biofuels– for automotive propulsion. Bioenergy consumption multiplied in recent years, and currently provides some 11-14% of the world primary energy consumption. There is however a significant difference in percentage of the primary energy mix, growth rate, type, and use between developing countries –where traditional bioenergy (mostly firewood) remains the main energy source– and industrialised countries –where a rapidly growing biofuel sector drives the booming cultivation of (dedicated) bioenergy crops. Bioenergy might also provide a substantial source of alternative energy in the future.

Proponents of bioenergy, and more specifically of biofuels, argue that the large-scale development of bioenergy could be part of the solution for diversifying energy sources, enhancing security of energy supply, and meeting environmental and rural development objectives. In the light of the

[1]The online abstract of this paper for the International System Dynamics Conference promised System Dynamics models of the ‘EU27 bioenergy/biofuel sector’. Given the current world food/bioenergy controversy, it has been decided to present a similar world-model dealing with the ***world food/bioenergy crisis***. The more detailed European model is developed and discussed in (Pruyt 2008b): it generates insights into the interactions between the EU agricultural bioenergy sector and the EU biofuel production sector, and their joint development.

[2]Biological feedstocks include wheat, corn, and other grains, wood and wood waste, straw, crop harvest residues, sugarcane, sugar beets, rapeseed, sunflower, soybeans, algae, vegetal and animal waste.

current world food crisis, proponents of biofuels argue that biofuels are responsible for only a minor share (some 3%) of current food price rises[3]. US Agriculture Secretary Ed Schafer was quoted saying: 'We recognise that biofuels have an impact, but the real issue is about energy, increased consumption and weather-related issues in grain producing countries' (BBC News 2008a).

Opponents of biofuels on the other hand argue that they are to a large extent –some 30% (BBC News 2008b) or more[4]– responsible for current food price rises. Hence, opponents argue that biofuels threaten (agricultural) food security, diverting land from food production to energy production (BBC News 2008a). They point out that this leads to serious negative impacts on the poor in urban areas, poor nations, international trade flows, and possibly to negative impacts on small-holders and poor in rural areas. Biofuel opponents also point out potential environmental dangers, such as deforestation, destruction of natural ecosystems, mono-culture expansion, agricultural intensification, excessive use of fertilisers and pesticides.

This divide between proponents and opponents of biofuels has not been resolved at the world summit dedicated to the world food crisis, held in Rome in June 2008[5], and agreements on (limitations of) biofuel production have not been reached. Decisions are on the other hand made in several countries to stop or to freeze current and future biofuel projects. Jean Ziegler, Special UN Rapporteur for the Right to Food, has also called for a 5-year moratorium on biofuel production using current methods (FAO 2008c).

However, that might be undesirable too. Bioenergy might namely also revitalise the agriculture sector, generate more income for farmers and the agricultural sector as a whole, attract more agricultural investments, and hence, foster rural development and alleviate poverty. It might also improve (rural) access to sustainable energy (FAO 2008a), both in the short and the long run: first generation biofuels –which compete directly with food crops for the same arable land, and hence, increase the cost of food production– are often argued to be an intermediate step, necessary for a successful transition towards second generation biofuels –which do not compete directly for the same arable land and do not affect food crop prices to the same extent.

The controversy and framing of the policy issue as 'Food against Bioenergy' is highly undesirable and counter-productive. The dynamics of food and biofuel production –and hence of food and fuel security– are complex, interlinked, and need to be studied as a whole. The interactional effects between, and joint dynamics of, agricultural food and bioenergy production need to be studied in order to design appropriate policies and make good decisions –reconciling present and future, food and energy security, and economic, social, and environmental dimensions. The food/bioenergy issue is therefore actually about sustainable development. And the policy/ethical tradeoff between short-term food security and long-term energy security might not really be a tradeoff: both food and energy security are needed, and they might even reinforce one another on the system level if managed properly. But to manage complex issues properly, a thorough understanding of the issues is necessary. Since the mental assessment of the dynamics over time of complex issues is almost impossible for unassisted human beings[6], there is also a need for appropriate tools, e.g. simulation models, to help generate this understanding.

System Dynamics is a method for investigating the *dynamics over time* of complex issues. System dynamicists model the (underlying) structure of the issue and simulate the model(s) to get an understanding of the modes of behaviour of the issue, and experiment with the models to design robust policies that lead to desirable behaviour. System Dynamics modelling is holistic in a sense that important 'side effects' are treated as effects (Sterman 2000). Both *dynamics over time* and *side effects* are important in the case of the biofuels/food issue: a large and rapid expansion of bioenergy production 'affects virtually every aspect of the field crops sector, ranging from domestic

---

[3]The cereal/food import bill of developing countries increased some 10 % in 2005/2006, 33-37% in 2006/2007, is forecast to rise by 56% in 2007/2008 (FAO 2008d, p30), to ease from their recent record peaks, but to average, over the next 10 years, well above their mean levels of the past decade (OECD-FAO 2008).

[4]According to an unpublished Word Bank report leaked to The Guardian (Chakrabortty 2008), food prices are estimated to have risen by 140% between 2002 and February 2008, biofuels are estimated to have been responsible for an increase of 75%, and higher energy and fertiliser prices for an increase of only 15%.

[5]See `http://www.fao.org/foodclimate/hlc-home/en/`

[6]Successful mental simulations related to the energy/food issue, probably supported by models, can nevertheless be found, among else in (Müller, Schmidhuber, Hoogeveen, and Steduto 2007; FAO 2008b).

demand and exports to prices and the allocation of acreage among crops [and consequently] farm income, government payments, food prices' (Westcott 2007, p1), and wildlife areas, now and in the future.

Several System Dynamics models have been developed to study bioenergy-related issues. Flynn and Ford (2005) have modelled and simulated carbon cycling and electricity generation from dedicated energy crops. Tesch, Descamps, and Weiler (2003) have developed a System Dynamics model of global agricultural and biomass development. Bantz and Deaton (2006) have developed and used a System Dynamics model to envision possible growth scenarios for the US biodiesel industry over the course of a decade. John Sheehan has developed a System Dynamics model for the US to picture the possibilities of biofuels until the mid-$21^{s}t$ century. Scheffran, Bendor, Wang, and Hannon (2007) have developed a spatial-dynamic model of bioenergy crop introduction in Illinois. Others have developed bioenergy submodels in larger System Dynamics energy models or dealt with biofuel-automobile market interactions. But in spite of the fact that several bioenergy-related System Dynamics models have already been developed for several regions and bioenergy-related aspects, that does not seem to be the case for all regions and all aspects. Currently, it seems that there is an urgent need for System Dynamics kind of models and studies related to biofuels and food production on the world, regional (e.g. EU), and local levels.

1.2 Aims and Organisation

A basic System Dynamics model related to the world food/bioenergy is therefore developed in this paper. This world food/bioenergy model generates insights into the possible impact of bioenergy crop cultivation on food crop cultivation, food prices, food shortages, and hence, the world food crisis.

In this model, the focus lies on bioenergy crops –instead of bioenergy from waste or forestry– because they have the greatest interaction effect with food production, are currently already feasible, are argued by proponents to be a prerequisite for the development of second generation biofuel technologies, and are assumed by the European Environmental Agency (2006, p8) to provide the largest potential in the long-term. The purpose of the simple version of the System Dynamics model presented here is exploratory: the model still needs to be refined, extended, and validated. At this point, insights can be generated, but validated foresights –not to mention forecasts– cannot be generated with the current model and data.

The boundaries of the highly-aggregated world biomass model are first of all discussed in section 2, a causal loop diagram is presented in section 3, the simulation model is briefly discussed in section 4, simulation runs are analysed in section 5, and concluding remarks are presented in section 6.

2 Boundaries of the Model

Many of the concerns and aspects discussed in the introductory section could actually be brought together in a systems model. The world model presented in the current section is a highly-aggregate and simple System Dynamics model. It is the first version of this model, which means that there is still room for improvement and extensions. The model is not, and cannot be, used to prove one or the other position in the food/bioenergy debate. It could however be used to integrate several causal effects –assumed to be important by different parties– in the same system model, and to generate and analyse the impact of different (sets of) assumptions on the modes of behaviour of the system model. Likely modes of behaviour of different opinions (e.g. proponents and opponents), modelled as different sets of (structural and parameter) assumptions, could be explored too.

The population dynamics of –and between– 'rich' (overnourished) and 'poor' (undernourished), their respective crop demands (reflecting their lifestyles), and the dynamics of the crop supply to satisfy their demands are modelled endogenously.

Industrialisation-related enrichment and lifestyle changes, and per capita biofuel demand increases drive the model exogenously. The desired food buffer, additional investments in crop yield and crop land, and distributional inefficiencies are also modelled exogenously.

Not included yet, but possibly important extensions to be included endogenously are:

- the link between (bio)fuel demand and crop prices;
- environmental/ecological aspects such as deforestation, impact on natural ecosystems, monoculture expansion, agricultural intensification, use of fertilisers and pesticides;
- other resources and local conditions (soil types, availability of arable land, water, and labour);
- and import and export between regions and countries.

3 Causal Loop Diagram of the Model

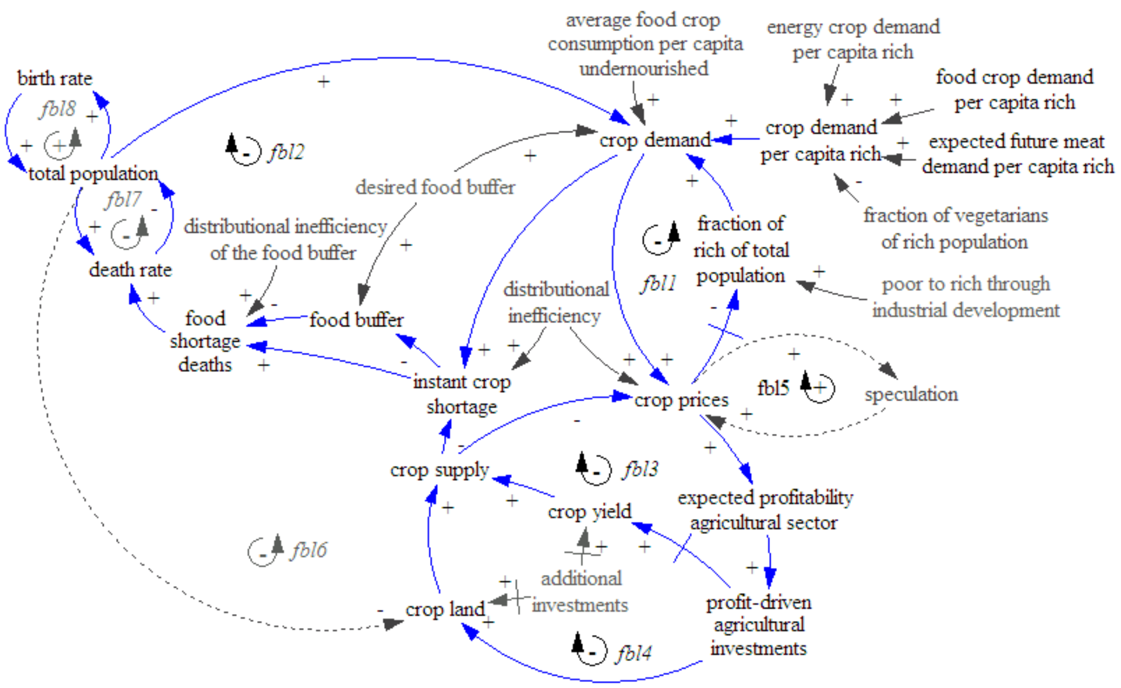


Figure 1: Causal loop diagram of the simple world biomass model

The main feedback loops, as displayed in the causal loop diagram[7] in Figure 1, are:

[7]Following symbols are used in the causal loop diagrams in this paper:

- $\overset{\rightarrow}{+}$ represents a positive causal influence. It indicates that if the influencing variable increases (decreases), all things being equal, the influenced variable increases (decreases) too above (under) what would have been the case otherwise, or $A \overset{\rightarrow}{+} B \Rightarrow \frac{\partial B}{\partial A} > 0$. In other words, 'a positive arrow from A to B means that A adds to B, or, a change in A causes a change in B in the same direction' (Richardson 1997, p249).
- $\overset{-}{\rightarrow}$ represents a negative causal influence. It indicates that if the influencing variable increases (decreases), all things being equal, the influenced variable decreases (increases) under (above) what would have been the case otherwise, or $A \overset{-}{\rightarrow} B \Rightarrow \frac{\partial B}{\partial A} < 0$. In other words, '[f]or a negative link from A to B one says A subtracts from B, or a change in A causes a change in B in the opposite direction' (Richardson 1997, p249).
- $\overset{\not\rightarrow}{+}$ and $\overset{-}{\not\rightarrow}$ represent a positive and a negative causal influence with a delay.
- ⟲ and ⟳ represent negative feedback loops. A feedback loop is called negative or balancing if an initial increase (decrease) in variable A leads after some time to a decrease (increase) in A.

- the balancing ***crop demand impoverishment*** loop (*fbl1* ⊖): An increasing *fraction of rich of the total population* increases the *crop demand* above what it would have been otherwise, which increases –ceteris paribus[8]– the *crop prices*, which decrease after some delay the *fraction of rich of the total population*.

  Additionally important for this loop are *(i)* the exogenous flow of *poor to rich through industrial development*, *(ii)* the *distributional inefficiency* which exacerbates –or even creates– increasing *crop prices*, and *(iii)* the *constitutive elements of the crop demand*, namely the *average food crop consumption per capita undernourished* and the *grain demand per capita rich*, which comprises the *energy crop demand per capita of the rich*.

- a balancing ***crop demand mortality*** loop (*fbl2* ⊖): An increasing *crop demand* increases –ceteris paribus[9]– *instant crop shortages* which in turn decrease existing *food buffers*, which might lead to *food shortage deaths* of the undernourished, increasing the *death rate*. An increasing *death rate* decreases –ceteris paribus– the *total population*, which in turn decreases the total *crop demand*.

  Additionally important for this loop are *(i)* the *distributional inefficiency* which exacerbates –or might even create– increasing *instant crop shortages*, *(ii)* the *desired food buffer*, and (iii) the *distributional inefficiency of the food buffer* which might exacerbate the number of *food shortage deaths* in case of instant crop shortages.

- a balancing ***price profit yield supply*** loop (*fbl3* ⊖): Increasing *crop prices* increase, ceteris paribus, the *expected profitability of the agricultural sector*, which leads to more *profit-driven agricultural investments*. If these *profit-driven agricultural investments* are directed towards improving *crop yields*, then, after some delay time, *crop yields* increase, which leads to an increasing *crop supply*, and –ceteris paribus– to decreasing *crop prices*.

  Additionally important for this feedback loop (and *fbl4*) are *additional investments* (e.g. through government subsidies) that are not endogenously driven by expectations related to future profitability increases.

- a balancing ***price profit land supply*** loop (*fbl4* ⊖): This feedback loop is basically the same as feedback loop 3, except that the investments are directed towards expansion of *cropland* instead of improvement of *crop yields*.

- a reinforcing ***speculation*** loop (*fbl5* ⊕): Strong changes of *crop prices* might lead to *speculation* reinforcing the *crop price* changes. This speculation effect is not fully elaborated here.

- a balancing ***population and urbanisation*** loop (*fbl6* ⊖): The increase of *cropland* discussed in feedback loop 4 might be constrained by an increasing *total population* and related urbanisation. This feedback loop is not included in the simulation model discussed in section 4.

- the usual ***demographic*** loops (*fbl7* ⊖ and *fbl8* ⊕).

This causal loop diagram already allows to draw several conclusions –even without constructing and simulating a System Dynamics simulation model as in section 4:

- If the delay time in *fbl1* ⊖ is sufficiently long, and the rise of *crop prices* –caused by an increased crop demand driven exogenously by the flow of *poor to rich through industrial development* in *fbl1* ⊖ (and possibly reinforced by *fbl5* ⊕)– is sufficiently high and sustained,

---

- ⊕ and ⊕ represent positive feedback loops. A feedback loop is called positive or reinforcing if an initial increase (decrease) in variable *A* leads after some time to an additional increase (decrease) in *A*.

[8]Ceteris paribus = everything else being equal. Here it means that '*crop supply* and *speculation* remaining the same' remain the same.

[9]In other words: with unchanged *crop supply* and *distributional inefficiency*

then *fbl3* ↻ and *fbl4* ↻ might lead to a sustained growth of the yield and/or *crop land*, and hence, of the *crop supply.*

- *Crop demand* is driven by the size of the *population* and the *lifestyle* of the 'rich' which requires a much higher per capita crop demand to satisfy this meat-rich, crop-abundant, and energy-demanding lifestyle. This corresponds to the observation that '[d]ramatic growth in world population during the last half-century coupled with rising lifestyle expectations are two of the main drivers increasing demand for food and other agricultural commodities [and that these] demands signify long-term trends that will continue to be important until at least 2050' (FAO 2008d, p29).

- The low *average per capita food crop consumption of the undernourished*, is not something that might be changed to alleviate the pressure on *crop prices* and *instant crop shortages.* On the contrary, the lifestyle of the *rich*, reflected by their high *per capita crop demand*, might actually offer the necessary leverage point to alleviate pressures on *crop prices*: lower per capita meat consumption, lower per capita food crop demand, and lower per capita energy crop demand (than would be the case otherwise) might significantly temper *crop demand* and *crop prices.*

- But *energy crop demand per capita of the rich* will almost certainly be higher instead of lower. Fuel demand increases outstripping fuel supply increases, cheap fossil fuel resources being depleted, and resulting fossil fuel price increases, will almost certainly lead to a higher *energy crop demand.* This implies –as long as second generation biofuels are not technically feasible and economically viable– increased competition with food crops, diversion of land to energy crops, and higher crop and food prices.

  Following this line of reasoning, the root cause of this problem is the lack of cheap (and sustainable) liquid fuel supply to satisfy the rising liquid fuel demand. Biofuels –and hence the demand for and cultivation of energy crops– are just a potential solution to fill the gap or satisfy the demand.

  The biofuel part is kept exogenous here, such that different, highly uncertain, biofuel scenarios can be simulated. In a second step, biofuels might also be modelled endogenously in order to investigate feedback effects between *crop prices* and *energy crop demand*: higher *crop prices* will –everything else being equal– attenuate the *energy crop demand.*

- The model also points out –although quite simplistically– that *instant crop shortage* and *crop prices* are influenced by more or less the same variables, but that they need to be distinguished. Both could be artificially high: *speculation* might for example increase *crop prices* in the absence of a real *instant crop shortage*, and distributional inefficiencies and distortions might for example cause regional *shortages* without raising price levels in other regions. But higher crop and food prices do not have to be problematic if it does not lead to a further impoverishment of the relatively poor and if food shortages are absorbed by a sufficiently big *food buffer* that is effectively and efficiently deployed.

- The latter might be a problem if the *desired food buffer* is too low, and/or if the *distributional inefficiency* of the *crop supply* and/or the *distributional inefficiency of the food buffer* are too high, which is not caused by bioenergy crop cultivation.

4 Simulation Model

In this section, the simple simulation model will be introduced. It will be simulated in section 5.

Figure 2 shows the population view of the simulation model, including the population structure of 'rich' (read: overnourished) and 'poor' (read: undernourished) and the constitutive parts of their respective 'crop demands'. The total per capita *crop demand of the rich* is much higher than the per capita *crop demand of the poor.* The *total crop demand* equals the *desired percentage buffered*,

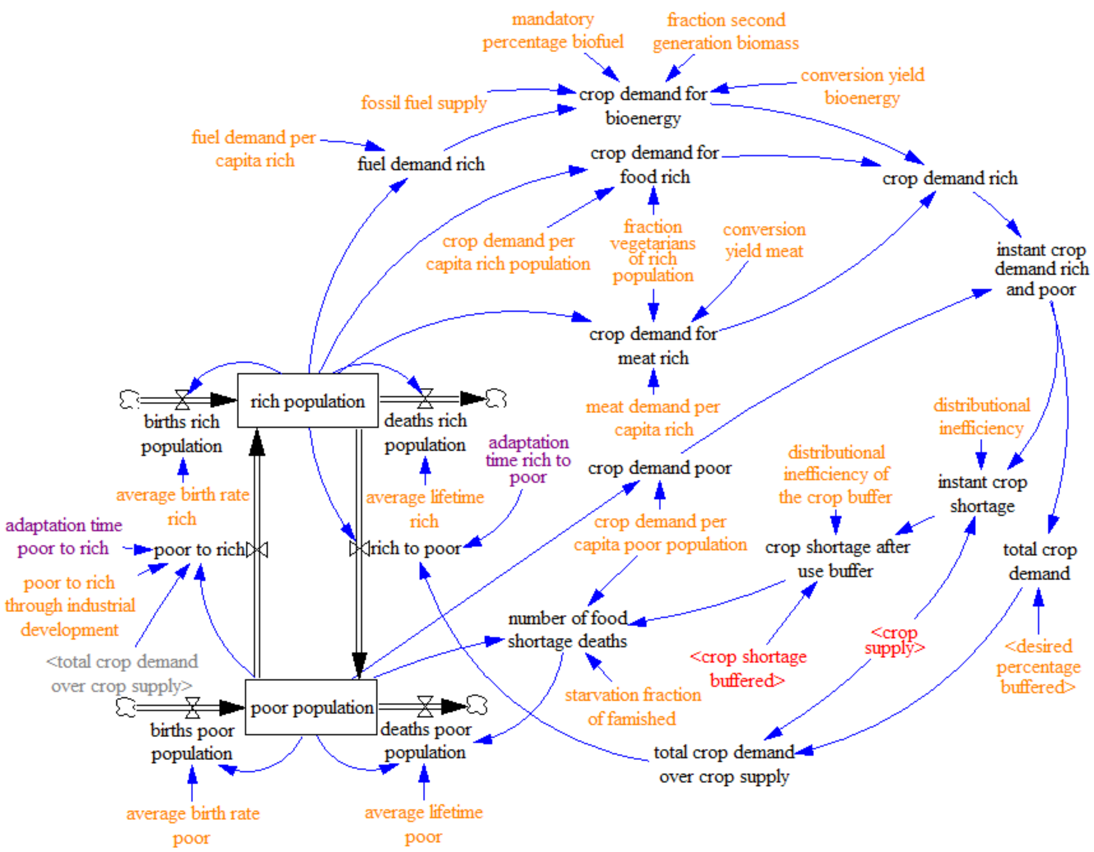
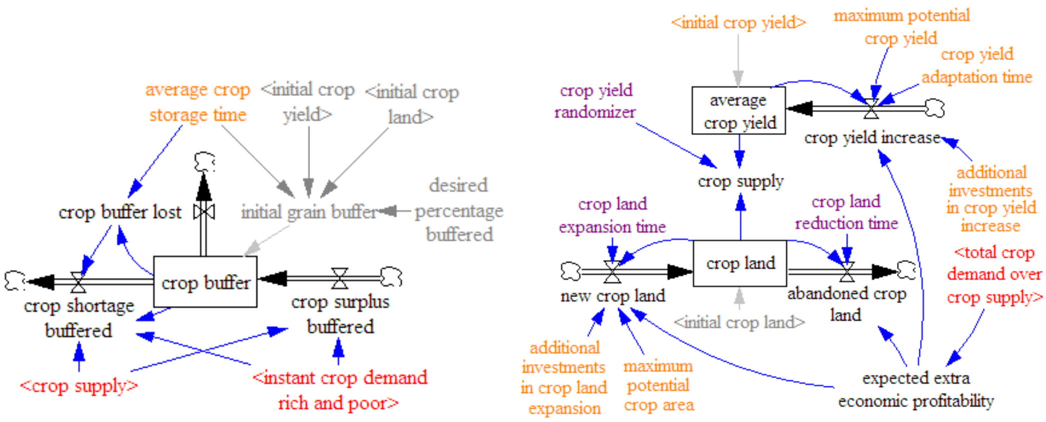


Figure 2: Rich and poor population, their crop demands, possible shortages, and consequences.



(a) Crop buffer (b) Crop area, yield, and supply

Figure 3: Crop area, yield, supply (left) and crop buffer (right)

times the sum of the *crop demand of the rich* and the *crop demand of the poor*. In this simplistic version of the model, the *total crop demand over crop supply* is a proxy for the fraction of market price over production cost, or in other words, the *extra economic profitability*, which –in this version of the model– equals the *expected extra economic profitability*. If this proxy is greater than unity, it gives rise to a pauperisation flow '*rich to poor*'. If this proxy is smaller than unity, it leads to an enrichment flow '*poor to rich*'. The enrichment flow *poor to rich* is also driven exogenously by a flow of *poor to rich through industrial development*.

An *instant crop shortage* occurs in this model if the *instant crop demand rich and poor* is greater than the *crop supply* times the *distributional inefficiency*. This *instant crop shortage* could then be buffered (*crop shortage buffered*) with a certain degree of inefficiency (*distributional inefficiency of the crop buffer*), which results in the *crop shortage after use of the buffer*. The *number of food shortage deaths* then equals the *crop shortage after use buffer* divided by the *crop demand per capita of the poor population* times the *starvation fraction of the famished*, that is, if this number is smaller than the *poor population*.

The *crop shortage buffered* and the *crop supply* originate from two other views displayed in Figure 3. Figure 3(a) shows the crop buffer which increases in case of surpluses, and decreases to buffer shortages and because of decay after an *average crop storage time*. Figure 3(b) contains the structures for:

- the *crop land*, which are extended or abandoned depending on whether the *expected extra economic profitability* is greater than or smaller than unity,
- the *average crop yield*, which is extended if the *expected extra economic profitability* is greater than unity, and
- the *crop supply*, which can be randomized in order to simulate natural variability of harvests.

5 Simulations and Policy Analysis

At this point, it should be emphasised once more that the model is used in an exploratory way to generate interesting insights and more understanding. This means that modes of behaviour and behavioural sensitivity are focussed on. The model cannot be used to generate (numerically) precise forecasts/predictions or exact measures of sensitivity to parameter changes.

5.1 Data Used for the Base Case

Table 1 displays the values assumed in the base case simulation run for all constants and parameters. Values of lookup variables assumed in the base case simulation run are displayed in Table 2.

5.2 Base Case and Other Scenarios

The values displayed in tables 1 and 2 are also used for the other simulations, unless explicitly mentioned. The main goal of these simulations is to illustrate the resulting mode of behaviour. The scenarios described below build each time upon the previous scenario, changing only one or a few factors:

- To set a primal base case, it is assumed in scenario **S00** that crops are not, and will not, be cultivated for biofuel production: *crop demand for bioenergy* $= 0$, at all times. It is therefore implicitly assumed that fossil fuel supply (or other alternatives besides liquid biofuels) will be sufficient to accommodate the liquid fuel demand over the 21st century. Scenario S00 is in fact the ***no-biofuels base case*** scenario.
- Scenario **S01** equals scenario S00 with the exception that bioenergy crops *are* cultivated for biofuel production. This scenario is the ***biofuels base case*** scenario. The fraction of first

Table 1: Constants & parameters assumptions of the reference run of the world biomass model

CONSTANTS & PARAMETERS	BASE CASE	BOUNDS	EXPLANATION / SOURCE
adaptation time poor to rich [yr]	5.5	1–10	= assumption
adaptation time rich to poor [yr]	5.5	1–10	= assumption
average birth rate poor [10^{-3} p/(p.yr)]	26	20–32	= assumption
average birth rate rich [10^{-3} p/(p.yr)]	20.3	19–21	world average '07 ±10% (CIA 2007)
average crop storage time [yr]	5	2–8	= assumption
average lifetime poor [yr]	45	40–50	= assumption
average lifetime rich [yr]	75	70–80	= assumption
conversion yield bioenergy [l/kg]	0.35	0.35–1	
conversion yield meat [kgmeat/kg]	0.15	0.02→0.28	bovine→poultry (IMAGE-team 2001)
crop demand per capita poor [kg/person/yr]	155.5	124–186.5	assumption: 50% of rich ±20%
crop demand per capita rich [kg/person/yr]	311	248–373	assumption: (681-55.5/0.15) ±20%
crop land expansion time [yr]	10	2–18	= assumption
crop land reduction time [yr]	2	1–3	= assumption
crop yield adaptation time [yr]	10	5–15	= assumption
desired percentage buffered [dmnl]	0.1	0.05–0.15	= assumed value policy variable
distributional inefficiency [dmnl]	0.05	0–0.1	= assumed value policy variable
distributional ineff. of crop buffer [dmnl]	0.25	0–0.5	= assumed value policy variable
fract.add. crop land thr.ex.inv. [dmnl]	0		= assumed value policy variable
fract.add.crop yield incr.thr.ex.inv. [dmnl]	0		= assumed value policy variable
initial crop land [Gha] (if not as variable)	1.38	1.54	(FAO 2008e, d) (Müller 2007)
initial crop yield [kg/ha/yr]	3000	2500–3500	(Gilland 2002, p59)
initial population [10^9 person]	6	5.9–6.1	
initial fraction poor [dmnl] (undernourished)	0.135	0.15–0.12	800.10^6 in 2000 (FAO 2004)
initial fraction rich [dmnl]	0.86	0.85–0.88	idem
max.pot. crop area [Gha] (if not as var)	4.4	3.52–5.28	(Müller 2007) ±20%
maximum potential crop yield [kg/ha/yr]	5000	4400–6600	= assumption ±20%
meat demand per cap. rich [kgmeat/p/yr]	55.5	41–70	by '50 (Millennium Ecosystem Ass.)
starvation fraction of famished	0.2	0.1–0.3	= assumption
fraction rich above poverty threshold	0.2	0.1–0.3	= assumption

Table 2: Lookups of the reference run of the world biomass model

LOOKUPS VARIABLES	VALUES BASE CASE
poor to rich thr. industrial development	(2000,0),(2100,0)
fraction second generation biomass	(2000,0),(2010,0.01),(2030.28,0.2),(2050,0.5),(2075,0.8),(2100,0.9)
fossil fuel supply [10^{12} l/yr]	(2000,4.4),(2005,4.9),(2008,5.2),(2013,6.2),(2025,6.2),(2100,6.2)
fuel demand per capita rich [l/(person.yr)]	(2000,848),(2008,970),(2100,970)
fraction vegetarians of rich population	(2000,0.1),(2100,0.2)
mandatory percentage biofuel	(2000,0),(2010,0.01),(2100,0.2)

generation bioenergy crops decreases in this scenario and in the scenarios in the remainder of this subsection, following an inverse S-function, equal to 1-*fraction second generation biomass* (see table 2).

- Scenario **S02** equals scenario S01 with the exception that the *fossil fuel supply* decreases linearly from 6.2 10^{12} l/year in the year 2025 to 1 10^{12} l/year at the end of the century[10].
- Scenario **S03** equals scenario S02 with the exception that the *fraction of vegetarians of the rich population* linearly increases to 90% and the *fuel demand per capita of the rich* linearly decreases after 2008 to 500 l/person/year by the end of the century[11]. The cause of these actions is not what matters here: they might emanate autonomously from the rich population, might be caused by high energy and food prices, or might be steered by policies.

[10] The lookup variable *fossil fuel supply* assumes, more precisely, following values: (2000, 4.4 10^{12}), (2005, 4.9 10^{12}), (2008, 5.2 10^{12}), (2013, 6.2 10^{12}), (2025, 6.2 10^{12}), (2100, 1 10^{12}).

[11] *fraction vegetarians of rich population*: ((2000, 0.1), (2100, 0.9)); and *fuel demand per capita of the rich*: ((2000, 848), (2008, 970), (2100, 500)).

- Scenario **S04** equals scenario S03 except that the *fraction of additional crop yield increase through exogenous investments* amounts to 10% instead of 0%, that the *distributional inefficiency* is 0%, and that the *distributional inefficiency of the crop buffer* is 0% (both rather utopian). These changes are in fact policies.

The simulation results of these five scenarios are displayed in figure 4. There it can be seen that –using these model assumptions and data– the introduction of biofuels in case of a stagnating fossil fuel supply (**S01** compared to **S00**) leads to a relatively small but gradual shift of people from the *rich population* to the *poor population* due to an increased *total crop demand* and resulting increase of the crop and food prices[12]. The increased *total crop demand* is met by profit-driven increases in *crop yield* and *crop land*, and intermediate *crop shortages* are accommodated by the *crop buffer*.

The introduction of biofuels combined with a linearly decreasing *fossil fuel supply* from 2025 on (**S02**), leads to an increasing *total crop demand* –stemming from an increased first generation biofuel demand (not completely taken over by second generation biofuels)– from the moment the fossil fuel supply falls short of fossil fuel demand (here in the year 2032). The *crop supply* reacts to this increasing *total crop demand*. This reaction is delayed, given that *extra-economic profits* drive investments in *crop yield* improvement and *crop land* extension, which only take effect with a delay. The resulting steeply increasing *total crop demand over crop supply* –a proxy for extra-economic profits and prices– pushes many people out of the *rich population* into the *poor population*, and leads –given the insufficiency of the *desired percentage buffered*– to a rapid depletion of the *crop buffer*, and –in this model– to a gigantic *number of food shortage deaths* (some 1.7 billion), wiping out the entire *poor population*.

Scenario **S03** –in which the *fraction of vegetarians of the rich population* increases linearly to 90%, and the *fuel demand per capita of the rich* linearly decreases to 500 l/person/year– prevents the catastrophe of scenario S02 from happening. The slightly higher *total crop demand* leads to a gradual improvement of the *crop yield* and a gradual increase of the *crop land*, while most of the intermediate food shortage is accommodated by the *crop buffer*. It nevertheless leads –for most of the century– to a slightly smaller *rich population* and slightly larger *poor population* than in scenario S00, and to acute *food shortage deaths* in the order of 100 million of the undernourished.

The measures taken in scenario **S04** –additional (non-profit-driven) investments in crop yields and (utopian) total elimination of distributional inefficiencies– on top of the high fraction of vegetarians and decreased fuel demand already included in scenario S03, makes that the *food shortage deaths* of scenario S03, are avoided altogether. The size of the *poor population* is consequently larger than in scenario S03.

5.3 Univariate Sensitivity Analyses

In this subsection, the sensitivity of the model to changes in parameters and constants –one at a time– is tested, always starting from scenario S02 as discussed and simulated in subsection 5.2. Two reasons lie at the basis of the decision to start from scenario S02, namely:

- that the combination of bioenergy crop cultivation and decreasing (relatively cheap) *fossil fuel supplies* is a very likely one;
- and that the goal of this analysis is the discovery of parameters and constants that enable turning the highly undesirable mode of behaviour and effects of scenario S02 into acceptable ones. This sensitivity analysis therefore focusses on behavioural sensitivity.

[12] The difference between the number of people in the *poor population* in scenarios S02 and S01 increases from 0 in the year 2002 to 26 million at the beginning of 2008. Comparison of the order of magnitude of this simulated difference with data about the real-world increase of the worldwide undernourished population, gives an indication of the usefulness of the model –in spite of the following four remarks: *(i)* the model has not calibrated yet, *(ii)* the obtention of exact outcomes is not aimed at in this paper, *(iii)* biofuel subsidies and other distortions are not included in this model, and *(iv)* the real-world size of the population of undernourished is also caused by other structural causes and events (high energy prices, war, disasters, et cetera).

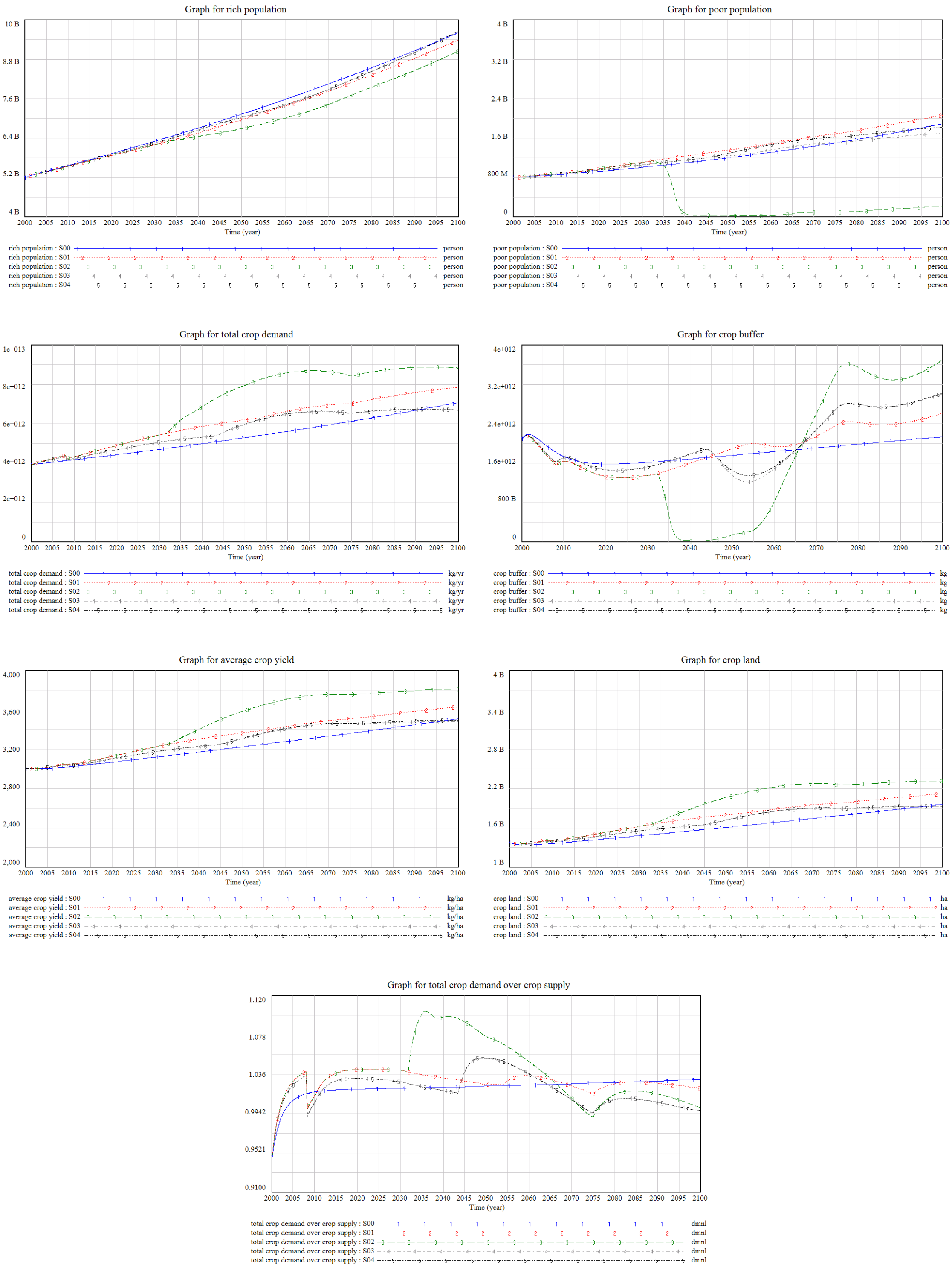


Figure 4: Simulated dynamics of the *rich population*, *poor population*, *total crop demand*, *crop buffer*, *crop yield*, and *crop land* for the base case scenarios S00, S01, S02, S03, S04

Following univariate sensitivity runs are worth mentioning:

- The *adaptation time rich to poor* –which is a proxy for time it takes before the 20% poorest slice of the *rich population* falls into poverty– is decreased from 5.5 years as in S02 to only 1 year in sensitivity run **S02a**.

  Figures 5(a) and 5(b) show that the results are very sensitive to this decrease in adaptation time: it not only leads –compared to scenario S02– to an increased shift of persons from the *rich population* to the *poor population*, but also to a tremendous decrease of the number of *food shortage deaths* –caused by a lower *total crop demand*, an almost sufficient *crop buffer*, and hence, a curtailment of *instant crop shortage*s. This leads to a booming *poor population.* The lower *total crop demand* also leads to a more moderate expansion of the *crop land* size and increase of the *average crop yield* resulting in a lower *crop supply* than in scenario S02. In fact, people shift too rapidly in this simulation run from the rich population to the poor population, hence eroding the (crop) demand. A sufficiently long delay before rich become poor is actually needed to sustain the demand until the slowly increasing supply catches up.

- Figures 5(c) and 5(d) show that the model is –starting from S02– only numerically sensitive to a decrease of the *fraction rich above poverty threshold* from 20% to 10% (**S02b**), and even less numerically sensitive to an increase of the *starvation fraction of famished* from 20% to 30% (**S02c**).

- Figure 5(e) shows that the model –starting from scenario S02– is not behaviourally sensitive to an increase of the *poor to rich through industrial development* by 10 million persons per year in scenario **S02d**. The *rich population* is significantly larger, but so is the *rich to poor* flow, and the collapse of the *poor population* occurs earlier.

- Figure 5(e) shows the influence of:

  - a 20% decrease –relative to scenario S02– of the *maximum potential crop yield* to 4400 kg/ha/yr (scenario **S02e**);
  - a 20% increase –relative to scenario S02– of the *maximum potential crop area* to 6600 kg/ha/yr (scenario **S02f**);
  - a 20% decrease –relative to scenario S02– of the *maximum potential crop area* to 3.52 Gha (scenario **S02g**); and
  - a 20% increase –relative to scenario S02– of the *maximum potential crop area* to 5.28 Gha (scenario **S02h**).

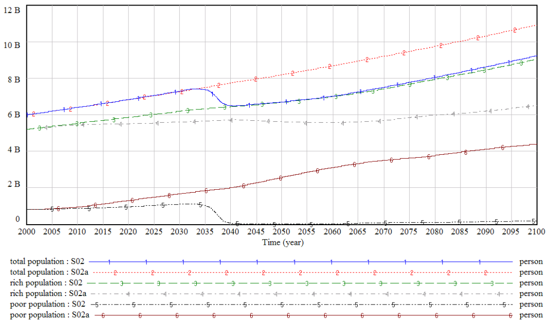
  These changes only have a slight numerical impact on the size of the *poor population* and *rich population*: a decrease of the *maximum potential crop yield* is compensated by an increase of the *crop area*; an increase of the *maximum potential crop yield* cannibalises the increase of the *crop area*; and vice versa. Figure 5(f) shows this compensational effect for the area of cropland. Compare for example the effects on the crop land in scenarios S02e and S02h: a 20% decrease of the *maximum potential crop yield* has, in this model, about the same effect on the size of the *cropland* as a 20% increase of the *maximum potential crop area.*

- Figure 5(g) shows that the model –starting from scenario S02– is behaviourally sensitive to an increase of the *desired percentage buffered* from 10% to 20% (scenario **S02i**).

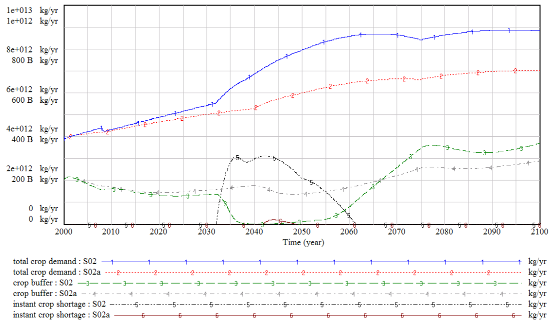
- 5(h) shows that the model –starting from scenario S02– is behaviourally sensitive to an increase of the *conversion yield of bioenergy* to 1 (scenario **S02j**)[13].

The model is –starting from scenario S02– only slightly numerically sensitive to an increase of the *crop storage time*, to changes in the *average birth rate of the rich*, the *average birth rate of*

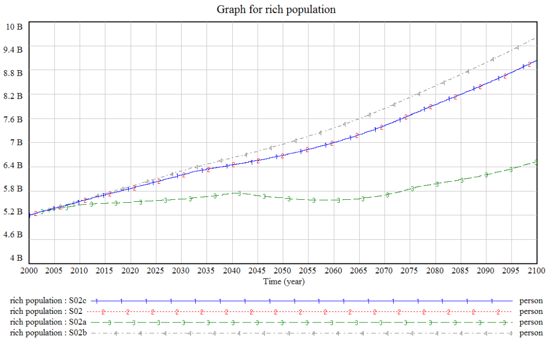
[13] Although a *conversion yield of bioenergy* of 1 is impossible, it is used here to simulate the impact of higher total biofuel yields that could be obtained with crops such as sugar beet, palm oil, et cetera. Even with a *conversion yield of bioenergy* of 1, does the total yield in this model not increase above 50% of the highest possible total yield.



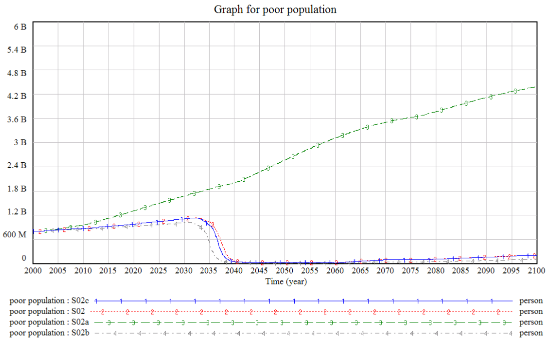
(a) S02a vs S02: total, rich, and poor populations



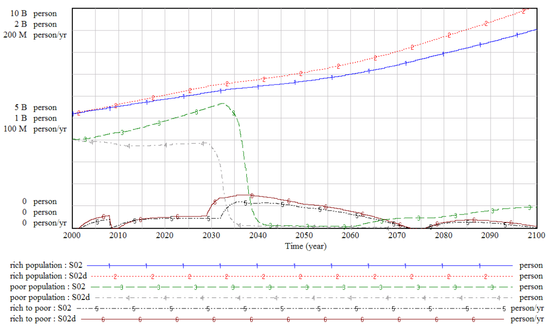
(b) S02a vs S02: crop demand, buffer, and shortage



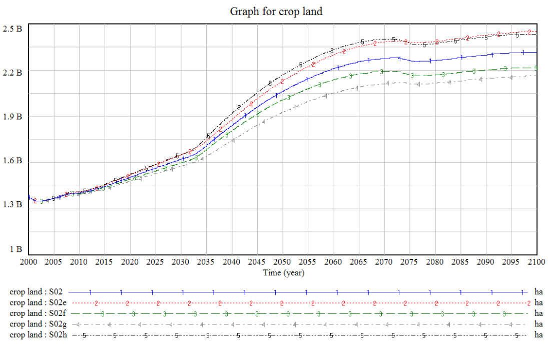
(c) S02b and S02c vs S02 and S02a: rich population



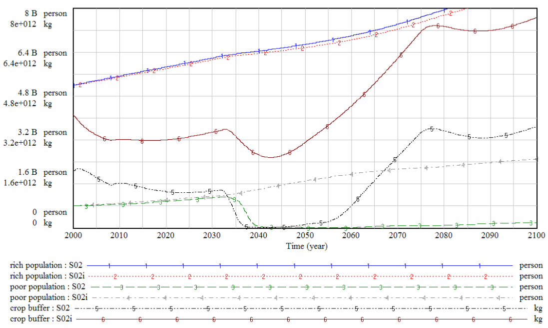
(d) S02b and S02c vs S02 and S02a: poor population



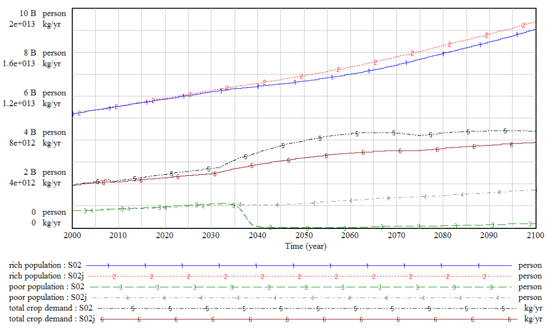
(e) S02d vs S02: rich and poor population, rich to poor



(f) S02e, S02f, S02g & S02h vs S02: crop land



(g) S02i vs S02: rich and poor population, crop buffer



(h) S02j vs S02: rich and poor population, crop demand

Figure 5: Graphical output of some of the univariate sensitivity analyses

the poor, the *average lifetime of the rich*, and the *average lifetime of the poor*. The model is not sensitive to a change in the *adaptation time of poor to rich*.

5.4 What If? – Experiments

System Dynamics models such as the one presented in this paper, can be used as virtual laboratories to assess the dynamics of scenarios and experiment with policies before their real-world realisation/implementation. One such 'What If?'-experiment will be conducted in this subsection. It will be looked at what happens if first generation biofuels break through, but second generation biofuels do not take over. The scenarios described below also build upon the previous scenario, changing only one or a few factors. The scenario of departure is scenario S01, discussed in subsection 5.2. The scenarios discussed here mirror the scenarios discussed in subsection 5.2.

- Scenario S11 equals scenario S01, except that the lookup variable *fraction second generation biomass* is at any time 10 times lower than in S01.
- Scenario S12 equals scenario S11, except that the lookup variable *fossil fuel supply* decreases linearly from 6.2 10^{12} l/year in 2025 to 1 10^{12} l/year in 2100.
- Scenario S13 equals scenario S12, except that the *fraction of vegetarians of the rich population* increases to 90% by 2100 and the *fuel demand per capita of the rich* decreases to 500 l/person/year in 2100.
- And scenario S14 equals scenario S13, except that the *fraction of additional crop yield increase through exogenous investments* amounts to 0.1, and that the *distributional inefficiency* and *distributional inefficiency of the crop buffer* are eliminated.

The simulation results are displayed in figure 6. There it can be seen that a marginal penetration of second generation biofuels has a significant negative impact on the rich and poor populations, especially from the moment fossil fuel supply becomes insufficient to cover liquid fuel demand. Increased crop yields and crop lands cannot prevent a collapse of the poor population. The linear increase of the *fraction of vegetarians of the rich population* and the linear decrease of the *fuel demand per capita of the rich* do not allow to prevent the collapse of the poor population any more. Additional crop yield increases through exogenous investments and a complete elimination of all distributional inefficiencies are needed to prevent the collapse of the total poor population. Even in case of scenario S14, a significant number of food shortage deaths cannot be avoided. Since the elimination of all distributional inefficiencies is rather unrealistic, it could be concluded that a full breakthrough of second generation biomass is needed.

6 Conclusions and Future Work

6.1 Conclusions

The following conclusions are based on the high-level causal loop diagram, the simple (version of the) System Dynamics simulation model discussed in this paper, some reflections beyond the boundaries of the simple model, and some insights from related models (i.e. (Pruyt 2008b)).

System Dynamics models –both qualitative and quantitative models– are useful to study the potential dynamics over time of complex issues from a systems perspective. The complex issue studied here is the food/biofuels issue. Although the development of bioenergy crucially depend on many endogenous and exogenous developments (such as food and energy prices, the investment in –and the development of– biomass technologies, political and societal acceptation), and on competitive pressures (from other energy technologies, agricultural food production, et cetera), it has been modelled exogenous here in order to focus on the resulting dynamics of crop cultivation, agricultural food production, and poor and rich populations.

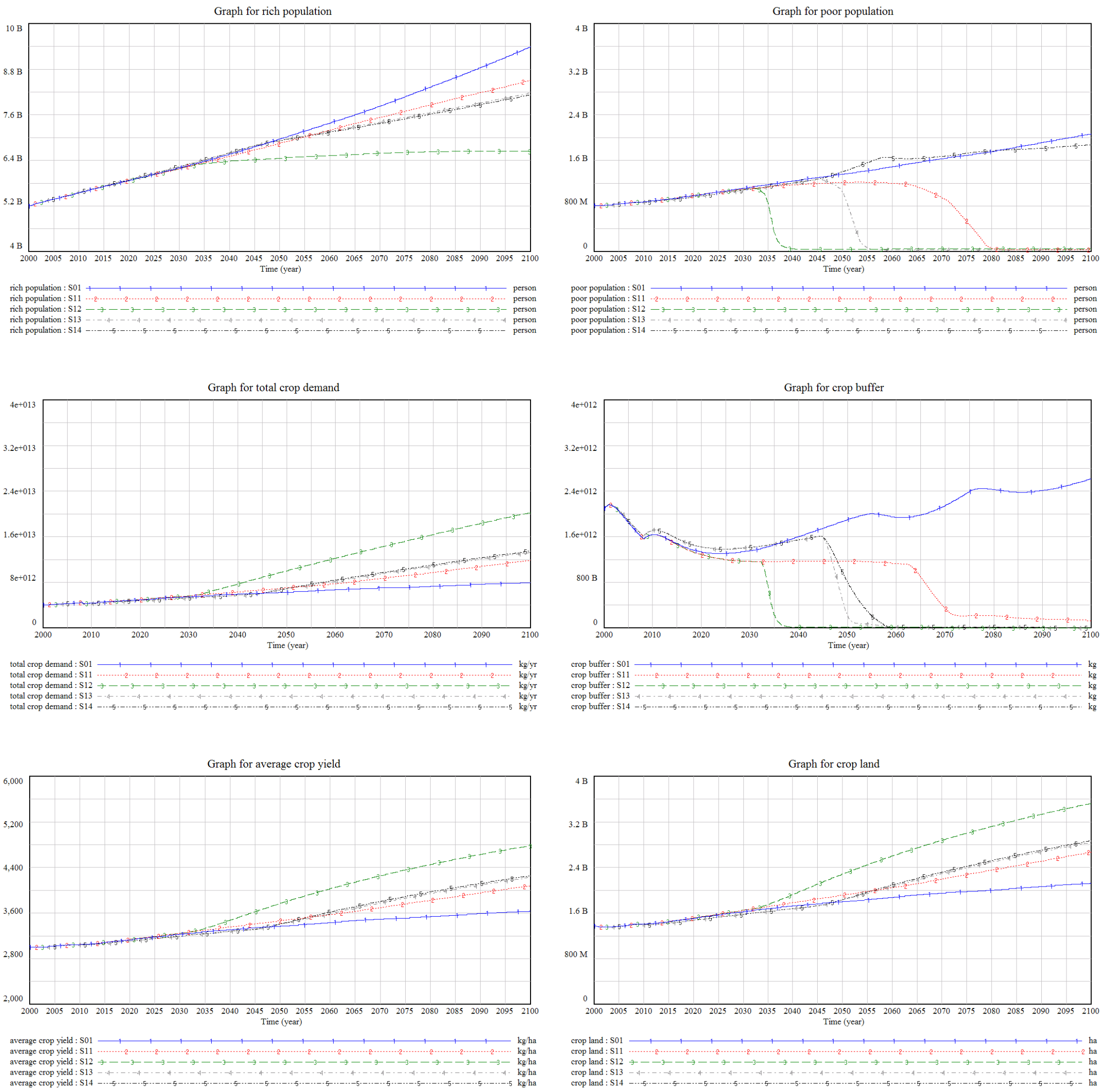


Figure 6: Simulated dynamics of the *rich population*, *poor population*, *total crop demand*, *crop buffer*, *average crop yield*, and *crop land* for scenarios S01, S11, S12, S13, S14 (no breakthrough of second generation biofuel technology)

The System Dynamics model discussed in this paper could and should be extended to include at least the effect of high crop prices and food shortages on bioenergy cultivation and the biofuel sector as a whole: the development of the bioenergy/biofuels sector will most likely, in case of extreme food crises and/or high crop prices, be curbed by high prices and/or political intervention.

The favorable context of high fossil fuel prices and the political willingness to mitigate climate change could be expected to lead to the large-scale introduction of (future) first generation biofuels, which might prepare the market for the introduction, in a later stage, of second generation biofuels. First and second generation biofuels might contribute to increased energy security and mitigation of climate change if, and only if, appropriate bioenergy cultivation and biofuel production techniques are used, and these introductions do not lead to undesirable side effects outweighing their positive contributions.

The large-scale introduction of (future) first generation biofuels will also, impact the dynamics of food crop production and prices, as well as the richness/poverty of subsections of the population, since the crop land for which food and bioenergy crops compete, is scarce and cannot be expanded instantly, and several food crops could be used as feedstock for first generation biofuel production[14]. A serious take-off of bioenergy production combined with a lack of sufficient (potentially available) crop land to accommodate the take-off of bioenergy crops in wealthy parts of the world, high opportunity cost for area expansion, and/or long conversion times, might actually lead to exportation of their problem, and thus food, land and environmental problems in less wealthy parts of the world, in turn (in)directly impacting the wealthy parts of the world too.

Rising food prices threaten at first the food security of the poor, and by extension, countries that are already heavily dependent on food imports or whose dependence on food imports is currently rising. That is the case for many developing countries. Food insecurity will most of all rise for the (urban) poor in these net food importing countries. Rising food prices also raise the cost of food relief, leading to less food for the same emergency aid budgets.

However, these higher prices might also generate more revenues for farmers with sufficiently fertile land and other parts of the agri-alimentary business, and possibly –that is, if continuously increasing fossil fuel prices do not put a spoke in the wheels of farmers and the agricultural sector as a whole– increase the willingness to investment in yield improvement and land expansion and other aspects of the agricultural sector, which might lead, over time, to increased crop yields and expanded crop land areas.

Rising food prices might therefore also boost domestic production in some countries and actually improve the longer-term food security, exports and export revenues for agriculture-oriented developing countries, and hence, offer better prospects for rural populations that depend on agriculture for employment and livelihood.

Biofuel-induced yield improvement and land expansion might however be problematic too if they lead to mono-culture expansion, agricultural intensification, excessive use of fertilisers and pesticides, repression of rural poor through scale enlargement, deforestation (for example of rainforests) and destruction of ecosystems, and even globally increasing GHG emissions[15].

More endogenous investments of extra-economic profits in yield improvement and land expansion might also lead over time to higher bioenergy supplies, which might result –ceteris paribus– in lower prices and decreasing extra-economic profits if and when second generation biofuels take off and reduce the demand for bioenergy crops faster than the demand for food crops increases. This might even –if not managed well at the system level[16]– lead to a (temporary) downturn of the agricultural sector.

---

[14]This diversion of crops destined for food production towards biofuel production might be expected in case of high liquid fuel prices.

[15]These aspects are not included in this simple version of the model. They could be included, but might also be reflected on beyond the boundaries of the System Dynamics model.

[16]Individual actors in the field cannot avoid a bust of the system: the system –if not regulated well– might force them to act in such a way that a system downturn becomes unavoidable.

So, instead of resisting the introduction of biofuels altogether, policy makers might want to make policies that exploit the blessings (the positive effects, such as increased future energy security, increased investments in the agricultural sector) and prevent the curses (negative effects, such as increased food insecurity and impoverishment for the poor).

On the economic dimension, policymakers might want to make sure:

- that farmers can profit from higher prices, but that they have sufficient incentives to reinvest their extra economical profits in technological improvements (crop yields) and/or environmentally sound cropland expansion.
- that first generation biofuels are introduced gradually –not too suddenly/hastily– with the clear long-term objective of realising a transition towards the large-scale use of (predominantly) second generation biofuels. Managing the introduction of biofuels therefore not only means getting them sufficiently off the ground, but also preventing their introduction to take place too rapidly and/or at the expense of other sectors/dimensions. It would be interesting in this respect to design adaptive biofuel policies that would automatically decrease incentives given to bioenergy production when fossil fuel or food prices increase or when the introduction exceeds the desired transition path, and vice versa.
- that the bioenergy cropland that becomes vacant, when second generation biofuels break through, is deployed profitably for increased food crop production to attain the 50% increase in food supply by 2030 as pleaded for at the Rome Food-Climate Summit by UN Secretary General Ban Ki-Moon. That could help to prevent the collapse of the agricultural sector, caused by a boom and subsequent bust of first generation biofuels, and at the same time to achieve the 50% increase in food supply.
- that distributional inefficiencies and market distortions are taken away or decreased. This might be difficult to realise because '[t]rade treatment of biofuels [and basic food supply] is often overshadowed by domestic concerns with energy [and basic food] self-reliance' (FAO 2008d, p30). It could be assumed that the more threatened fuel supply and basic food supply will become, the more 'strategic' and 'protective' the behaviour of local and regional policymakers will be.
- that the negative aspects of speculation (impoverishment of the poor and increasing food insecurity for the undernourished) are tackled, while preserving the positive aspects, such as price signalling and fund raising, offering incentives to increasing future supply.
- that non-intrusive crop yield improvement, biofuel yield conversion improvement, and second generation biofuel technologies are invested in as long as higher crop supplies are required.
- that those who risk to fall into poverty during a food crisis are supported so that they can bridge the food crisis. Suchlike supportive policies allow to sustain total demand until supply catches up, and doing so, helps to avoid harmful cyclic system behaviour or –worse– a downward spiral.

On the social dimension, policymakers might want to make sure:

- that the distributional aspect of the food crisis –one of the root causes and the prime moral issue– is tackled by those who have the means, namely rich nations, especially those nations gaining from high fuel prices –another root cause of the issue.
- that the poor are provided minimally –in case of food price rises– with the means to buy the necessary basic food requirements, instead of dumping cheap food surpluses under the veil of aid, and hence, distorting local agricultural markets and ruining local farmers.
- that food aid is immediately provided in case of serious local/regional shortages, independent of the financial consequences: promises about food aid should also be expressed in terms of amounts of food required, not in financial terms.

- that there is, at any moment, a sufficiently large food buffer for emergency relief. This strategic buffer cannot be left to the market alone.
- that in case of a real *world-wide* food crisis, i.e. one that cannot be buffered, food is given the priority over bioenergy: many first generation biofuel crops could be used for food consumption too. However, the biofuel sector then needs to be aided to survive the crisis. Otherwise, one *bad* (food crisis) will be traded for the other *bad* (breaking off the energy transition), or expressed differently, one *good* (current food security) will be secured at the expense of the other *good* (future energy security).

  This would imply exceptional action against the 'market' (and static first generation biofuel policies), because the market incentives for more biofuels –which become ever more attractive with increasing fossil fuel prices[17]– need to be outstripped (as explained above, without destroying the biofuel sector and hence nipping the sustainable energy transition in the bud).

On the environmental dimension, policymakers might want to make sure:

- that increasing crop land does not lead to deforestation of natural forests, destruction of ecosystems, wildlife areas, and reduction of the diversity of species.
- that attempts to increase crop yields do not lead to harmful agricultural intensification with excessive use of fertilisers and pesticides, and reduction of the diversity of species through mono-culture expansion.
- that increasing crop land and crop yields do not lead to irreversible depletion of –previously renewable– environmental resources, such as water resources.

'Rich' citizens could also act. Useful citizen actions include: switching to low-meat or vegetarian diets, reducing (fossil) fuel use, and reducing food waste.

The final conclusion of this paper is that the question 'Food or Energy' is actually the wrong question: ***both food and energy (security) are needed***. The question that really matters is: *how* could the long-term energy security be increased by means of biofuels, without compromising short-term food security, and/or destroying ecosystems and natural reserves. The way biomass is introduced and produced should be the main topics in the political discussion surrounding biofuels. Although these questions are not thoroughly addressed in this paper[18], they could be investigated with this and similar System Dynamics models. Currently it could already be concluded from the System Dynamics model that a gradual and controlled introduction of biofuels is needed. This study confirms, in that sense, similar conclusions from several recently issued studies, such as the unpublished UK government-commissioned Gallagher-report and recent FAO reports.

6.1.1 Future Work

The simulation model discussed in this section only deals with the high-level dynamics of some aspects of the world food/bioenergy issue. Many important aspects related to the food/biofuel issue have not been dealt with in the current version of the simulation model. Projected future work related to this model includes:

- extending the current model with:
  - some small refinements related to the calculation of costs, prices, profits, technological progress of the bioenergy conversion yield, etc.
  - additional sectors, feedback loops, and boundaries:
    - a ***(bio)fuel demand-crop prices*** feedback loop,

[17] High(er) fossil fuel prices can be expected given the continued medium-term market tightness (IEA 2008).

[18] For a thorough analysis of the introduction and transition of the European bioenergy sector see (Pruyt 2008b)

    * an ***energy-economy*** feedback loop,
    * environmental/ecological aspects and feedback loops,
    * aspects related to resources and local conditions,
    * trade flows between regions/countries, and the trade flow distortions (subsidies, protective tariffs, et cetera).
  - several subscripts which would allow able to deal with: different regions/countries and local conditions, different crop types, different lifestyle profiles[19], etc.

- collecting and using better data and calibration of some variables (such as the *adaptation time poor rich* and *adaptation time rich poor*);
- development of different models for different world-views;
- exploration of different scenarios (e.g. a 50% increase of the total crop demand by 2030) and different types of uncertainties[20]; and
- designing policies and testing their appropriateness and robustness.

References

Bantz, S. and M. Deaton (2006, April). Understanding U.S. biodiesel industry growth using system dynamics modeling. In *Proceedings of the Systems and Information Engineering Design Symposium*, pp. 156–161. DOI 10.1109/SIEDS.2006.278731. 3

BBC News (2008a, 4 June). Bioenergy: Fuelling the food crisis? Available online: http://news.bbc.co.uk/go/pr/fr/-/2/hi/europe/7435439.stm. 2

BBC News (2008b, 6 June). UN plan to increase food supplies. Available online: http://news.bbc.co.uk/go/pr/fr/-/2/hi/europe/7439015.stm. 2

Chakrabortty, A. (2008, Friday July 4). Secret report: biofuel caused food crisis. Internal World Bank study delivers blow to plant energy drive. *The Guardian*. 2

CIA (2007). *World Fact Book*. 9

de Vries, B., M. Janssen, and A. Beusen (1999). Perspectives on global energy futures: simulations with the TIME model. *Energy Policy 27*, 477–494. 19

European Environmental Agency (2006). *How much bioenergy can Europe produce without harming the environment?* Luxembourg: Office for Official Publications of the European Communities. 3

FAO (2004). The state of food insecurity in the world 2004. Technical report, FAO, Rome. 9

FAO (2008a, June). Bioenergy and food security. Information sheet for the High-Level Conference on World Food Security: the Challenges of Climate Change and Bioenergy HLC/08/BAK/7, FAO, Rome. 2

FAO (2008b, June). Bioenergy policy, markets and trade and food security. Technical background document from the expert consultation held on 18 to 20 February 2008 FAO, Rome: HLC/08/BAK/7, FAO, Rome. 2

FAO (2008c, April). Climate change, bioenergy and food security: Civil society and private sector perspectives. Information document for the High-Level Conference on World Food Security: the Challenges of Climate Change and Bioenergy: HLC/08/INF/6, FAO, Rome. 2

[19] See for example (Pruyt 2008a; de Vries, Janssen, and Beusen 1999).
[20] See (Pruyt 2007).

FAO (2008d, April). Climate change, bioenergy and food security: Options for decision makers identified by expert meetings. Information document for the High-Level Conference on World Food Security: the Challenges of Climate Change and Bioenergy: HLC/08/INF/5, FAO, Rome. 2, 6, 17

FAO (2008e). Forests and energy - key issues. Technical report, Rome. 9

Flynn, H. and A. Ford (2005). A system dynamics study of carbon cycling and electricity generation from energy crops. In J. Sterman, N. Repenning, R. Langer, J. Rowe, and J. Yanni (Eds.), *Proceedings of the 23rd International Conference of the System Dynamics Society*, Boston. System Dynamics Society. 3

Gilland, B. (2002). World population and food supply: Can food production keep pace with population growth in the next half-century? *Food Policy 27*, 47–63. 9

IEA (2008). Medium-term oil market report. Studies, International Energy Agency. 18

IMAGE-team (2001). The IMAGE 2.2 implementation of the sres scenarios: a comprehensive analysis of emissions, climate change and impacts in the 21st century. Technical report, RIVM, Bilthoven. 9

Müller, A., J. Schmidhuber, J. Hoogeveen, and P. Steduto (2007, January). Some insights in the effect of growing bioenergy demand on global food security and natural resources. Paper presented at the International Conference *Linkages between Energy and Water Management for Agriculture in Developing Countries, Hyderabad, India. 2*

OECD-FAO (2008). OECD-FAO Agricultural Outlook 2008-2017*. OECD-FAO. 2*

Pruyt, E. (2007). Dealing with uncertainties? Combining System Dynamics with Multiple Criteria Decision Analysis or with Exploratory Modelling. In Proceedings of the 25th International Conference of the System Dynamics Society*, Boston, MA, USA. 19*

Pruyt, E. (2008a, July). Dealing with multiple perspectives: Using (cultural) profiles in System Dynamics. In Proceedings of the 26th International Conference of the System Dynamics Society*, Athens, Greece. 19*

Pruyt, E. (2008b, July). Towards large-scale European bioenergy/biofuel production? Working Paper Delft University of Technology*. 1, 14, 18*

Richardson, G. (1997). Problems in causal loop diagrams revisited. System Dynamics Review 13*(3), 247–252. 4*

Scheffran, J., T. Bendor, Y. Wang, and B. Hannon (2007). A spatial-dynamic model of bioenergy crop introduction in Illinois. In Proceedings of the 25th International Conference of the System Dynamics Society*, Boston, MA. System Dynamics Society. 3*

Sterman, J. (2000). Business dynamics: systems thinking and modeling for a complex world*. Irwin/McGraw-Hill: Boston. 2*

Tesch, T., P. Descamps, and R. Weiler (2003). The COSMOPAD modelling framework: Conceptual system dynamics model of planetary agricultural and biomass development. Proceedings of the Digital Earth Conference, Brno*. 3*

Westcott, P. (2007, May). Ethanol expansion in the United States: How will the agricultural sector adjust? United States Department of Agriculture FDS-07D-01*. 3*