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► To cite this version:

Bruno Dorin, Pierre-Benoît Joly. Modelling world agriculture as a learning machine? From mainstream models to Agribiom 1.0. Land Use Policy, 2020, 96, pp.103624. 10.1016/j.landusepol.2018.09.028 . hal-02106267

HAL Id: hal-02106267

<https://hal.science/hal-02106267>

Submitted on 31 Aug 2020

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Modelling world agriculture as a learning machine? From mainstream models to Agribiom 1.0

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Introduction

Since the late 1960s and the work of Jay Forrester (1971), global modelling has been widely used to construct representations of future earth systems. Often this is done to objectify concerns related to planetary boundaries (Rockstrom et al., 2009), which began with Malthus's 1798 magnum opus *An Essay on the Principle of Population as it Affects the Future Improvement of Society*. They have been notably used to analyse questions related to food security during the 1960s and 1970s, liberalisation of international trade during the 1980s (Cornilleau, 2016) and, from the 1990s, climate change (Dahan, 2007; Edwards, 2010) and other environmental issues (e.g., soil, water, biodiversity).

The making and use of global models raise several questions including: what are their political backstories and the policy implications of the futures they produce? What do they make (in)visible? How are they linked to public decision-making? Do they close down (produce virtual realities that should not be discussed) or open up (provide tools to explore a plurality of possible futures) (Stirling, 2008)? Do they perform as boundary objects that connect different social worlds, i.e., diverse scientific and policy-making communities (Star and Griesemer, 1989)?

In this article, we focus on world agriculture and food modelling to address these questions. We draw on economic sociology and Science and Technology Studies (STS) to propose a theoretical and analytical framework (Section 1). We follow the inspiration of Alain Desrosières and other STS scholars who posit that economic models are hybrid, both tools of evidence and tools of government (Desrosières 2014). We draw on the distinction introduced by Frank Berkhout and colleagues between models as "truth machines" and scenarios as "learning machines". We then develop a dual analysis. Section 2 provides a brief socio-history of world agriculture modelling and identifies trends in mainstream modelling. Section 3 analyses the Agrimonde experience, a foresight initiative based on the Agribiom model, which reveals some political dimensions made invisible by the mainstream models. We show that whereas mainstream models are generally constructed as "truth machines", it is possible to design an economic model as a "learning machine".

In both Sections 2 and 3, our analysis shows that economic modelling is context dependent, and that knowledge and politics are coproduced (Desrosières, 2008; see also Jasanoff, 2004). In particular, we show that genealogies of ways of knowing are the product of interactions between epistemic communities and institutional strategies. We demonstrate, also, that path-dependency, related to technical devices that support modelling and epistemic communities, creates strong irreversibilities in modelling methods and tends. This legitimates a narrow set of solutions for world agriculture and food production problems and, hence, to future land use and access to resources. All these

models are value-laden and, as Pritchard et al. (2016) suggest, analysing their production, frameworks, calculations, tools and the ideas that shape the models “helps us to understand how, for instance, certain solutions to world hunger – such as large-scale land deals geared towards production of commodity crops for export – ‘make sense,’ while other solutions – such as large-scale land reform to feed the poor – seem radical and unlikely in the current conjuncture (Wolford, 2015)”. Against this background, Agrimonde and Agribiom show that using an economic model instead as a “learning machine” reveals actors, processes and possible futures that are made invisible in mainstream models.

1. Theoretical and conceptual framework

In this paper, we adopt a theoretical and conceptual framework inspired by economic sociology and STS (e.g. Callon, 1998; Pinch and Swedberg, 2008). More specifically, we draw on the seminal work of the statistician and historian Alain Desrosières (2014, posthumous book) who highlighted the dual role of economics as a tool of both evidence and government. We thus aim to identify different ways of designing economic models according to their political implications.

We distinguish two main types of models: models as “truth machines” vs. models as “learning machines”. This distinction, introduced by Berkhout et al. (2002),¹ enables us to contrast traditional models of world agriculture built and used to produce evidence-based predictions, with models and scenarios built and used as learning machines. In the latter, the traditional dichotomy between “analysis” and “participation” is erased. Participation provides resources for scenario building (policy learning) while also generating critical self-reflection and preparing the conditions for change (organisational learning). According to Berkhout and colleagues, it is in this joint sense that scenario tools can be regarded as learning machines.

Epistemological choices embedded in ways of modelling have political implications for at least two reasons. First, any model rests on framing (choice of frame: what to consider and what not to consider) and a set of assumptions that condition its outputs. By definition, models as learning machines have to be transparent in their variables and processes, whereas models as truth machines may rest on complex technical calculations with many assumptions that make them behave as “black boxes” (Latour, 1987) and complicated to handle. In this latter case, the symbolic power of mathematics is mobilized to build credibility and to enable communication across epistemic boundaries (Gieryn, 1999). We thus assume that frames and assumptions are much less visible in truth machines and, hence, hardly questioned. Conversely, models as learning machines have to allow stakeholders (non-modellers) to identify issues that are not taken into account in the frame and must explain the dependence of certain key results on specific assumptions in order to enable effective participations.

The second political implication, intertwined with epistemological choices, corresponds to the opposition between technocratic models and decisionist models, pointed out long

¹ In their paper, Berkhout et al. apply the concept of learning machines to scenarios only. In this paper, we show that it is possible to use this concept also for specific types of models.

ago by Max Weber. In the case of models as learning machines, scenarios with debate on values and political choices come first; then comes the modelling dedicated to the analysis of plausibility and consistency of the desired (and undesired) futures. Such a relationship between science and politics is the hallmark of the French School of “*La prospective*” (Berger, 1964; Jouvenel, 1967; Godet, 1977...), which suggests that the best way to predict the future is to invent it.

As mentioned above, our use of “learning machine” encompasses both scenarios and models. We expand the definition beyond scenarios for two reasons. First, all types of scenarios do not act as learning machines. The literature distinguishes three types of scenarios (Borjeson et al., 2006): projections or predictive scenarios (“what will happen” under the business-as-usual assumption of no major policy changes); explorative scenarios (what might happen under given conditions); normative scenarios (how a specific objective can be achieved). Predictive scenarios can hardly be used as learning machines because they do not allow for participation. Second, whereas most models are usually considered as truth machines, some models may be used as learning machines if their development is opened up to non-modellers. One of the objectives of this paper is to demonstrate the feasibility of this proposal, based on the analysis of a real-life experience.

Stating that models are both tools of evidence and tools of government also has key theoretical and methodological implications. From a theoretical point of view, this means that models are determined both by the context within which they are created (questions raised, actors’ interests, institutional landscapes, etc.) and by internal rules of the community of researchers (norms of scientific production, standards of proof, etc.). STS scholars use the concept of co-production (of knowledge and political order) to analyse such strong interactions between science and politics (Jasanoff, 2004).

In this article, we use a dual strategy to enable an analysis of these two sides of models. We first analyse the genealogy of mainstream world agriculture modelling, based on a vast review of literature and models,² and our own participant observation or direct involvement in modelling exercises over the last thirty years. In this genealogy, we pay attention to ways of modelling and to institutional dimensions. This allows us to characterise mainstream models as truth machines, to show their growing complexity and to suggest that they lead to narrowing future prospects for agricultural production and food consumption. We then turn to an original initiative, the Agribiom model and the Agrimonde foresight exercise, and show that in this case, both model and scenarios have the characteristics of a learning machine.

Throughout the paper, we adopt a political economy perspective as we pay attention to the influence of the economic and institutional contexts on modelling modes. However, our analytical framework is coproductionist. Hence, we do not look for causal mechanisms that would explain changes of models (Anderson et al., 2013). We also focus on internal dynamics related to the scientific discipline and interactions with the institutional context.

² The next section is mostly based on McCalla and Revoredo (2001), van Tongeren and al. (2001), Drogué and al. (2006), Reilly and Willenbockel (2010), Leblond and Trottier (2016). We also draw on the Master Thesis of Nelly Leblond, directed by one of the authors, who identified and characterised 56 different world agricultural models (Leblond 2012), and the authors’ own knowledge or research on the models mentioned in these reviews.

2. Mainstream modelling: institutional and epistemic evolutions

2.1. A brief history of world agriculture modelling

Drawing on our literature review, we identify four recent waves of world agriculture modelling.

The first wave was spurred by concerns in the 1960s over possible world food shortages (the concept of food security had yet to emerge), in a context of persistent food crises in South Asia, drought-induced famines in Africa and unexpected shortages in the world food supply more generally. The United Nations Food and Agriculture Organization (FAO) took the lead in producing world food surveys, and quantified national balances in staple foods as well as average national availability of food calories per capita. The US Department of Agriculture (USDA) and, on a smaller scale, the Organisation for Economic Cooperation and Development (OECD), produced projections of world food supply and demand based mostly on extrapolations of historical trends related to land use, yields, livestock production, population growth, income and per capita consumption.

The second modelling wave was triggered by the 1972-74 crisis when food prices rose by as much as 100%, and in some cases 200%. This crisis was a cruel reminder that prices have a direct influence on producer and consumer behaviour, and international trade.³ The USDA produced the first model of world agriculture which computed supply and demand equilibria using prices (Rojko et al., 1971). It proposed the GOL – Grain (wheat, rice and coarse grains including corn), Oilseeds (oilcake and soya bean), and Livestock (beef, pork, etc.) – model for 28 regions, using 930 dependent variables in a 930-equation system (Rojko and Schwartz, 1976; Regier, 1978). In Europe, Linnemann et al. (1979) proposed the MOIRA model, an equilibrium model of international trade. Computation of this new generation of models was difficult at a time when computing capacities were still limited and costly.

The third wave of models is related to trade liberalisation and was catalysed by the Uruguay Round (1986-1994), which, for the first time, included agriculture in the GATT negotiations, and which was concluded by the creation of the World Trade Organization (WTO). During this period, several groups of researchers focused on agricultural trade were created, mostly in the agricultural economics departments of US universities (Josling et al., 2010). In 1980, with support from the USDA, six US agricultural economists created the International Agriculture Trade Research Consortium (IATRC), which now counts 200 members, mainly from North America. In 1984, Iowa State University and the University of Missouri established the Food and Agricultural Policy Research Institute (FAPRI), with a grant from the US Congress, in order to produce forecasts for the US agricultural sector and international commodity markets. Finally, in 1991, the Global Trade Analysis Project (GTAP) was created at Purdue University. It developed easily-accessible databases and models, and organised short courses for a broad range of individuals. Today, GTAP claims to have 7,000 networked participants worldwide. These academic initiatives and networks interacted closely with national and international organisations. For instance, IATRC contributed to the calculation of Producer and

³ The importance of price was further argued in the influential contribution on hunger from Dreze and Sen (1989).

Consumer Subsidy Equivalents with the FAO and the OECD's Ministerial Trade Mandate Model (McCalla et al., 2010). With much attention and resources for world agriculture and trade modelling, economists progressively favoured Computable General Equilibrium (CGE) models. These models combine the abstract general equilibrium structure formalised by Arrow and Debreu with empirical data, to compute equilibrium prices and quantities on a set of agricultural and non-agricultural markets (Suwa, 1991; Wing, 2004). Since the 1990s, CGE models have become the standard tool to analyse aggregate welfare and the distributional impacts of policies whose effects can be transmitted through multiple markets (Devarajan and Robinson, 2002).

The fourth major modelling wave, from the late 1990s, is related to climate change. Agriculture modelling (usually CGE based) is no longer the monopoly of economists but integrated in earth models such as IMAGE (from the Dutch RIVM) used by the IPCC (Intergovernmental Panel on Climate Change) to construct climate change scenarios (Armatte, 2007). The International Institute for Applied Systems Analysis (IIASA) and its models (APPA, GLOBIOM, etc.), have become increasingly influential in this integration of biophysics and economics (Ermolieva et al., 2015). Today, world agriculture is no longer framed in terms of food balance or trade only, but also of adaptation to (and mitigation of) climate change.⁴

2.2. Different ways of modelling world agriculture

This brief history highlights three approaches to world agriculture modelling:

(1) *Balance models* (input-output and macro-econometric models) usually compute regional potential productions (supplies in tonnes or monetary equivalents) combining historical trends, crop/livestock models and expert assumptions on future productivities and land uses. Potential consumptions (demand in tonnes, kilocalories or monetary equivalents) are based primarily on population and diet scenarios derived from historical trends. Supplies and demands are then balanced through trade, which limits *de facto* these models (and others) to “commodities” easily tradable on international markets, such as cereals, oilseeds, sugar and milk powder (as opposed to fruits, vegetables and fodder, for instance).

(2) *Economic equilibrium models* integrate supply and demand functions that represent economic constraints. In economic equilibrium models, prices are endogenous. Under the assumption of perfect competition, equilibrium prices are set to equate supply and demand. Supply/demand elasticities or functions with Constant Elasticity of Substitution (CES production and utility functions) are at the core of market-clearing models. These (fixed) coefficients (over time) are crucial and very sensitive parameters. They are based on data whose availability limits the set of commodities considered or leads to the extrapolation of coefficients from one region (such as North America) to another (such as Africa). Similarly, product quality differentiations are disregarded.

⁴ During this period, models were also built to investigate growing environmental problems such as erosion of soils, water or biodiversity, but climate change (partly through deforestation for agriculture) remains the dominant environmental component of global models, probably because its impact is unquestionably global.

There are two types of equilibrium models. Partial Equilibrium models (PE) aim to represent an economic sector, in our case, agriculture, while CGE models embrace the whole economy. CGE models allow the reallocation of production factors from agriculture to other sectors and vice-versa. They include economy-wide capital and labour markets as well as public transfers to account for the feedback effects of intersectoral relationships. Empirical CGE models emerged gradually after Johansen's (1960) model for Norway, often considered their forerunner. Personal computers and the circulation of software and code facilitated their diffusion. Their empirical relevance depends on the number of activities or markets that are represented. Hence, the shift to CGE models spurred both the quest for commensurability at the world level, and demand for international databases.

(3) *Integrated models* stem from energy policy analysis and were first developed in the 1970s (Matarasso, 2007). They aim to model socio-economic and biophysical systems and their interactions. In the case of agriculture, PE or CGE models are combined with biophysical models of production of the main commodities, and/or energy, water or climate models allowing to test different levels of constraints on natural resources (e.g. Rosegrant, 2012: 49).

Given the influence of land-use changes and agricultural practices on global Greenhouse Gases (GHG) emissions (and the influence of climate on agricultural production), integration of agriculture and climate modelling has been a major trigger for the development of increasingly complex and comprehensive integrated models. In order to foster comparability and convergence of results, a standardisation process was promoted (see hereafter comments on AgMIP), which includes the use of common future scenarios (typically on population and economic growth). Currently, the IMPACT model of IFPRI⁵ uses scenarios developed in the IPCC's fifth assessment report (IPCC, 2014), with shared socioeconomic pathways (SSPs) that represent different societal futures, and representative concentration pathways (RCPs) that quantify potential GHG emissions and the resulting radiative forcing. In IMPACT-3, SSPs are based mainly on population growth scenarios, produced by the IIASA, and economic growth scenarios, produced by the OECD.

Overall, regardless of the input scenario, IMPACT or other models support trade liberalisation to maximize comparative advantages, and see few other ways to increase agricultural productivity than to specialise in one or a few products and to use the same kind of industrial inputs promoted by the Ford and Rockefeller foundations five decades ago, in India and elsewhere (Lele and Goldsmith, 1989). Driven by the economic theory of comparative advantages (hence specialisation), and simulating the yields of monocultures that have become the most important worldwide (e.g. 13 crop functional types with the vegetation model LPJmL: Bondeau et al., 2007), these integrated models have no option but to totally ignore how biodiversity, plant-plant and plant-animal synergies below and above the ground (from soil fungi to trees, from soil bacteria or

⁵ IMPACT, developed by IFPRI at the beginning of the 1990s, is a "model designed to examine alternative futures for global food supply, demand, trade, prices, and food security" (www.ifpri.org). Its 2017 version (IMPACT-3) integrates 39 crops in 159 countries. The solution of the system of equations is world market prices for all commodities that satisfy market-clearing conditions with the sum of global net trade equalling zero.

worms to cattle), can boost both land productivity and resilience to climate change, soil fertility, water saving, nutritional security and biodiversity conservation.

In fact, mainstream models share a set of value-laden characteristics that are not discussed as such but encoded in their technical specifications: *(i)* international trade is equated with internal trade; *(ii)* land and labour productivity gains are based on genetics, irrigation, chemicals and mechanisation of large-scale specialised production; *(iii)* consumers' rising incomes and preferences lead to increased consumption and better nutrition, notably in animal proteins.

2.3. The hidden costs of complex modelling

The above analysis shows a strong tendency to increase the complexity⁶ of mainstream models, mostly to endogenise relations between socio-economic, technological and environmental effects. The costs of this complexification are overlooked, which we explore with two examples.

First, the standardisation of parameters and functional forms leads to standardised representations of reality. The Agricultural Model Intercomparison and Improvement Project (AgMIP), a major initiative hosted by Columbia University and supported by many public and private organisations since 2010 (Jones et al., 2017), illustrates this point. AgMIP aims to “link the climate, crop, and economic modelling communities with cutting-edge information technology to produce improved crop and economic models and the next generation of climate impact projections for the agricultural sector” (www.agmip.org). A comparison of 10 leading global models (including IMPACT-IFPRI and GLOBIOM-IIASA) organised within the AgMIP consortium shows a significant variability in general trends across models, even when key assumptions are harmonised (Schmitz et al., 2014; von Lampe et al., 2014). This variability is considered a weakness in relation to the implementation of “evidence-based” policy. Against this background, AgMIP pushes for standardisation of language, data, modelling devices, hypotheses, etc. Standardisation of parameters and functional forms is supposed to allow comparison and discussion of scenarios from different models. However, this reduces the representation of very diverse agricultural production and consumption systems. This reduction (even misrepresentation)⁷ is amplified in current models, which, usually, represent only technologies designed in developed countries. These technologies are considered at the global technology frontier and have been *de facto* promoted around the world as part of the Green Revolution. However, many other technologies exist and may contribute to agricultural sustainability in the long run in many respects: biodiversity, saving or filtering of water, soil fertility, resilience to economic or climate shocks, carbon sinks, employment, etc.

⁶ The words “complex” and “complexity” are understood in their common meaning, and not in the sense of Morin (1990), for example: current models are totally incapable of modelling “complexity” or complex systems in Morin’s sense.

⁷ E.g., standard production functions cannot accommodate multiple real world technologies, since they have very few parameters (cost shares of the calibration year in Cobb Douglas functions, or sigma in CES functions); the functional forms were chosen for analytical tractability, not compatibility with observation of the real world (Ghersci and Hourcade, 2006).

A second cost – the generalisation of economic equilibrium-based models and their integration in other models – raises a seldom debated, important epistemological issue. As Morgan (2012) argues, twentieth century economists came to share and apply two general assumptions, the “individual utility maximisation” of economic man, and the “equilibrium tendency” in aggregate system models, and their combination. Let us just focus briefly on economic equilibrium. First, Machlup (1958) describes economic equilibrium as a “useful fiction”, a methodological device in abstract theory that is neither observable nor operational since it is a constellation of selected variables that are interrelated to one another in such a way that they have no inherent tendency to change. Second, equilibrium conveys the idea of harmony and goodness, but this may be misplaced (e.g., there may in fact be high unemployment or high erosion of natural resources). Third, it assumes a highly centralized form of organization, with an invisible auctioneer, but to which all would have access. Fourth, it is based on Newtonian physics and determinacy and ignores both path dependency and higher levels of order and new systems which might emerge once a threshold or bifurcation point is reached (Hoffman, 2016).

Interestingly, AgMIP highlights some important blind spots related to the lack of validation of models and sensitivity analyses. Results are highly dependent on key variables, such as elasticities, whose reliability is questionable, especially over the long run. These limitations might seem surprising to non-specialists, since scientific models used for policy are expected to be validated and their conditions of use carefully defined. The modellers now acknowledge these limitations. For instance, in the case of IMPACT:

Structural simulation models like IMPACT and global CGE models that focus on long-run scenario analysis are inherently difficult to validate. [...] Structural simulation models involve many parameters and functional forms that are hard to estimate econometrically, and the models are designed to be used for scenario analysis that is often outside the domain of historical data. (Robinson et al., 2015: 17)

According to our theoretical framework, evidence-based models as those mentioned above may be considered as “truth machines”. As any model, they are based on an analytical framework and a set of assumptions that condition their results. And as shown before, mainstream models only represent the industrial production systems promoted since the Green Revolution. They do not model the much more complex, territory-based, biodiverse production systems that are important to many small farmers and are now promoted by policies in favour of agroecology. Hence, mainstream models incorporate a policy framework that makes important processes (e.g. biological synergies) and issues (e.g. small-scale farming) invisible, preventing the exploration of alternatives to global large-scale industrial agriculture. Also, and despite the relative technical simplicity of industrial agriculture, mainstream models are increasingly complex as they tend to endogenise economic, biological and environmental factors. This trend reinforces the invisibilisation. As their complexity creates opacity, these models become more and more difficult to discuss and, therefore, can hardly be used as “learning machines”.

3. Agribiom and the invisible hand on land

The contrast of the aforementioned models with an alternative way to design and use a quantitative tool – the Agribiom model and its use in the Agrimonde foresight platform – allows a wider reflection on the politics of modelling. Agribiom and Agrimonde were launched in 2006 by two French institutions, CIRAD⁸ and INRA.⁹ They were created in the French foresight tradition, which uses modelling and scenarios to construct desired futures and test their consistency and viability.

3.1 Agribiom: a boundary platform in a boundary space

3.1.1 Agribiom's technical attributes

Agribiom is a world food balance model which objectives were to help renewing analyses and debate on past and future consumption, production and trade in food biomass¹⁰. Its construction started in 2006 at CIRAD, to support two projects: Agrimonde, a French collective interdisciplinary scenario-building exercise on food and agriculture (Paillard et al., 2011 (2014: Springer)); and Nexus Land-Use (Souty et al., 2012), an integrated model of competition over land use between food and bioenergy (Dorin et al., 2009a) within the general equilibrium framework of Imaclim-R (Sassi et al., 2010).

The core of Agribiom is physical balances between supplies and uses of food biomass, either on the past (from the 1960s to date) or on the future (simulations based on exogenous sets of assumptions), at various geographic scales (from country to global level). Agribiom does not compute equilibrium prices but food balances in calories for five aggregates of products/origins (plants, grazing animals, non-grazing animals, freshwater fish and sea fish). These unusual metrics and aggregations were chosen to allow simple, all-encompassing and robust retro-prospective analyses, in order to capture a wider range of knowledge beyond economics (social and engineering sciences, corporate and government expertise, farmers and consumers, NGOs, etc.). They also aim to generate new sets of data and analyses that are able to communicate with mainstream economic tools, in order to push, test and validate new perspectives with these tools.

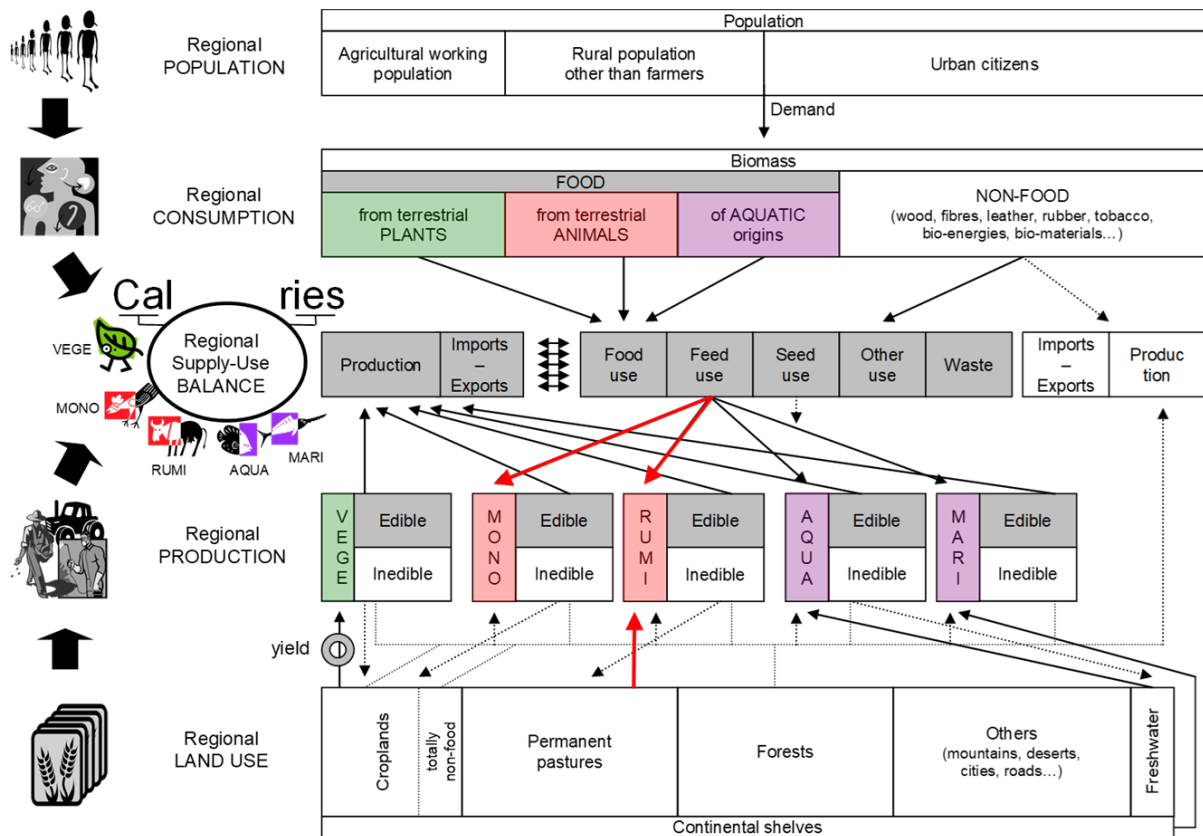
Figure 1 depicts the general architecture of Agribiom, with food (edible biomass) supply-use balances coloured grey and positioned in the middle of the figure. These balances are driven primarily (but not solely), on the one hand, by demand for food from plant, animal and aquatic origins (grey shaded box at the top of the figure), which depend, in turn, on populations and their specificities (size, preferences, level of wealth, public policies, etc.), and on the other hand, by more or less intensive production of edible biomass from crop land, pasture and water (grey shaded boxes at the bottom of the figure), linked to land use.

⁸ Centre de Coopération Internationale en Recherche Agronomique pour le Développement (www.cirad.fr)

⁹ Institut National de la Recherche Agronomique, France (www.inra.fr).

¹⁰ One of the authors of this paper – Bruno Dorin – is the main author of Agribiom, an economist who worked previously eight years in India where he observed the disconnection of standard agricultural models and their results with the realities and needs of the country.

Figure 1. Schematic presentation of AGRIBIOM 2007



3.1.2 Some analytical and political implications of Agribiom

Mainstream models only include products for which data and/or functional forms are available, i.e., the monocultured staples that have been cherished by the past half century of agricultural science and industrialisation. This prevents conceptualising other possible productions, but also crop-crop and crop-animal combinations that are fundamental (but forgotten) components of land productivity (e.g. Thornton and Herrero, 2001). To overcome this bias, Agribiom uses the mediating unit of the kilocalorie¹¹ to aggregate (past) or represent (future) a much larger range of productions and, hence, of possible crop-crop and crop-animal synergies that could become the main drivers of land productivity instead of genetic and chemical inputs.

With its high level of aggregation, Agribiom questioned the presumed technological advances of developed countries. Notably, it estimated that average Asian yields in food calories per hectare of cultivated land outpaced those of the OECD countries. Hence, it called into question the dominant view that low agricultural productivity is a major reason why some countries are poor, and that barriers to “modern agricultural technology” jam the whole developmental process (Gollin et al., 2002; Murata, 2002). This dominant view is based on comparisons of annual crop-by-crop output per hectare. But while the single annual-crop model dominates in developed countries with a continental

¹¹ For the pros and cons of the calorie and for more technical details on Agribiom, see Dorin (2011). In Agribiom, supply-use balances are computed also for carbohydrate, protein and fat.

climate, in tropical and subtropical countries, several crops can be harvested yearly with good irrigation and fertilisation. In the multi-crop model, farmers have no interest in maximising the yield of one crop if it jeopardises the returns from others. They may be below the technical frontier for each crop, but at the technical frontier for their specific combination of crops (and livestock).

This example shows how mainstream models are shaped strongly by knowledge and data on industrial-scale food production and consumption systems in developed countries. They take no or little account of traditional tropical crops or animal species, or of mixed systems relying on complex plant and animal synergies. In fact, they encode the “World Without Agriculture” (Timmer, 2009)¹² where developed countries already are, by systematically promoting large-scale industrial agriculture and trade, and making smallholders invisible (Leblond and Trottier, 2016), despite the fact that they still largely dominate and will continue to dominate world agriculture (Dorin, 2017). In contrast, with more simplicity and flexibility, Agribiom allows more leeway for constructing collectively richer representations about possible futures, and for testing their consistency from a biophysical standpoint (including a global balance of exports and imports between the regions considered, but independently of market mechanisms).

Agribiom was designed intentionally as a simple model that would be used as a learning machine. Simplicity is considered a virtue in the philosophy of science, and the credibility of a model is conditioned by its ability to reproduce studied phenomena in simple ways, which minimizes the risk to produce artefacts. In the case of Agribiom, the modeller was prevented from creating a black box because it was clear from the outset that the model would be designed to be a “companion” to expert interactions and discussions, thus requiring transparency. However, such collective explorations would be impossible without a mediator tool. An interface was built with Microsoft Access specifically for the Agrimonde foresight exercise. It allowed collective visualisation and discussion of historical evolutions at various geographical scales, exploration of econometric components, interactive simulations, archiving and sharing of sets of quantitative results (scenarios or variants) along with their assumptions. Such an interface is still generally lacking in mainstream models.¹³

Since it was designed as a learning machine, Agribiom and its use in the Agrimonde foresight exercise implement an original articulation between production of knowledge and social dynamics. The use of the tool has fostered the emergence of a language for collective exploration and spurred strong productive interactions that allowed scenarios to be translated into a wide set of hypotheses on human and natural behaviours. The interface incorporates this role and allows fluid and rapid interactions among academics, experts, policy makers and modellers. Hence, Agribiom renders the scenario not just a set of input variables that allows simulations but the co-production of possible futures under conditions of biophysical consistency and potentiality.

¹² i.e. no more than 3% of GDP and employment

¹³ IMAGE is one tentative notable exception; constructing interfaces is extremely time consuming and provides no academic reward.

3.2 Agrimonde's foresight: making visible invisible actors and their scenarios

3.2.1 Institutional strategies, actors involved, epistemic and political choices

As Lattre-Gasquet and Hubert (2017) highlight, the international context strongly influenced the launch of Agrimonde in 2006. First, in the mid-1990s, a working group was established to rethink the role of agricultural research and address CGIAR's (Consultative Group on International Agricultural Research) funding crisis. This group concluded that, over the previous fifty years, research had developed a technological package, called the Green Revolution in the 1960s and supported by a political framework, which had greatly contributed to meeting growing needs but had harmful and dangerous limits (Cornilleau and Joly, 2014). An alternative model, the "Doubly Green Revolution", was proposed, and French institutions influenced by Michel Griffon (2006, 2013),¹⁴ were eager to investigate it further. Second, in the early 2000s, the United Nations initiated the Millennium Ecosystem Assessment (MEA, 2005) to assess the consequences of ecosystem changes on human well-being and to establish a scientific basis for actions to improve conservation and sustainable use of these systems. CIRAD and INRA directorates, having noted the absence of their researchers from this exercise, concluded that a number of them should be prepared to participate in such debates. Third, in 2004, some French researchers participated in the launch of the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD, 2008). Debate was lively on the methods to study the relationship between agriculture and development and, especially, the role and limits of economic models. For the French institutions, which had neither an influential world agriculture model nor any real expertise in global foresight, it seemed essential to develop these areas and support the French researchers who were participating in IAASTD. The launch and implementation of Agrimonde were also influenced by FAO projections for agriculture (Bruinsma, 2003), the IPCC's third and fourth assessment reports (IPCC, 2001, 2007), World Bank reports (WB, 2006, 2007), the sharp increases in food prices in 2007-08 and the rising price of oil.

The Agrimonde foresight was managed as an autonomous platform that was accountable to its sponsors (INRA and CIRAD). The three-component platform comprised a *think-tank* debating some *scenarios* (generated or revisited) with a *quantitative tool* (Agribiom) and the expertise of its members (Dorin et al., 2009b). In this context, Agribiom first revisited past structural evolutions through its eyes, in a way that also allowed participants (agronomists, sociologists, economists, etc.) to learn to work together and build an atmosphere of trust. Huge efforts and time were devoted to going back as far as the available data allowed, with the scanning and processing of almost 30 million pieces of data, mostly from Faostat.¹⁵ Then, Agribiom led discussions on future qualitative scenarios, translating them into a few quantitative parameters, checking their global consistency and their implications for the six regions of the MEA chosen by the think-tank that carried out the analyses.

¹⁴ Michel Griffon, an influential agro-economist from CIRAD, had much international involvement (member of IFPRI's advisory committee, Scientific Secretary of CGIAR, etc.), created the URPA foresight unit at CIRAD, became Scientific Director of CIRAD and, later, Deputy Director of ANR (French National Research Agency). He played a leading role in the launch of Agrimonde and, from the outset, all agreed to test and investigate his ideas further.

¹⁵ At the time of its reform (which was abandoned in 2008), which further complicated the work.

Hence, Agrimonde's ambitions were "imagining the future to act today, combining foresight and research" (Hubert and Caron, 2009). Agribiom played a crucial role in designing and effectively unfolding the interactions among scenario building, modelling and stakeholder values and knowledge. It helped to create a common language, foster collective learning, stimulate imagination and reduce inconsistencies, which enabled statistics, models and scenarios to be used as learning machines (Berkhout et al., 2002).

3.2.2 Two Agrimonde narratives about feeding the planet in 2050

Agrimonde built and compared two scenarios that "offer[ed] fundamentally different internal logics based on different worldviews and discourses" (Vervoort et al., 2014: 392).

The first scenario, "Agrimonde Global Orchestration" (AGO), is a projection scenario inspired by the Global Orchestration scenario in the MEA (2005) and its quantitative figures produced by IFPRI's IMPACT model. In this scenario, further economic growth and free trade reduce poverty significantly, but more than double demand for animal food products by 2050. Consequently, production of plant-based food needs to increase by 85% (from 2003), mostly soybeans and maize for animal feed. Despite a sharp increase in intercontinental trade, per capita availability of animal-based food remains very unequal between rich and poor countries. Yields continue to increase, assuming further progress in biotechnology, irrigation, chemical fertilisers, pesticides and information technology. However, due to the large demand for feed, cropland areas need also to increase along with pasture. Carbon emissions from land use changes are then expected to continue and other greenhouse gas emissions to worsen.

The second scenario, "Agrimonde 1" (AG1,) is a normative transforming scenario based on agroecological production and fair consumption. In this scenario, deep changes in technologies, markets and consumption patterns allow agriculture to meet growing demands, preserve ecosystems and human health, provide jobs in rural areas and reduce worldwide inequalities. On the supply side, AG1 assumes complex highly-productive agro-ecosystems that save on capital, inputs and water by boosting local biological synergies amongst numerous plant and animal species. Such agro-ecosystems call for deep, extended and long-term reforms across the sector. Hence, AG1 yields in 2050 are assumed to be almost the same as those observed in the early 2000s, but with the ability to sink more carbon and to achieve more biodiversity in croplands than today. On the other hand, AG1 prescribes a per capita daily food availability of 3,000 kcal everywhere, with 500 kcal from animal origins (the world averages in the early 2000s), and therefore an important substitution of animal proteins with plant proteins in rich countries. This solves the current problems of under- and over-nutrition and, overall, in AG1, world production of plant food calories needs to increase by only 30% to feed both humans and animals in 2050.

3.2.3 Making other possible futures visible to the academic world

This drastic difference between AGO and AG1 (+85% vs +30%) is based mainly on a global rebalancing and equalisation of plant and animal food consumption per capita, a scenario that cannot emerge from mainstream models based on demand functions calibrated on past human behaviours (e.g. Gouel and Guimbard, 2018), with ever more animal products when living standards rise. It took some time for academia to consider other food-feed demand scenarios than those forecasted by demand functions, and to publish work

describing their relevance and the challenges involved. Agrimonde contributed to this academic change.¹⁶ Noteworthy, the report “Eating the Planet” (Erb et al., 2009), issued eighteen months after Agrimonde’s first publication (CIRAD and INRA, 2008), contributed in the same direction. Its “biomass-balance model” has many similarities to Agribiom and produces results in line with the AG1 scenario (Erb et al., 2016).

A second invisibility in mainstream models concerns the processes and technologies used to increase land productivity. Specialization in a few large-scale monocultures, with inputs from laboratories and the chemical industry, has been widely incentivised since the 1960s agricultural modernization phase. However, land productivity can also be increased through biodiversity and ecological intensification and, since the early 2010s, this radical shift in perspective has been supported by a burgeoning literature referring to “agroecology” (Gliessman, 1990; Altieri, 1995; Wezel et al., 2009).¹⁷ Agribiom, with its high level of aggregation, has allowed this agroecological perspective to be at the heart of the AG1 scenario on the production side. As shown in section 2, it is technically impossible to integrate the diversity and complexity of local agro-ecosystems into mainstream models. Yet, despite the fact that the myriad of complex and localised agroecological options could not be modelled by Agribiom, the platform allowed Agrimonde experts to consider and make visible this possible change of sociotechnical regime (Dorin, 2017). This could not have emerged from current integrated models despite their apparent greater sophistication.

3.2.4 Opening modelling spaces to discuss societal choices

In the two contrasting Agrimonde scenarios, consumption and production patterns affect land use, trade, ecosystem services, rural livelihoods and nutrition-related diseases. This shows that the bases for scenario-making are value laden. Here, what comes first is societal choice, followed by modelling to express it and analyse the consistency and plausibility of the scenarios.

In the period 2012 to 2016, “Agrimonde-Terra” (a second INRA-CIRAD foresight initiative focused on land use and food security in 2050) was implemented. It mobilised around 80 international experts in thematic workshops and its model, Globagri, drew on Agribiom, although not all its principles (INRA and CIRAD, 2016). In both exercises:

Each participant had expectations, i.e. ‘images of the futures where technical and social aspects are tightly intertwined’ (Borup et al., 2006) which were not necessarily shared. The exercises drew on existing ‘repertoires’ and were able to generate alternative ideas. [For instance,] some of the participants in Agrimonde had strong views about ecological intensification and its potential contribution to global food security. They managed to discuss, share and improve these ideas during the course of Agrimonde but also in other

¹⁶ Without being exhaustive, we can trace the influence through papers citing Agrimonde: Tansey (2013), Tomlinson (2013), Keats and Wiggins (2014), Lang (2014), Odegard and van der Voet (2014), Westhoek et al. (2014), Billen et al. (2015, 2018), Bodirsky et al. (2015), Fourat and Lepiller (2015). From Agribiom or its descendants: Dorin and Le Cotty (2012), Le Cotty and Dorin (2012), Brunelle et al. (2012), Brunelle et al. (2014), Ranganathan et al. (2016), Le Mouël and Forslund (2017).

¹⁷ 827 references on the Web of Science during 2000 to 2016 include the words “agro-ecological”, “agroecological”, “agroecology”, “agro-ecology” or “ecological intensification” in their titles, 29% between 2000 and 2009 vs 71% in 2010 to 2016.

instances [IAASTD, SCAR, GCARD, GFAR, HLPE, Future Earth...]. (Lattre-Gasquet and Treyer, 2016: 49-50)

Overall, “both exercises have opened space for more diverse visions in global and national debates on food security and land use change. To do so, they were designed to maintain a link and some comparability with widely used global quantitative modelling exercises” (Labbouz, 2014). As a result, the best-known world agriculture models, IMPACT and GLOBIOM, were adapted and used to support and discuss scenario narratives developed by regional stakeholders, especially in East and West Africa (Vervoort et al., 2014; Palazzo et al., 2016). Such a dialogue would have been barely imaginable only a few years earlier. Agribiom contributed to such epistemic and politic transformation, and also to argument that foresight should be at the centre of development studies (Sumberg and Gioacchino, 2016).

Conclusion

In order to provide a political economy analysis of world agriculture models, this article follows the inspiration of Alain Desrosières and other STS scholars who posit that economic models are hybrid, both tools of evidence and tools of government. We show that, although mainstream models of world agriculture are designed as “truth machines”, it is possible to construct alternative models that can be used instead as “learning machines”. This extends the distinction developed by Berkhout et al. (2002) from scenarios to economic models, and reveals the underlying politics of knowledge.

We first provided an analysis of the evolution of world agriculture modelling, paying attention to both the content of models and the context of their production (namely the institutions and communities that co-evolve with the ways of modelling). We show that this evolution may be described as a sequence of waves. For each wave, modelling modes are influenced both by expected uses (analyses of global balance, prices, international trade, climate change) and epistemic dimensions (general computable equilibrium, integration of biophysical modules, etc.). We demonstrate that mainstream models, although considered as truth machines, are political in two ways. First, as any model, mainstream models are partial representations of the reality; their results depend on an analytical framework and a set of assumptions. In mainstream models, this techno-political frame is characterised, as we have argued, by the animalisation of diets and the Green Revolution model of industrialisation (artificial intensification and specialisation into few large-scale mechanized production). In doing so, these models make invisible key actors (e.g. small farmers) or alternative technologies (e.g. plant-plant and plant-animal biological synergies). Second, mainstream models are political in the sense that, as truth machines, they are not constructed to support debates and foster collective learning. As they are increasingly complex, they become black boxes, making it very difficult to figure out to which extent some hypothesis (e.g. perfect competition, individual utility maximization) or key parameters (e.g. price elasticities) condition their results.

Against this background, the Agribiom model and the Agrimonde foresight exercise demonstrate that it is possible to adopt alternative ways of modelling that have influence on both science and policy debates. Our analysis shows that Agribiom and Agrimonde are better seen as learning machines. For a model of world agriculture to be a learning machine, we highlighted three basic conditions: (i) the model has to be flexible enough to

allow the exploration of both historical pathways and very different future trajectories, including normative scenarios; (ii) the model has to privilege simplicity and comprehensiveness, thus aggregated virtualities (regions, products, processes...) instead of detailed but selective sub-models that do not better capture the complexity and potentiality of the real world, or even reduce the representation of the latter; (iii) the model has to be transparent through an interface that makes it understandable and accessible to a wide range of stakeholders. When these conditions are met, the model can become a tool for exploring alternative trajectories collectively, constructing desired futures, testing consistency and identifying critical points. The key objective is not more prediction and prescription but collective learning. In such modelling perspectives (Hoffman, 2016), what matters is not “speaking truth to power” (the traditional positivist stance) but, instead, opening up the debate and fostering democratic learning and action.

As with mainstream modelling, Agribiom model and Agrimonde scenarios are the product of epistemic choices and institutional strategies. The fate of these alternative ways of modelling will depend on future interactions between institutional dynamics and the evolution of scientific communities. However, whatever the future of these ways of modelling, our article highlighted the need for epistemic plurality and the need to engage seriously in the production of models as learning machines. This is essential for improving science-policy interactions and the quality of the democratic process.

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