The GLU Model

Can we feed the world and survive it?

by Kai Neumann, Consideo GmbH

Abstract

The Global Land Use Model developed for a project for the German Environment Agency explores the potentials for biotic resources - food/non-food, material/energetic - using a system dynamics model and data from the FAO and the World Energy Outlook. It looks at the land use for forests, extensive or intensive agriculture, and for infrastructure, the development of the population and its plant and animal based diet, the waste of food and the use of both wood and non-wood biomass for materials and energy generation. The GLU Model also looks at the relative impacts of the global land use on greenhouse gases in the atmosphere. The simulations indicate that the current trajectories even without the assumption of major yield losses as a result from climate change would not allow us to further feed the world. Unless the world takes concerted action the logic would be a continued deforestation. However, a combination of moderate changes in diet, food waste, energetic use of biomass, and the utilization of extensively used land would allow for afforestation substituting steel and concrete with an end of life energetic use of biotic materials for a significant contribution to tackling climate change as would the shift towards organic farming that, too, would help to capture carbon from the atmosphere plus its additional benefits for biodiversity and resilience to extreme weather.

Objective of the GLU Model

The GLU Model (Global Land Use Model) was developed to support the ICARE Simulation Model (Neumann, Hirschnitz-Gabers, 2022) for the German Environment Agency by Consideo and Ecologic Institute to explore the role of resource efficiency for the global energy transition and greenhouse gas emissions. Next to the classic materials like copper or neodymium the study looked at the potentials to substitute greenhouse gas intensive steel and concrete (Churkina, et.al. 2020) through biotic resources. For that question we wanted to know what potential for biotic materials as well as for their energetic use there will remain after feeding the growing population and what that would imply for greenhouse gas emissions and sequestration.

The model has a huge potential to explore many more aspects, like the role of extreme weather, the differentiation of regions in the world, the potential for even more afforestation etc.. This paper for the system dynamics community only describes the model and some selected scenarios and conclusions that should contribute some valuable memes to the public discussion. However, the paper is not a complete documentation of the model.

The system dynamics GLU Model

The GLU Model uses 529 factors and runs in monthly steps from 1990 to 2100. We have chosen system dynamics model for two reasons: First, because of the synchronization with the ICARE model - hence the monthly steps - that used a process modeling approach based on system dynamics. Second, because of the delayed processes like afforestation or a successive change of diet, the development of the size of the population, or the cascading use of biotic materials with their end-of-life energetic use.

Note: the software iMODELER directly translates causal loop diagrams (CLD) into quantitative system dynamics models with no need for explicit stock and flow factors. However, the GLU Model uses the formula for stocks so it could be transferred into other system dynamics tools.

Another note: the screenshots reveal additional factors that are not featured in this paper, e.g. to consider the area needed for installations of renewable energy or the effects from severe weather. The potential effects from these additional factors for the scenarios of this paper is set to zero to limit the complexity of the scenarios and explore the effects of the measures under ceteris paribus conditions.

Structure

The GLU Model looks at the same regions of the world as the ICARE model that is based on the data from the World Energy Outlook (WEO) by the International Energy Agency (IEA, 2015). Model wise the regions were just cloned, connected, and their data adopted accordingly. To differentiate the regions of the world allows for further elaborated scenarios considering varying farming practices and diets in the world. Nevertheless, the GLU Model also features factors for a world market for food and biotic materials.

For each region the model (figure 1) looks at the available area for agriculture resulting from the conversions (flows) to agricultural area from forests and underutilized areas (Jering, et.al., 2013) and the conversions from agricultural area to forests or built area.

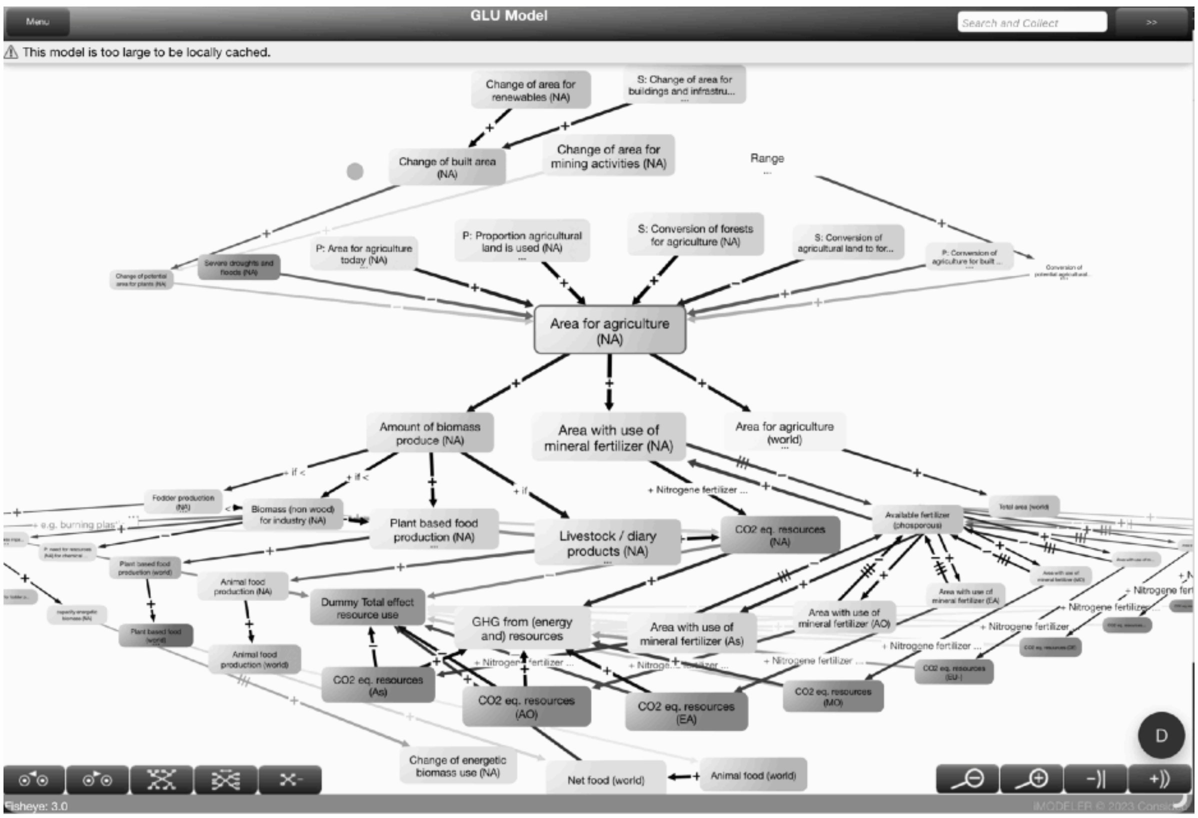

Figure 1: GLU Model from the perspective of agricultural area in North America

The area for agriculture is further differentiated into conventional and organic farming practices as well as alternative farming practices like permaculture, terra preta or agroforestry.

The use of the produce from agricultural land starts with the need for fodder production, continues with the amount dedicated for non-food industrial use and as a result leaves the rest for plant based food (figure 2).

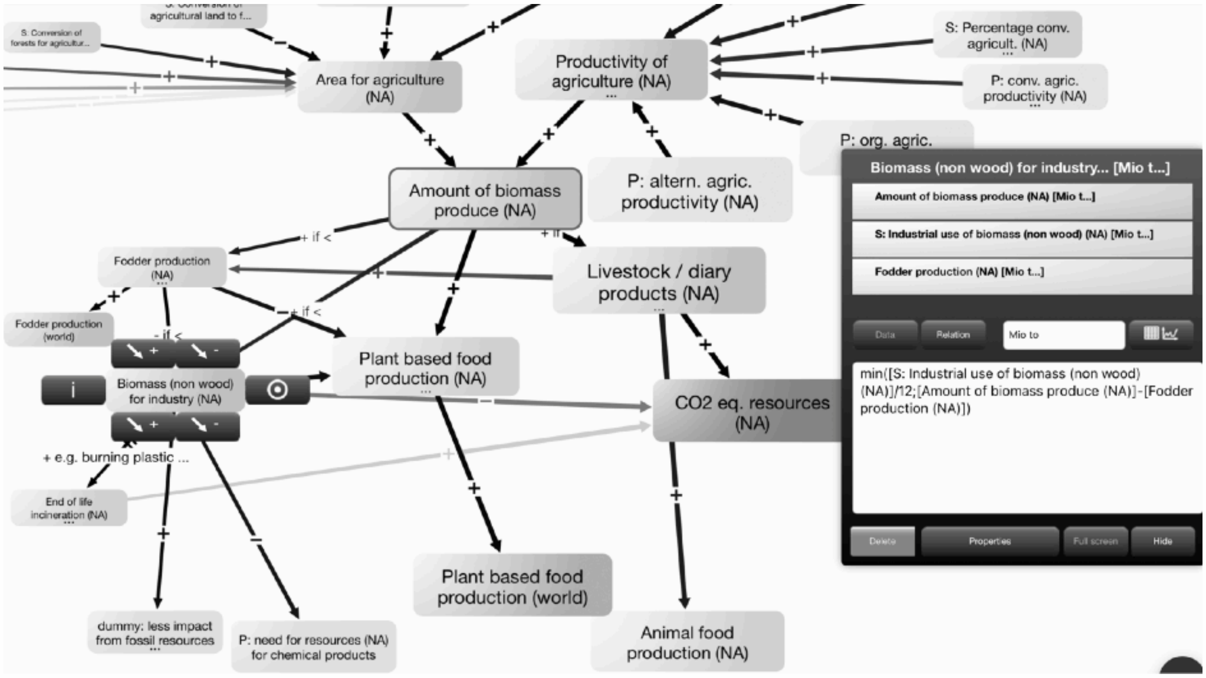

Figure 2: GLU Model from the perspective of biomass produce in North America

The GLU Model (figure 3) looks at the people's diet distinguishing just the amount of animal products as a combination of meat, eggs, milk, and cheese per person starting with the United Nations (UN) Food and Agriculture Organization's (FAO) projections. Food waste described by just one factor per region represents the waste all along the chain from field to the consumer and adds to the demand per person.

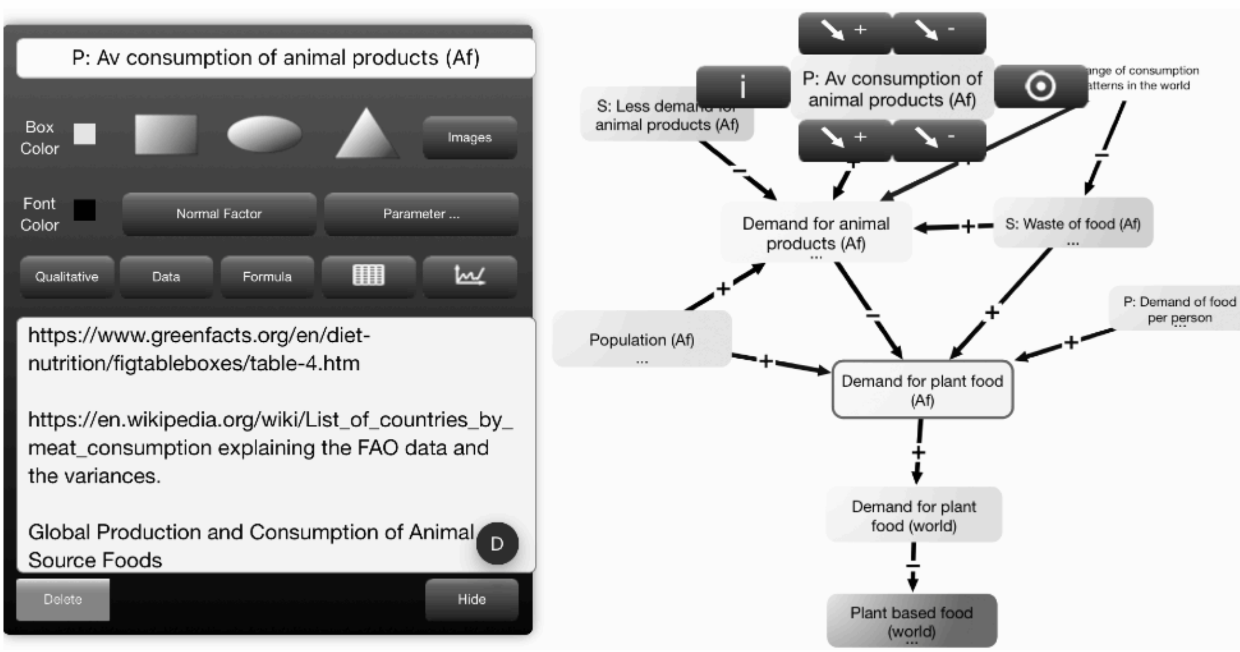

Figure 3: GLU Model from the perspective of the demand for plant food in Africa

Note: Since the factor to describe the shift to alternative farming practices summarizes agroforestry, permaculture, terra preta and the use of legumes the model looks just at change from the supply side offering more legumes based products. It doesn't consider a change of diet towards the use of more legumes to change the production by demand from the consumer side. Legumes come with two major benefits: unlike grain they offer the same yield from organic farming practices as from conventional farming practices and they are healthier than the consumption of grain like wheat (Harrari, 2011).

Forests result from the allocation of area and the amount of harvested wood (figure 4). The wood can either be used as fire wood or for materials. If used for materials there will be an end of life energetic use and the parameter for a life span of material use implies the different applications as well as a possible cascading use.

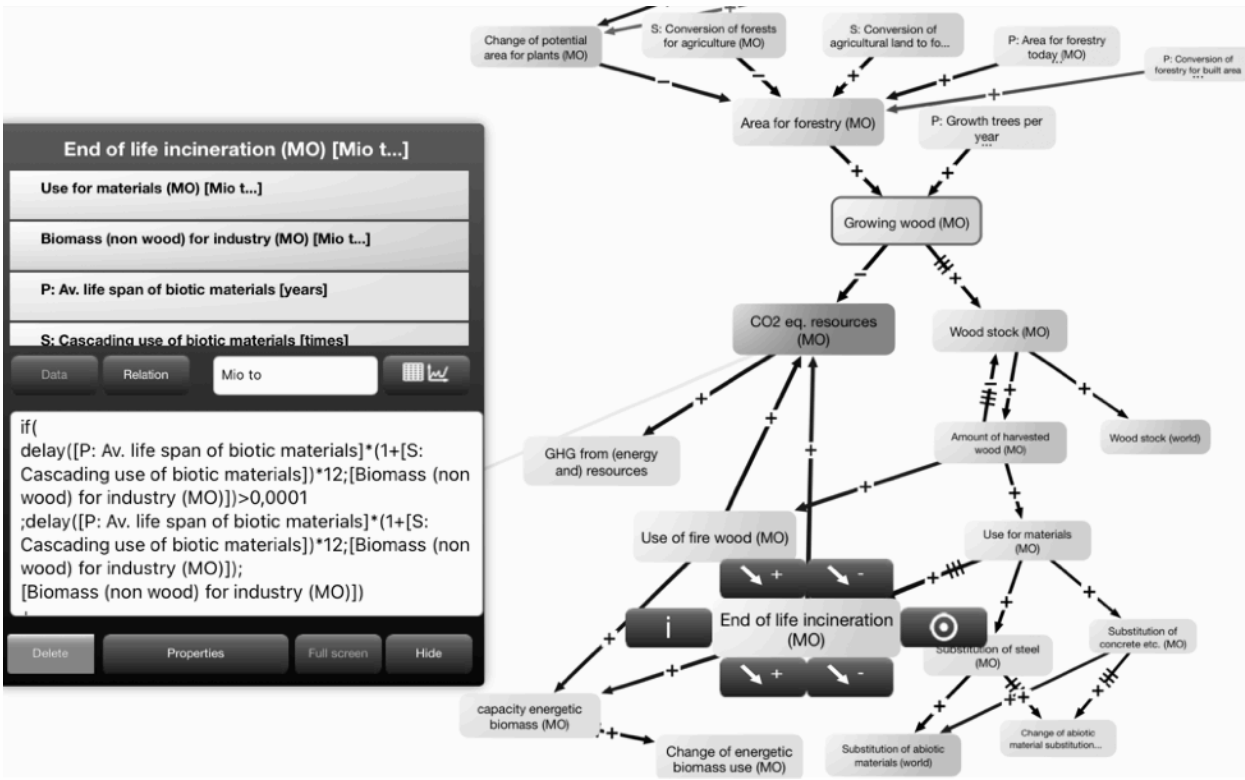

Figure 4: GLU Model from the perspective of growing wood in the Middle East

The growth of wood minus the energetic use of wood plus the material use as a substitution for greenhouse gas intensive steel and concrete contributes to the total reduction of greenhouse gas in the atmosphere though the effect from material use with the end of life combustion remains relative. The model simplifies the system since it doesn't consider the difference of older forests with physical decomposition of old wood versus the harvesting of mature trees making space for younger trees and their capturing of carbon dioxide (CO_2). The model uses just one parameter for growth of wood per area.

The GLU Model does not try to look endogenously at the choices of production driven by markets and policies. Instead the choices are made by the user of the model and the result is the theoretical surplus or shortage of food in the world (figures 6 to 9).

Next to the potential to feed the world the model looks at the effects from LULUCF on the total of greenhouse gases expressed by carbon dioxide equivalents (CO_{2eq}) that also include the methane from cattle or the nitrous oxide from mineral fertilizer for agriculture.

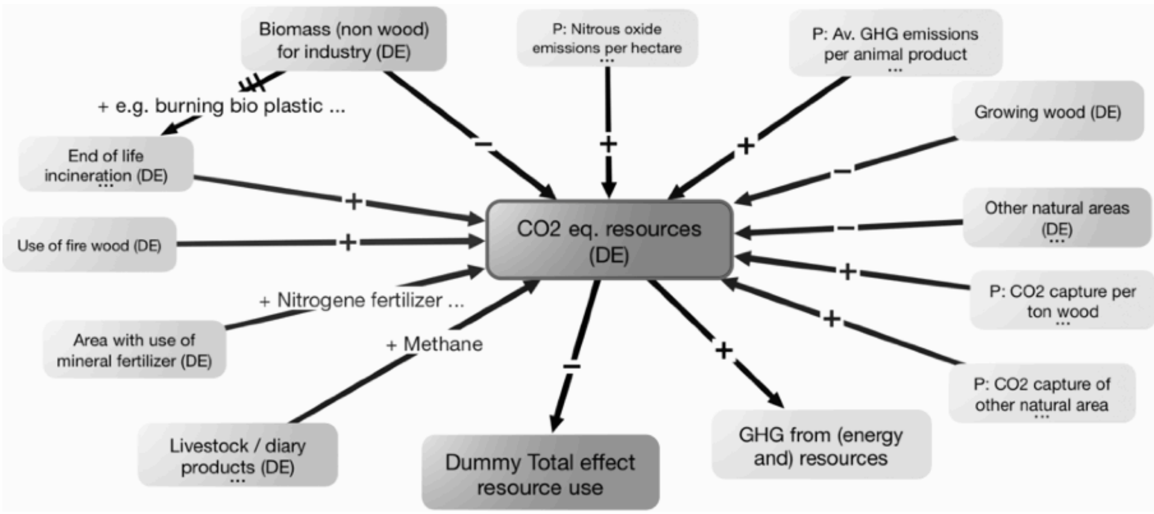

Figure 5: GLU Model from the perspective of the carbon dioxide equivalents in Germany

Data

The data behind the model mostly comes from the FAO. The projected development of the population from the OECD. Some of the factors offer more than one source named in the description of the factors. For example the capturing of CO_2 out of the air by trees knows different figures from different studies that could be used for sensitivity analyses.

For the crops and their yields the GLU model uses the average yield by staple foods in the different regions. There are, of course, crops with higher yields but usually neither for consecutive years nor on all soils.

Limitations

The GLU Model comes with numerous limitations. Of course, as it only uses average values it could only remain valid as changes are considered to effect the average. For example, if the current composition of forests as a mixture of all kind of trees is changed e.g. by afforestation with more productive varieties of trees or by deforestation of less productive varieties the change won't be proportional to the area that is altered. The same is true e.g. for a change of diet if the model considers a mix of animal products from cattle, pigs and poultry and any change e.g. to just reduce the consumption of products from cattle would be over-proportional in its effects with regard to greenhouse gas emissions. Since the objective of the model is to explore the rough potentials of the whole planet and not detailed instruments this level of aggregation for the different dimensions of the model seems feasible. From a modeler's perspective it would be fairly easy to add more differentiation at different aspects of the model though one has to be careful to interpret an added level of detail to result in more precise scenarios. The potential of added details should rather be seen as a basis for a sensitivity analysis to explore the range of possible scenarios.

A quite substantial limitation stems from the original data from the FAO. As the FAO itself notes the data doesn't add up. E.g. the average productivity times the available area doesn't match the total yield - neither on a global nor on every regional level. The reasons are manifold ranging from lack of data or false data to varying definitions of regions, e.g. Europe or Latin America. Despite these flaws in data the magnitudes seem to be correct and the use of FAO data without alternative.

Parameters

The whole model features about 150 parameters. Here is a list of the parameters that basically can be used to define scenarios. Most of the parameters can be set explicitly for each region.

Also, most parameters are not a constant but a time series, e.g. the assumption of a growing proportion of alternative farming practices over time.

- Proportion of alternative farming practices (agroforestry, permaculture, terra preta, legumes etc.
- Amount of harvested wood
- Animal food production
- Cascading use of biotic materials (implying a design for recycling etc.)
- Change of area for buildings and infrastructure
- Conversion of agricultural land to forests
- Conversion of forests for agriculture
- Industrial use of biomass (non wood, e.g. for bioplastics and other chemical products)
- Less demand for animal products (increased proportion of vegan and vegetarian diet)
- Management of bio-waste (manure, wastewater-treatment, etc. to use less mineral fertilizer)
- Percentage of conventional agriculture (the rest would be organic farming practices)
- Proportion of harvested wood that is directly used energetically
- Waste of food (as a percentage along the chain from acre to transport to storage to production to retail to consumer)

For the business as usual scenario the model features time series that describe the continued increase of the proportion of animal products in the diet of people from Asia and Africa and time series that describe the continued conversion of land for infrastructure in all regions, and even a time series that assumes further improvements in yields from the use of fertilizer and optimized crops.

Validation

Since the model runs simulations from 1990 to 2100 the first 30 years to an extent could be used to validate the model. For the past the area and the average produce per hectare roughly matched the amount of food production needed to feed the world. Although the model allows to consider the effects from weather extremes we haven't included them in the data of the past.

Outputs

From the choices made with the scenarios the most important output is the amount of food that is lacking or available subtracting the demand from the produce. Another major output is the relative effect on CO_{2eq}. The scenarios then are defined by the aforementioned parameters describing the extent of organic farming, the use of wood as a building material, the area used for forests and their net carbon binding, all of which is relevant for policies and the fate of the world with regard to biodiversity.

Scenarios

From the seemingly endless number of possible scenarios we describe only three with this paper:

1. a 'business as usual' scenario (b.a.u. scenario) with continued growth in population, further improvements in conventional agriculture (seeds, fertilizer, high precision farming, etc.), further conversion of land for infrastructure, and a continued change in diet in Asia and Africa (more animal products).

2. based on the b.a.u. scenario a 'moderate change for good' scenario regarding food waste, diet (less animal products), afforestation with cascading wood use, and the conversion of parts of underutilized land.
3. based on the 'moderate change for good' scenario a 'consequent shift' scenario towards organic farming combined with change of diet in favor to legumes.

b.a.u. scenario

The b.a.u. scenario basically is the scenario that the economy is heading for. More industrial agriculture with improved seeds, targeted pesticides, use of mineral fertilizer and the whole prospect of digitized high precision farming on the one hand, and increased demand for processed food including meat and dairy products in all parts of the world on the other hand. With rising demand for fodder there will be growing need for deforestation. Without increased deforestation the simulation of the magnitudes shows (figure 6) that we face a global shortfall of supply of food (green plot) while the net sink function for greenhouse gases is shrinking (red plot) with the area for forests (blue plot). The turquoise plot shows the development of the global populations. This scenario clearly describes that the current trajectory of demand and supply won't work - even without the assumption of major catastrophes from climate change.

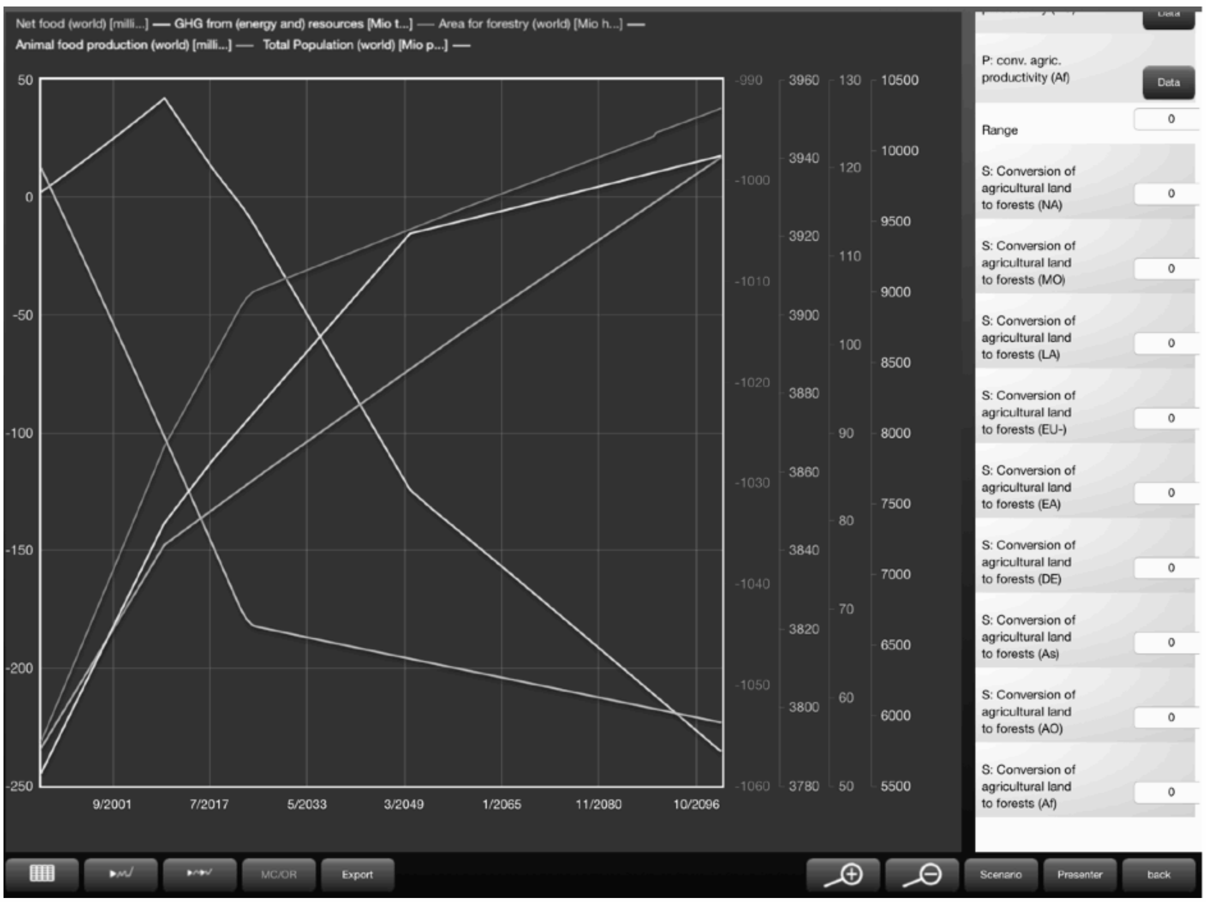

Figure 6: GHG emissions, food supply and area for forests in the b.a.u. scenario

moderate change for good scenario

Since a lot of levers could be combined to describe alternative narratives for the future we used a monte-carlo simulation to explore the bandwidth of possible developments (figure 7).

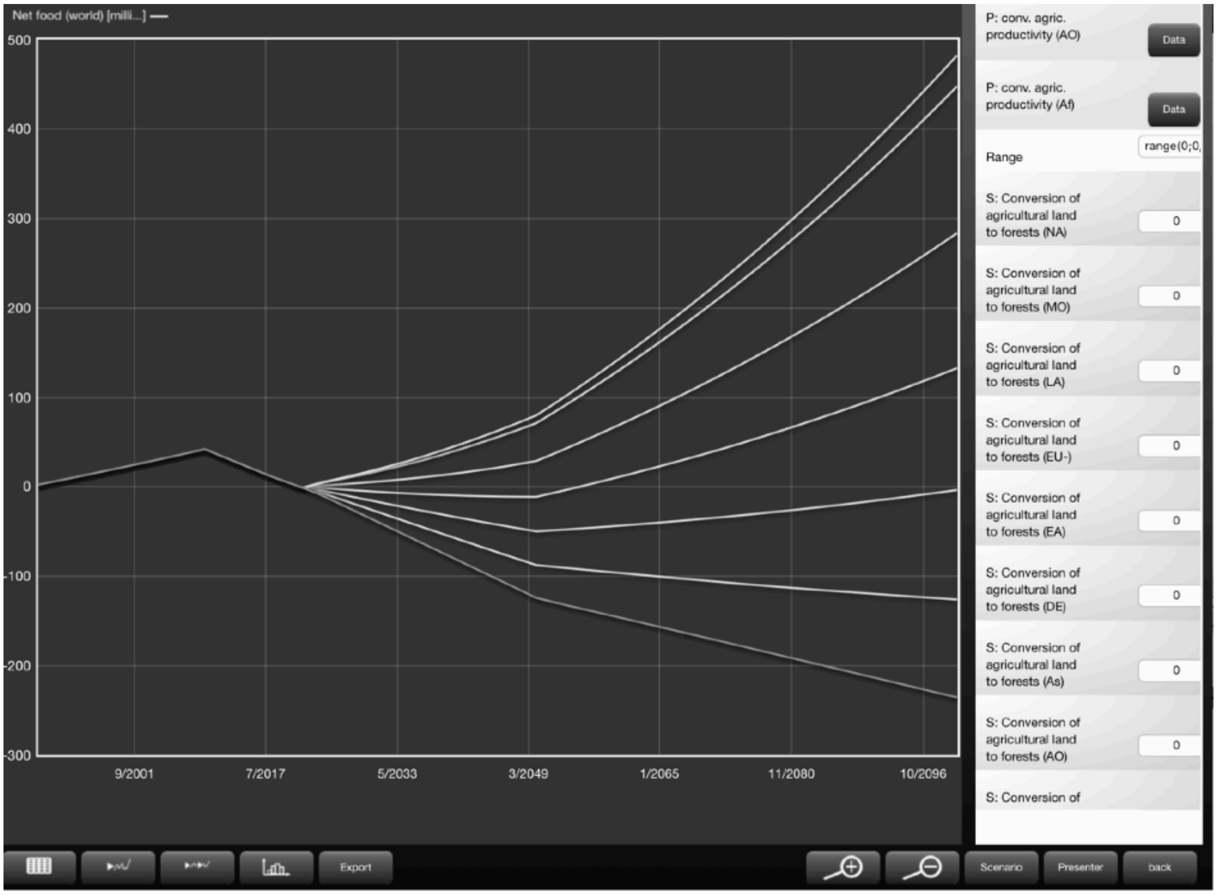

Figure 7: GHG emissions, food supply and area for forests in the b.a.u. scenario

Different combinations of less food waste, less consumption of animal products, more conversion of under- or not utilized potential agricultural area would lead to scenarios with sufficient surpluses of food for the world's population that would even leave room for afforestation. The 'moderate change for good' scenario assumes that the world decides to eat 50% less animal products, to waste 50% less food and to utilize 50% for the untapped potential for agricultural area.

Figure 8 shows how as a consequence the area for forests could be increased and how the net sink function of the system for greenhouse gases could increase. The variances in the green plot for the surplus or shortage of food on the world market is an artifact from the overlapping dynamics from the different regions the GLU-model considers.

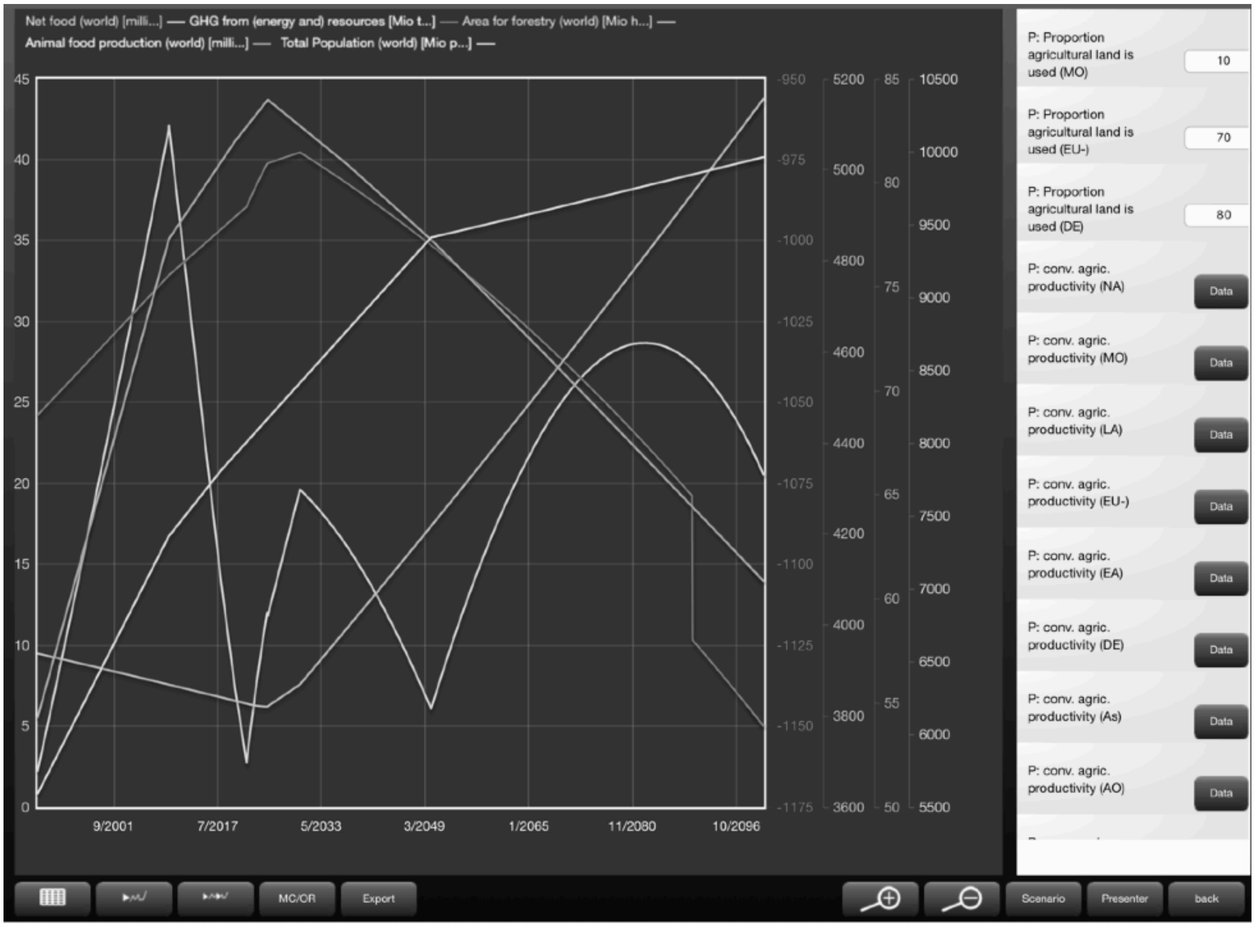

Figure 8: GHG emissions, food supply and area for forests in the moderate change scenario

consequent shift scenario

The fate of our quality of life on earth not just depends on the supply of food but also on eco system services that come with biodiversity. That's why a lot of people argue for organic food production while the counter argument claims that the productivity of organic agriculture is way lower and thus it would require more deforestation. The simulations could only confirm that a ceteris paribus diet and variety of crops would require more forest area to be used for agriculture with all the implications for greenhouse gases and biodiversity. However, if we assume a change in diet away from grain like wheat towards healthier legumes that offer high yields without the use of mineral fertilizer and pesticides we could theoretically get to 100 percent organic farming in the world as figure 9 shows with the 'consequent shift' scenario.

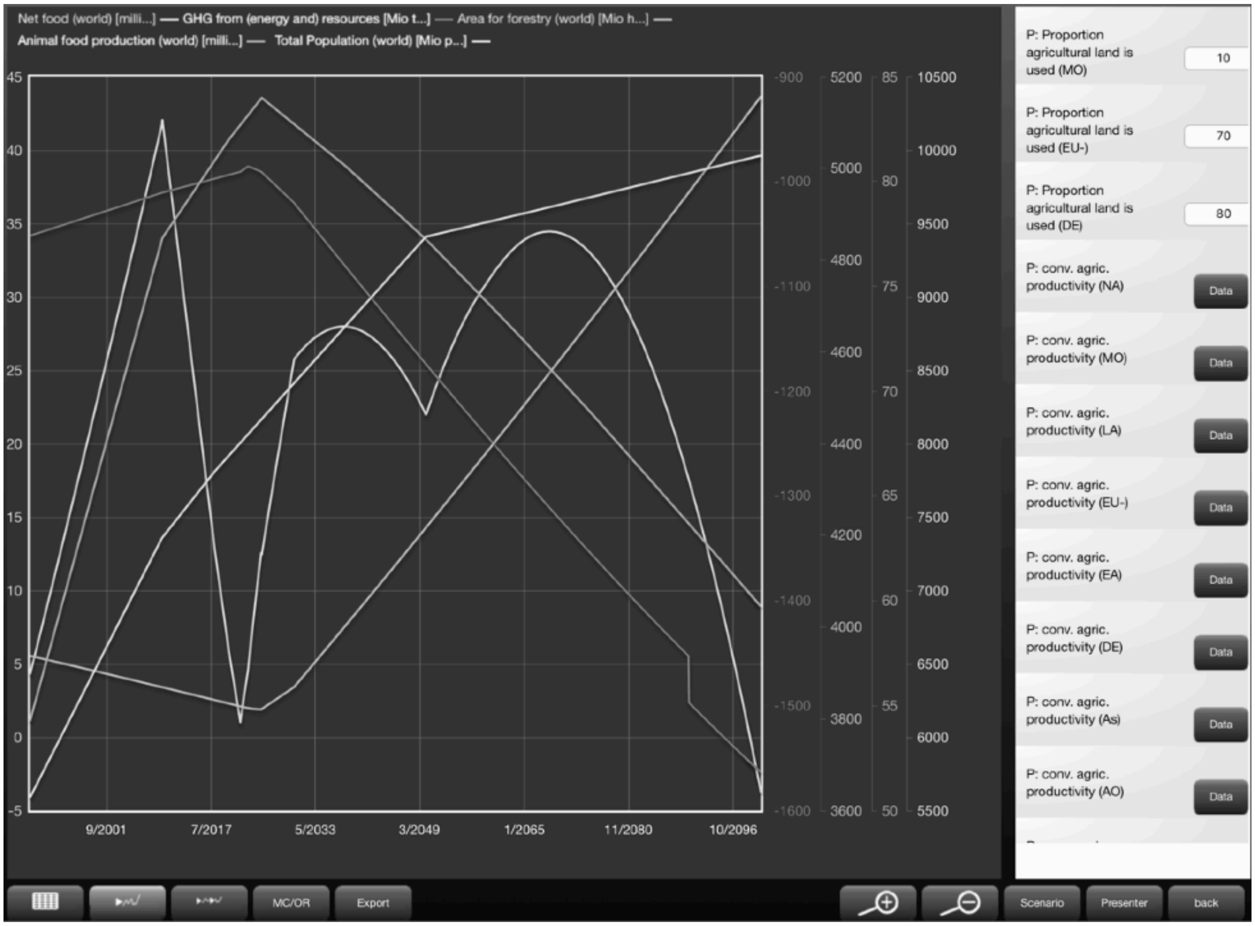

Figure 9: GHG emissions, food supply and area for forests in the consequent shift scenario

Again, just looking at the magnitudes the scenario shows that we can have the same area for forests and have more of a net carbon sink compared to the with mainly conventional farming.

Interpretation

Originally, the GLU-model's purpose was to explore the global potentials to use biotic materials as a substitute for steel and concrete. Realizing, that unlike probably most of us learned at school, that feeding the world is not just a matter of distribution - at least not for much longer - inspired us to use the model for further explorations. There have been wheat shortages for some consecutive years due to extreme droughts in Russia and the US, there is the dramatic loss of biodiversity and the ongoing debate whether we need industrial farming or organic farming.

Even without the consideration of prices, patents, and trade barriers the model allows to look at the realistic magnitudes of biotic resources. Of course, there are more levers than just the shift towards more legumes to achieve similar yields from organic farming compared to conventional farming, e.g. more labor intensive permaculture or agroforestry. Organic farming does not just imply less greenhouse gas emissions because of less use of mineral fertilizer, and more biodiversity because of less pesticides. It also has the potential to be more resilient to climate change and if labor intensive it could counter the troublesome mega trend of urbanization without perspective in the so called global south (Neumann, Grimm, 2020).

The model already features more details like fish and aquatic cultures that are not mentioned in this paper and yet it is less of a finished work than rather a tool that can be improved by adding more details, updated data and more elaborated scenarios. Only system dynamics could make these dynamics over time transparent.

So far GLU-model allows to backup three important memes for the public discourse:

1. On the current trajectory we won't be able to feed the world much longer even if we consider advances in agricultural productivity, neglect the thread from climate change, or consider transforming even more forests into arable land.
2. We would just need to waste less food, eat less animal products, and utilize more agricultural land to even be able to grow more woods.
3. To the extent that we change our diet to more legumes we could feed the world with organic farming with all its benefits for biodiversity, resilience, and reduction of greenhouse gas emissions.

References

Agrawal, S. (2017): Geographic Aspects of Vegetarianism. In: Mariotti, F. (ed.): Vegetarian and Plant-Based Diets in Health and Disease Prevention, Elsevier, pp.93-106, doi: 10.1016/B978-0-12-803968-7.00006-X

Bruinsma, J. (Ed.), "World agriculture: towards 2015/2030. An FAO perspective," FAO, Earthscan Publication Ltd, London, 2003.

Churkina, G., et al., "Buildings as a global carbon sink," Nat Sustain, vol. 3, no. 4, pp 269–276, 2020, https://doi.org/10.1038/s41893-019-0462-4, https://doi.org/10.1038/s41893-019-0462-4

Galli, A., Moreno Pires, S., Iha, K., et al. (2020): Sustainable food transition in Portugal: Assessing the Footprint of dietary choices and gaps in national and local food policies. Sci Total Environ.; 749: 141307. doi: 10.1016/j.scitotenv.2020.141307

Harari, Y.N. (2011), Sapiens - A Brief History of Humankind. Penguin Random House, London, 2011.

IEA (2015): World Energy Outlook 2015. www.iea.org/weo

Jering A, Klatt A, Seven J, Ehlers K, Günther J, Ostermeier A, Mönch L. Globale Landflächen und Biomasse nachhaltig und ressourcenschonend nutzen. Umweltbundesamt, Dessau, 2013

Neumann, K., Hirschnitz-Garbers, M., Material efficiency and global pathways towards 100% renewable energy systems – system dynamics findings on potentials and constraints, J.sustain. dev. energy water environ. syst., 10(4), 1100427, 2022, doi: https://doi.org/10.13044/j.sdewes.d10.0427

Neumann, K.; Grimm, F. (2020). Bioeconomy - the intelligent way. Consideo GmbH, Lübeck doi: 10.13140/RG.2.2.31251.96801

Neumann, K. (2021). Wrong memes: Organic farming and battery electric vehicles. In "Sustainable Development and Resource Productivity - the Nexus Approaches", Harry Lehmann (Ed.), Routledge, New York

Muller, Adrian; Christian Schader, Christian; El-Hage Scialabba, Nadia; Brüggemann, Judith; Isensee, Anne; Erb, Karl-Heinz; Smith, Pete; Klocke, Peter; Leiber, Florian; Stolze, Matthias & Niggli , Urs (2017) Strategies for feeding the world more sustainably with organic agriculture. Nature Communicationsvolume 8, Article number: 1290 (2017)

Röös, Elin; Mie, Axel; Wivstad, Maria; Salomon, Eva; Johansson, Birgitta; Gunnarsson, Stefan; Wallenbeck, Anna; Hoffmann, Ruben; Nilsson, Ulf; Sundbarg, Cecilla; Watson, Christine A. (2018) Risks and opportunities of increasing yields in organic farming. A review. Agronomy for Sustainable Development (2018) 38: 14

Seufert, Verena; Ramankutty, Navin; Foley, Jonathan A.(2012): Comparing the yields of organic and conventional agriculture. Nature 485, 229-232.

Stubbs, J.J., Scott, S.E., and Duarte, C. (2018): Responding to food, environment and health challenges by changing meat consumption behaviours in consumers Nutr. Bull., 43 (2) (2018), pp. 125-134, doi: 10.1111/nbu.12318

Thompson, J., Millstone, E., Scoones, I., Ely, A., Marshall, F., Shah, E. and Stagl, S. (2007) Agri-food System Dynamics: pathways to sustainability in an era of uncertainty, STEPS Working Paper 4, Brighton: STEPS Centre

Wozniak, H., Larpin, C., De Mestral, C., Guessous, I., Reny, J., & Stringhini, S. (2020): Vegetarian, pescatarian and flexitarian diets: Sociodemographic determinants and association with cardiovascular risk factors in a Swiss urban population. British Journal of Nutrition, 124(8), 844-852. doi:10.1017/S0007114520001762