Overcoming the final frontier of climate change in viticulture: exploring interactions between society and environment using Agent Based Modelling and Companion Modelling approaches

Etienne Delay, Nicolas Becu

Overcoming the final frontier of climate change in viticulture: exploring interactions between society and environment using Agent Based Modelling and Companion Modelling approaches.

Etienne Delay[1] et Nicolas Becu[2]

[1]UMR 6042 CNRS, Laboratoire GEOLAB, 39E rue Camille Guérin 87036 Limoges, FR

[2]UMR 7266 CNRS, Laboratoire LIENSs, 2, rue Olympe de Gouges,17 000 La Rochelle, FR

Abstract: Climate change is a complex process that requires societies to seek viable solutions to enable them to adapt. Agent based modelling using co-constructed models can thus be contemplated as a means of understanding the manner in which societies in wine-growing areas take into account the different variables that influence their systems. Here we offer a reflection on three years of companion modelling carried out in the Appellation d'Origine Contrôlée areas of Banyuls-Collioure (Fr) and the Val di Cembra (It). This work has led us to co-construct six agent based models and to produce a future-oriented summary, enabling us to identify the macro-variables that influence this environment.

Keywords: Agent-based model, companion modelling, systemic, stakeholders, landscape

1. Introduction

Climate change is a complex process that exposes gaps in our understanding. These are defined by their anthropogenic origins (Guillemot 2014) and they raise questions about societies' ability to adapt to climate change (Hannah et al. (2013) vs Van Leeuwen et al. (2013)). These questions and solutions for adapting to climate change seem too complex, and the uncertainties too large, to be left to a formal, disciplinary scientific approach. Funtowics and Ravetz (1993), suggest resorting to "post-normal" science. This involves tackling complex problems in an inter-disciplinary manner, including bringing in various stakeholders, in order to provide solutions to integrate into societies.

In this paper, after having reviewed current work in this field, we propose the use of multi-agent systems (MAS), adopting a companion modelling approach. The method of co-construction was used on 6 models, in collaboration with stakeholders, in two wine growing areas: the AOC Banyuls-Colioures (Fr) and the Val di Cembra (It).

The co-constructed/companion models each bring an partial understanding of the system, but considered as a system of interactions they serve as a basis for us to see the world from a wine growing perspective, which allows us to outline stakeholders' abilities, as they perceive and view them, regarding the constraints they face and the adaptations that feel are available to them.

2. A short introduction to Agent Based Modelling

2.1. What is modelling?

The concept of modelling is almost inseparable from the scientific approach. A model is a simplified representation that allows us to think of the world based on hypotheses. For example, the heliocentric model of Copernicus (1473-1543) revolutionised the geocentric model and that of Pasteur (1822 – 1895) revolutionised the microbiological model. Modelling is therefore an intellectual construction that involves imagining interactions between a range of ideas and concepts. A model isn't made to be static but to allow us to put together reasoned arguments suitable for sharing (Le Page et al. 2010).

Simulation involves improving the model by introducing the time factor in order to move on from this static state, thus rendering the model dynamic (Coquillard et Hill 1997). It is generally applies to two situations: *i)* when the results we hope to obtain are unachievable by traditional analytical methods and *ii)* when the goal of a model is to mimic in detail the mechanics of a real process, for which it is therefore impossible to formulate equations (Manzo 2014, 665).

Multi-agent modelling is a paradigm of modelling derived from the crossover between computing (object-oriented programming, distributed systems etc.) and distributed artificial intelligence (artificial life, robotics, cognitive sciences) that emerged in the 1980s. For Ferber (1995, 11), the need to focus on distributed artificial intelligence results in several requirements, amongst which we will consider *i)* the need for a system to 'adapt itself to modifications of structure or environment' and *ii)* "*the complexity of the problems demands a local perspective"*. Ferber (1995, 13) defined this as *"[an] agent [such as] a physical or virtual entity: a. that is capable of acting in an environment, b. that can communicate directly with other agents, c. that is driven by a set of trends (in the form of individual objectives or a function of satisfaction, even of survival, that it is seeking to optimise, d. that possesses its own resources, e. that is capable of perceiving (albeit in a limited manner) its environment, f. has as its disposal only a partial vision of this environment (or possibly none), g. that possesses skills and offers services, h. that might be able to reproduce itself, i. whose behaviour aims to meet its objectives, taking into account the resources and expertise available to it, and, depending on its perception, the images and communications that it receives."*

We are interested here in the use of modelling and multi-agent simulation in social sciences, in the same way they are used in the experimental sciences, as a tool allowing us to access *in silico* (Knibbe 2013) socio-spatial configurations that are difficult to tackle by conventional methods. By applying these models, social scientists can gain access to the domain of experimental scientists (Peschard 2011) in the same way that biologists use the "Petri dish".

2.2. From system to model: theorising the world?

A method of study developed in the middle of the 20th century, in a cross-disciplinary manner, that broke away from the approach of reductionist modelling: systemic modelling [1]. This approach allows us to think of complex objects as a whole. Coquillard and Hill (1997, 3), suggested the definition: "*a system is a collection of objects in interaction*". The systemic approach can be linked to various scientific disciplines having an ambition to theorise. For Pumain (2003, 27): "*To theorise is first of all to try to escape from the paradox of "pure science" and above to look beyond the irreducible oneness of things, to try to construct a nomothetic view of the discipline ".*

To consider moving towards a systemic approach is not therefore neutral and involves going beyond the "tangible/real" in order to offer theoretical generalisations that can be applied to different realities.

A systematic approach allows an initial level of abstraction to be superimposed on the real, and the model can thus be regarded as being the driving force behind the system. The model therefore becomes a means of testing the formal hypotheses determined by the system.

---

[1] We can trace back the first systemic research to the 18th century, with the works of the abbot Bonnot de Condillac, then later to the works of Vilfredo Pareto in 1906, but the word itself didn't appear until the middle of the 20th century.

In France, in particular when looking at viticulture, we can single out an attempt at systemisation proposed by Auriac (1979). These works, as well as using General System Theory (GST) to put together a frame of reference, offer a new approach to viticulture geography by theorising the “vineyard-system” as a dynamic object.

2.3. Roles and status of the model

This need to distance oneself/abstract from ‘concrete/fixed’ forms of the world in order not to limit oneself to descriptions became apparent during the 20th century and was a definitive turning point for scientific models. It raises questions about the emerging need for theorisation in all the scientific disciplines.

Researchers (as observers) must change their point of view and concentrate on the phenomena of form generators Thom (2009, 93) questions this role of observer: “*Can one, in a landscape of phenomena, recognise an object or a thing if one has no prior concept of it? It’s a simple as that. If one doesn’t have a concept of an object, one doesn’t recognise it. [...] The possibility of recognition is a generality, an entity in an empiric landscape, is always, in my opinion, subject to conceptualisation.*”

This link between conceptualisation / formalisation and the recognition of a pattern in the results necessitates, in keeping with the deductive logic of Popper (1998), proceeding on an iterative basis by confronting hypotheses with experimentation and then by rejecting or confirming these hypotheses.

2.4. Empiricism and ABM/MAS: a place for post-normal science

One of the challenges for the social sciences has always been to move from the description of reality to the abstract that leads to theorisation. At the same time, more and more interdisciplinary studies no longer involve trying to predict the state of a future system, but rather to understand its organisation (Etienne and Collectif 2013,10). When the questions of research collide with great uncertainties and involve major social issues, their resolution goes beyond the factual scope of science and we then enter into the paradigm of “post-normal sciences” (Funtowicz and Ravetz 1993). The “post-normal” approach does not banish the uncertainties but to overcomes them by including the parties involved (Funtowicz and Ravetz 1993, 740). The quality of the solution to the problem no longer depends solely on scientific abstraction but also on the quality of the decision making process (Etienne and Collectif 2013, 10). The role of the scientist is thus redefined as a guide in this process. It reintroduces the legitimacy of an empirical approach.

However, empirical approaches to agent-based modelling must pass the challenge of translating the real world into a robust model. For Smajgl and Barreteau (2013, 2) this means succeeding in bringing a range of parameters from heterogeneous sources, closer to a range of valid results. Yet agent-based modelling mobilises more complex information that the links between the inputs and outputs of models, “*It also provides information on the structure of the population of target system so that up-scaling can be performed to generate a suitable artificial population.[...] Parameterisation is not only a matter of giving quantitative value to parameters, but to enable running the model with a set of values. Set of categories are particularly useful for qualitative or fuzzy approaches*”(Smajgl and Barreteau 2013, 3).

3. Climate change, land use adaptation and ABM

3.1. Climate change and adaptation

For over twenty years, the GIEC has been working on the long-term evolution of climate change and making populations aware of climate-related impacts that may arise. Climate change has become a powerful constraint that has added to those already weighing heavily on viticulture (Nemani et al. 2001; Jones et al 2005; White et al. 2006; Schultz 2010).

At the same time, controversies are appearing as regards the future of viticulture (Hannah et al. (2013) vs. Van Leeuwen et al. (2013)). Even though climate change itself is no longer disputed, it is the ability of wine-growers to make a profit from their environment and cultural practices that is now in question, as for example in the research program LACCAVE[2] (2012-2015) (C. Barbeau, Barbeau, and Joannon 2014; Neethling et al. 2016; Ollat and Touzard 2014; Viguié, Lecocq, and Touzard 2014).

3.2. Climate change and ABM

Questions relating to climate change investigated by means of multi-agent systems very rapidly face difficulties in that: *i)* the processes that influence climate change are not yet precisely understood and *ii)* there are not yet any social theories that are universally usable and appropriate in this context (Moss, Pahl-Wostl, and Downing 2001). In general, the studies we have identified on the subject of wine growing tend to address the society-environment link in economic terms.

The objective of these models, taken individually, is to offer decision makers a theoretical framework to help them to think about the effects of climate change. The "social" agents of the model are in the position of trying to maximise revenues in a system subject to certain constraints. Yet the modellers, in trying to sum up the knowledge of the subject find themselves in a dilemma about the degree of formality and the degree of abstraction of the said models (Banos and Sanders 2013; Moss, Pahl-Wostl, and Downing 2001). Using the classification method suggested by Banon and Sanders (2013), we studied eight articles that tackle climate change in viticulture from a multi-agent systems perspective.

By placing each of these studies using what we call in France a "horseshoe" grid (fig.1), we notice that none of them are in sections A or B. This absence reveals science's lack of objectivity regarding climate change and the difficulties it has in raising the level of abstraction. Also all of these works are based on particular viticulture areas and use formalisms tending towards KIDS[3] (Edmonds and Moss 2005).

This over-representation is probably linked to our need to base the models on a target viticulture area, where we are attempting to increase the efficiency and broaden the scope of the model. This need for a base, generally linked to climate data, and/or to the methods of gathering social information, concentrates efforts in understanding the dynamics on a focal point that then struggles to increase in scale and to suggest generic models higher in abstraction.

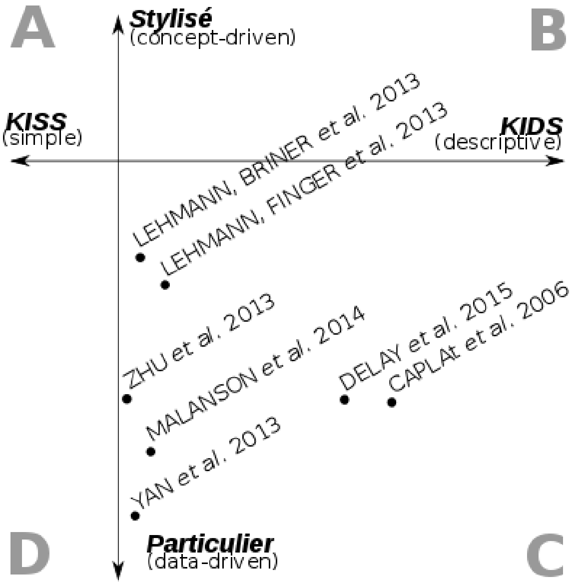

Figure 1: Placing the models in a "horseshoe" grid, as suggested by Banos and Sanders (2013).

4. Examples of the use of ABMs in understanding complex local socio-systems subject to climate change constraints

The interdisciplinary nature of multi-agent modelling applied to viticulture, in an

---

[2] LACCAVE : Long term impacts and Adaptations to Climate Change in Viticulture and Enology.

[3] KIDS, short for *Keep It Descriptive and Stupid*, is a modelling approach that seeks to describe interactions between agents as precisely as possible.

environment subject to climate change and its various associated uncertainties, led us to adopt a post-normal stance during our work. This entails involving all the stakeholders in the modelling process (Funtowics et Ravetz, 1993). Nevertheless, the range of problems to be addressed is so huge that implementing a co-construction with all of these actors, with the aim of establishing a model including all their points of view, appeared impossible. To include this multitude of viewpoints and designs into an object covering many forms of reality (Watzlawick 1976), we are instead suggesting an approach that combines several models associated with an analysis of the constraints and uncertainties of the models employed (Delay 2015).

Thus, based on the work of Neumann (2015), we first constructed an ontology of the field of climate change in regard to viticulture. Then we co-constructed, along with the stakeholders, 6 models, each responding to questions arising locally and corresponding to a limited part of the ontological domain, somewhat like a fragmented vision of the world. We will present them in pairs, then we will show the relationship between them.

4.1. Large spatial scale: the pathway to abstraction

The first models are Dion still alive and VICTOR: two multi-agent models that simulate the viticulture area on a small scale with agents aggregated in the form of towns, villages and market places. These two models bring us to replace the steep slope viticulture in the 'viticulture-system' by focusing our attention on the effects that orography produces on the structuring and the dynamics of wine-growing areas.

These two abstract models are based on theoretical data. That which interests us as modellers, along with the scientific and technical staff with whom we formalised the interactions, lies within the validation of relationships and the minimum processes necessary to produce the spatial dynamics observed in real life, enabling us to hypothesise and explore the implications that they might have on the space.

The *Dion still alive* model (Delay and Chevallier 2015) proposes to revisit the hypotheses put forward by Dion (Dion 1952) in his article "Querelle des anciens et des modernes sur les facteurs de la qualité du vin" / "Quarrel between the traditionalists and the modernists about wine quality factors". This work, apart from the reinterpretation of Dion with regard to simulation, also causes us to reflect on formalism, which could be seen to describe the evolution of quality over the long term. Here, the slope is a quality criteria much sought after locally by the agents, and that will influence the global spatial dynamics.

The VICTOR model (Delay, Leturcq, and Rodier, n.d.) is presented next, following the same formalism of description. This model explores the agricultural dynamics that arise in a winegrowing area when competition between two crops, vines and cereals, is introduced. It is therefore used to simulate the effect of different types of market on village communities. Here we will explore the effect of economic stimulation on the winegrowing area when it is in completion with subsistence farming. In this case, sloping land is considered a poor environment, unfavourable for cereal production. It therefore represents a refuge space for viticulture even when economic conditions favour cereals.

4.2. Meso-scale; towards taking into account viticulture dynamics

Next we explore "individual-centred" models at greater spatial scales using the models LAME (Delay et al. 2012) and CiVIsMe (Delay et al. 2015). These models attempt to formalise individuals' behaviours in a simplistic fashion, which, in a "plausibility of principal" (Varenne 2011), allow us to consider the spatial dynamics of the vineyard. The iterative construction of these models with the actors[4] ensures this "plausibility of principal" with the reality of the winegrowing area concerned.

The LAME model explores the importance of environmental factors, such as slope and accessibility, as the winegrowers' choose whether to reuse or abandon their plots. This work is first carried out in an artificial environment, and then the system is faced with real data.

The CiVIsMe, for its part, studies the ever-present cooperative effect found in all vineyards in structurally difficult situations. We use it to evaluate the implications of the cooperatives' remuneration policies. This model also allows us to identify the influence of the land itself and thus to explain any local differences that might arise in co-operative behaviours.

4.3. Finer spatial scales and local dynamics: abstraction assists in considering local dynamics

In this last stage, downscaling, we put the emphasis on very specific processes. Our objective here is to reply to the particular needs of the stakeholders involved in our study. These winegrowers and technicians, who also participated in the modelling previously described (by validating performance and discussing hypotheses and results), were especially interested in models based on their local areas. We therefore submitted the next two models, *acidityGIS* (Delay, Piou, and Quenol 2015) and CeLL (Delay and Caffarra 2015), in response to their requests. These models integrate economic data, along with spatial temperature data, in order to evaluate the impact of spatial heterogeneity on the models' performance.

Considering the impacts of climate change on the scale of the Mediterranean basin (Hannah et al 2013) inevitably isn't compatible with small-scale adaptations (Van Leeuwen et al. 2013). The wine growing area of Côte Vermeille is at greater risk from climate change than other regions. The *acidityGIS* model, used in a co-operative context, explores the possibilities offered by orography to maintain grape ripening according to the specifications of the Appellation d'Origine Contrôlée[5] system.

The CeLL model aims to offer winegrowers food for thought about their methods of combating insect pests. CeLL models the behaviour of a vine parasite known as the Eudémis or European Grapevine moth (Lobasia botrana). This Lepidoptera, which lays its eggs under the skin of the grape, is particularly temperature-sensitive. By means of an 'individual-centred" model, we simulate the behaviour of butterfly populations on a small scale in order to optimise pest-control strategies by the use of pheromone traps. The development of the CeLL model allows us to test *in silico* a certain number of variables and to show the potential results of different battle scenarios by the diffusion of pheromones appropriate for winegrowers.

4. The integration of multi-agent systems in a prospective local approach

This aspect of considering an area and climate change via several models has two advantages: *i.)* to produce direct results on which the stakeholders can act and *ii.)* to offer the researcher a system of models addressing the subject from different angles, each corresponding to the point of view of a particular group of actors. In the following

[4] The actors in this case are technicians from organisations involved in the area, such as the chamber of agriculture, the winegrowers' syndicates, agricultural cooperatives etc.

[5] Optimising the double ripening of the berries: polyphenolic maturity, technological maturity

section we present the second advantage of this multi-model approach.[6]

4.1. Looking ahead using a system of variables built on the basis of models

For the researcher wanting to look to the future using a system of models, the challenge is to build a meta-model capable of “thinking ahead”[7]. The MicMac method[8] put forward by Godet (1985) suggests the use of structural variables coupled with an approach based on graph theory in order to analyse interactions between different variables. We identified 11 macro-variables resulting in the clustering of several modelled processes.

The second stage of the method involves studying the types of relationship that variables have with each other and then constructing a network of dependencies based on graph theory. Figure 2 shows the interactions between the macro-variables dealt with by the models that were co-constructed with the stakeholders. This graph therefore represents the systemic vision that the stakeholders developed, in other words a synthesis of the abstraction that the stakeholders made via the modelling work that they carried out with us.

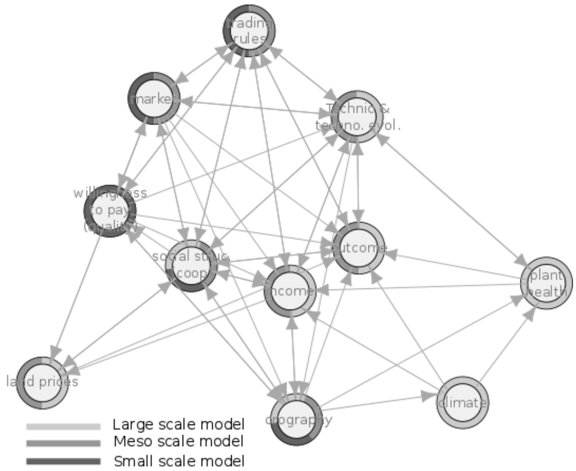

Figure 2: Diagram showing the interaction between structural macro-variables, in which we can observe the different spatial scales that apply to each variable.

The stakeholders from the Banyuls region verified these systems of variables and the interaction between them, at a round table workshop.

This meeting brought to light a perception shared by the winegrowing community in the area. We noticed the actors’ underestimation of the importance of the community level and the predominance of the global context, to which they respond mainly at an individual level. This shows the difficulty facing the cooperative organisations, which represent the broad majority of actors in this area, as they refuse to question [9] their methods and attribute their difficulties to external forces.

Focusing ourselves on climate and climate change, we see that these are indeed present in the minds of the stakeholders but that the solutions for adaptation are found on a local scale. Individually and collectively they feel that it’s impossible to influence global dynamics. Nevertheless local adaptation is possible, as some other works corroborate (Van Leeuwen et al. 2013; Viguié, Lecocq and

[6] The contribution of the method by producing of results employable by stakeholders was described by Delay, Piou, and Quenol (2015) and Delay and Caffarra (2015)

[7] We were inspired here by the work of Hannin, Brugière, and Aigrain (2010, 227), who identified 50 traits specific to viticulture.

[8] “Matrice d’Impacts Croisé-Multiplication appliquée à un Classement”

[9] At the same time, the actors regularly question the workings of the models. Two of the six models that we developed concern in particular the cooperative objective, whilst another explores the “co-operative factor” in parasitic insect control.

Touzard 2014), by redistributing the space constraints and using orography to respond to these new constraints.

5. Conclusion

Agent based models and complexity science are tools to help us consider the world in an integrated fashion. Even though they can be used as such to provide answers to ever-increasing social questions, using and diverting them with the aim of looking towards the future can be used more broadly to offer a systemic approach to the problems met by the stakeholders.

The construction, or co-construction with the stakeholders, of models allows access to what Weber (1922) identifies as "causal adequacy". This amounts to identifying consistent interactions from the point of view of the actors (empirical).

At the same time, "meaningful adequacy" (ibid.), that is to say consistent with reality, is identified in the general discussion during the validation exercise. The "distance" between these two types of adequacy shown in the systems of macro-variables helps us to understand the manner in which the stakeholders think about their area and their interactions. Thus the wheels of adaption and local dynamics can be partially put into motion by them on an individual basis, whereas a great number of variables, on a more global level, remain beyond their grasp.

The findings produced in these study areas demonstrate the need for quite specific local adaptations. The question remains as to the flexibility of our system of variables. It will be most interesting in future to continue to explore configurations where orography is less important in order to *i.)* evaluate the (longer term) durability of the variables in the systems and *ii.)* identify other means of local adaptation that could be transferable into different contexts.

6. Bibliographie

Auriac, Franck. 1979. "Système Économique et Espace Un Exemple En Languedoc." Thèse de doctorat, Montpellier, France: université Paul Valéry.

Banos, Arnaud, and Lena Sanders. 2013. "Modéliser et Simuler Les Systèmes Spatiaux En Géographie." In *Modéliser & Simuler*, edited by Franck Varenne and Marc Silberstein, Edition Matériologiques, 2:839–69. Collection Sciences & Philosophie. Paris (France).

Barbeau, Christine, Gérard Barbeau, and Alexandre Joannon. 2014. "Analyzing the Sensitivity of Viticultural Practices to Weather Variability in a Climate Change Perspective: An Application to Workable-Day Modelling." *International Journal of Vine and Wine Sciences* 48 (2): 141–52.

Bommel, Pierre. 2009. "Définition d'un Cadre Méthodologique Pour La Conception de Modèles Multi-Agents Adaptée À La Gestion Des Ressources Renouvelables." Thèse de doctorat, Université Montpellier II-Sciences et Techniques du Languedoc.

Bousquet, f. 2001. "Modélisation d'accompagnement Simulations Multi-Agents et Gestion Des Ressources Naturelles et Renouvelables." Habilitation à Diriger les Recherches, Lyon 1.

Caplat, Paul, Jacques Lepart, and Pascal Marty. 2006. "Landscape Patterns and Agriculture: Modelling the Long-Term Effects of Human Practices on Pinus Sylvestris Spatial Dynamics (Causse Mejean, France)." *Landscape Ecology* 21 (5): 657–70.

Coquillard, Patrick, and R.C. Hill. 1997. *Modélisation et Simulation d'écosystèmes: Des Modèles Déterministes Aux Simulations À Événements Discrets*. Dunod.

Delay, Etienne. 2015. "Réflexions Géographiques Sur L'usage Des Systèmes Multi-Agents Dans La Compréhension Des Processus d'évolution Des Territoires Viticoles de Fortes Pentes : Le Cas de La Côte Vermeille et Du Val Di Cembra." Thèse de doctorat, Limoges: Université de Limoges.

Delay, Etienne, and Amelia Caffarra. 2015. “A Virtual Pest to Test a Real Method of Integrated Pest Management: Agent-Based Models as a Tool to Explore the Behavior of L. Botrana During Mating Disruption.” In *GiESCO Congress*. Pech Rouge - Montpellier - (Lauréat du meilleur poster scientifique).

Delay, Etienne, and Marius Chevallier. 2015. “Roger Dion, toujours vivant !” *Cybergeo : European Journal of Geography*, May.

Delay, Etienne, Jeremy Bourgoin, Fabio Zottele, and Daniele Andreis. 2012. “LAME : Un Outil Pour Comprendre Les Dynamiques Spatiales Des Territoires Viticoles de Montagne.” In *IV Congrès International de La Viticulture de Montagne et de Forte Pente*, 80–85. Lyon.

Delay, Etienne, Marius Chevalier, Éric Rouvellac, and Fabio Zottele. 2015. “La coopérative : origine et conséquence des paysages viticoles de montagne ?” *Journal of Alpine Research Revue de géographie alpine*.

Delay, Etienne, Samuel Leturcq, and Xavier Rodier. n.d. “ViCTOr : paysage virtuel pour explorer les dynamiques de la VIticulture et de la Consommation en TOuRaine.” *Cybergeo : European Journal of Geography (accepté).*

Delay, Etienne, Cyril Piou, and Hervé Quenol. 2015. “The Mountain Environment, a Driver for Adaptation to Climate Change.” *Land Use Policy* 48 (November): 51–62.

Dion, Roger. 1952. “Querelle Des Anciens et Des Modernes Sur Les Facteurs de La Qualité Du Vin” 61 (328): 417–31.

Edmonds, Bruce, and Scott Moss. 2005. “From KISS to KIDS–an ‘Anti-Simplistic’ Modelling Approach.” In. Springer.

Etienne, Michel, and Collectif. 2013. *Companion Modeling: A Participatory Approach to Support Sustainable Development*. Springer Science & Business Media.

Ferber, J. 1995. *Les Systèmes Multi-Agents:Vers Une Intelligence Collective*. InterEditions.

Funtowicz, Silvio O., and Jerome R. Ravetz. 1993. “Science for the Post-Normal Age.” *Futures* 25 (7): 739–55.

Godet, Michel. 1985. *Prospective et Planification Stratégique*. Economica. CPE-Economica. Paris (France).

Hannah, Lee, Patrick R. Roehrdanz, Makihiko Ikegami, Anderson V. Shepard, M. Rebecca Shaw, Gary Tabor, Lu Zhi, Pablo A. Marquet, and Robert J. Hijmans. 2013. “Climate Change, Wine, and Conservation.” *Proceedings of the National Academy of Sciences* 110 (17): 6907–12.

Hannin, Hervé, Françoise Brugière, and Patrick Aigrain. 2010. “Mutation et Perspective de La Filière Vitivinicole.” In *La Vigne et Le Vin: Mutations Économiques En France et Dans Le Monde*. Vol. 1. La Documentation Française 5323. Paris: la Documentation française.

Janssen, Marco A., and Elinor Ostrom. 2006. “Empirically Based, Agent-Based Models.” *Ecology and Society* 11 (2): 37.

Jones, Gregory V., Michael A. White, Owen R. Cooper, and Karl Storchmann. 2005. “Climate Change and Global Wine Quality.” *Climatic Change* 73 (3): 319–43.

Knibbe, Carole. 2013. “L’évolution Expérimentale in Silico.” In *Modéliser & Simuler*, edited by F. Varenne and M. Silberstein, Edition Matériologiques. Vol. 2. Collection Sciences & Philosophie. Paris (France).

Küppers, Günter, and Johannes Lenhard. 2005. “Validation of Simulation: Patterns in the Social and Natural Sciences.” *Journal of Artificial Societies and Social Simulation* 8 (4).

Lehmann, Niklaus, Simon Briner, and Robert Finger. 2013. “The Impact of Climate and Price Risks on Agricultural Land Use and Crop Management Decisions.” *Land Use Policy* 35 (November): 119–30.

Lehmann, Niklaus, Robert Finger, Tommy Klein, Pierluigi Calanca, and Achim Walter. 2013. “Adapting Crop Management Practices to Climate Change: Modeling Optimal Solutions at the Field Scale.” *Agricultural Systems* 117: 55–65.

Le Page, C., Abrami, G., Barreteau, O., Becu, N., Bommel, P., Botta, A., Dray, A., Monteil C., et Souchère, V. (2010). Des modèles pour partager des représentations. In M. Etienne (Ed.), La modélisation d’accompagnement : une démarche participative en appui au développement durable (pp. 55–81). Quae Edition.

Malanson, George P., Ashton M. Verdery, Stephen J. Walsh, Yothin Sawangdee, Benjamin W. Heumann, Philip M. McDaniel, Brian G. Frizzelle, et al. 2014. “Changing Crops in

Response to Climate: Virtual Nang Rong, Thailand in an Agent Based Simulation." *Applied Geography* 53 (September): 202–12.

Manzo, Gianluca. 2014. "Potentialités et Limites de La Simulation Multi-Agents: Une Introduction." *Revue Française de Sociologie* 55 (4): 653–88.

Moss, Scott, Claudia Pahl-Wostl, and Thomas Downing. 2001. "Agent-Based Integrated Assessment Modelling: The Example of Climate Change." *Integrated Assessment* 2 (1): 17–30.

Neethling, Etienne, Théo Petitjean, Hervé Quénol, and Gérard Barbeau. 2016. "Assessing Local Climate Vulnerability and Winegrowers' Adaptive Processes in the Context of Climate Change." *Mitigation and Adaptation Strategies for Global Change*, February.

Nemani, Ramakrishna R., Michael A. White, Daniel R. Cayan, Gregory V. Jones, Steven W. Running, Joseph C. Coughlan, and David L. Peterson. 2001. "Asymmetric Warming over Coastal California and Its Impact on the Premium Wine Industry." *Climate Research* 19 (1): 25–34.

Neumann, Martin. 2015. "Grounded Simulation." *Journal of Artificial Societies and Social Simulation* 18 (1): 9.

Ollat, Nathalie, and Jean-Marc Touzard. 2014. "Long-Term Adaptation to Climate Change in Viticulture and Enology : The LACCAVE Project." *Journal International Des Sciences de La Vigne et Du Vin*, 1–7.

Peschard, Isabelle. 2011. "Modeling and Experimenting." In *Models, Simulations, and Representation*, edited by Paul Humphrey and Cyril Imbert, 42–61. New York: Routledge.

Popper, Karl Raimund. 1998. *La Connaissance Objective: Une Approche Évolutionniste*. Paris: Flammarion.

Pumain, Denise. 1998. "La Géographie Saurait-Elle Inventer Le Futur ?" XXXVI (110): 53–69.

———. 2003. "Une Approche de La Complexité En Géographie" 78 (1): 25–31.

Robinson, Derek T., Daniel G. Brown, Dawn C. Parker, Pepijn Schreinemachers, Marco A. Janssen, Marco Huigen, Heidi Wittmer, et al. 2007. "Comparison of Empirical Methods for Building Agent-Based Models in Land Use Science." *Journal of Land Use Science* 2 (1): 31–55.

Schelling, T. 1971. "Dynamic Models of Segregation" 1 (2): 143–86.

Schultz, Hans R. 2010. "Climate Change and Viticulture: Research Needs for Facing the Future." *Journal of Wine Research* 21 (2): 113–16.

Sebillotte, Michel, and Clementina Sebillotte. 2002. "Recherche Finalisée, Organisations et Prospective: La Méthode Prospective SYSPAHMM (SYStème, Processus, Agrégats d'Hypothèses, Micro-et Macroscénarios)." *Oléagineux, Corps Gras, Lipides* 9 (5): 329–45.

Smajgl, Alexander, and Olivier Barreteau. 2013. *Empirical Agent-Based Modelling: Challenges and Solutions: The Characterisation and Parameterisation of Empirical Agen-Based Models*. New York: Springer-Verlag New York Inc.

Thom, R. 2009. *Prédire N'est Pas Expliquer*. Paris: Flammarion.

Van Leeuwen, Cornelis, Hans R. Schultz, Iñaki Garcia de Cortazar-Atauri, Eric Duchêne, Nathalie Ollat, Philippe Pieri, Benjamin Bois, et al. 2013. "Why Climate Change Will Not Dramatically Decrease Viticultural Suitability in Main Wine-Producing Areas by 2050." *Proceedings of the National Academy of Sciences* 110 (33): E3051–52.

Varenne, F. 2010. *Formaliser Le Vivant Lois, Théories, Modèles ?* Paris: Hermann éd.

Varenne, Franck. 2011. *Modéliser Le Social: Méthodes Fondatrices et Évolutions Récentes*. Paris: Dunod.

Viguié, Vincent, Franck Lecocq, and Jean-Marc Touzard. 2014. "Viticulture and Adaptation to Climate Change." *Journal International Des Sciences de La Vigne et Du Vin*, 55–60.

Watzlawick, Paul. 1976. *How Real Is Real?: Confusion, Disinformation, Communication*. New York: Random House.

Weber, Max. 1922. *Economie et Société, Tome 1 : Les Catégories de La Sociologie*. Nouvelle édition 2003. Paris: Pocket.

Weisberg, Michael. 2013. *Simulation and Similarity: Using Models to Understand the World*. Oxford Studies in Philosophy of Science. New York: Oxford University Press.

White, Michael A., N. S. Diffenbaugh, Gregory V. Jones, J. S. Pal, and F. Giorgi. 2006. "Extreme

Heat Reduces and Shifts United States Premium Wine Production in the 21st Century.” *Proceedings of the National Academy of Sciences* 103 (30): 11217–22.

Yan, Dan, Uwe A. Schneider, Erwin Schmid, He Qing Huang, Lihu Pan, and Oliver Dilly. 2013. “Interactions Between Land Use Change, Regional Development, and Climate Change in the Poyang Lake District from 1985 to 2035.” *Agricultural Systems* 119: 10–21.

Zhu, Xueqin, Marco Moriondo, Ekko C. van Ierland, Giacomo Trombi, and Marco Bindi. 2014. “A Model-Based Assessment of Adaptation Options for Chianti Wine Production in Tuscany (Italy) Under Climate Change.” *Regional Environmental Change*, September, 1–12.