The future of social-ecological systems at the crossroads of quantitative and qualitative methods

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ABSTRACT

Urgent calls to transform societies toward more sustainability make the practice of anticipation more and more necessary. The progressive development of computational technologies has opened room for a growing use of quantitative methods to explore the future of social-ecological systems, in addition to qualitative methods. This warrants investigating issues of power relationships and discontinuities and unknowns that arise when mingling quantitative and qualitative anticipatory methods. We first reflected on the semantics attached to these methods. We then conducted a comparative analysis on the way the articulation of quantitative and qualitative methods was conducted, based on an in-depth analysis of a set of eleven anticipatory projects completed by several external case studies. We propose insights to classify projects according to the timing (successive, iterative or convergent) and the purpose of the articulation (imagination, refinement, assessment and awareness raising). We use these insights to explore methodological implications and power relationships and then discuss the ways to inform or frame anticipatory projects that seek to combine these methods.

1. Introduction

The emergence of a dominant narrative about the limitations of earth's resources (Díaz et al., 2019; Meadows et al., 1972) reflects a growing societal awareness about the role of human activities in the degradation of ecosystems. Scientific studies refer also to the associated concept of planetary boundaries (Rockström et al., 2009; Steffen et al., 2015). This narrative calls for an urgent need for deep transformations toward reinvented sustainable human-nature relations. Literature on transformation processes points out the importance of anticipation to trigger changes (Hebinck et al., 2018; Willow, 2022; Wyborn et al., 2020). Because the way we anticipate - i.e. think and use the future (Miller, 2015) - shapes our actions in the present, the practice of anticipation is central to conduct transformation toward sustainability.

Historically, anticipation has mainly resorted to qualitative practice that usually provided representations of the future in the form of narratives, stories or visual symbols. The first three of the five historical waves associated with futures studies (Schultz, 2015) are based on qualitative practice. It includes the "Oral Tradition" (the times of oracles, shamans and fortune tellers when only one future seemed to be possible), the "Written Age" (utopias and science fiction) and "Enlightenment and Progress" (inclusion of science and technology). By the mid-20th century, a scientific rationalisation of futures studies developed, associated with the prevalence of technological forecasting (Son, 2015). Quantitative simulations and models are thus fairly new anticipatory approaches, associated with the last two waves of Schultz' typology

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("Systems and cybernetics"; "Complexity and emergence"). Computational modelling and simulation is the process of creating and experimenting with a computerised model imitating the behaviour of a real-world process or system over time. While a number of anticipation activities, such as climatic modelling, rely exclusively on quantitative methods, a growing number of anticipatory works mix both quantitative and qualitative methods. Researcher groups attempt to use the complementarity between "both worlds" (Garb et al., 2008) to explore the future, taking advantage of the wide view and creativity permitted by qualitative methods as well as the "mathematical exactness" (Tapio et al., 2011) and "formal and explicit structuring" (Garb et al., 2008) of the quantitative methods (Robertson et al., 2017; Symstad et al., 2017). This evolution of the practice of anticipation modifies our way to probe the future and therefore our actions in the present.

Many works focus on the articulation between quantitative and qualitative anticipatory methods (AQQAM) (see for example Alcamo, 2008; Elsawah et al., 2020; Fortes et al., 2015; Haegeman et al., 2013; Ravera et al., 2011; Robertson et al., 2017; Symstad et al., 2017; Tapio et al., 2011). It reveals a considerable diversity both in methodological and procedural aspects, while pursuing a diversity of purposes. These studies describe and analyse the modalities of the AQQAM, but few question the implications of these modalities on the practice and use of anticipation, in particular on its transformative potential. Scholars identified several challenges linked to the AQQAM. The recent work of Elsawah et al. (2020) gives a comprehensive overview of these issues of articulation, related to the different ways in which the two types of methods treat multiscale processes, uncertainties, complexity, consistency or discontinuities. It raises questions of the integration of different types of knowledge, and of the translation between figures and narratives (Mallampalli et al., 2016). Elsawah et al. (2020) also mention issues of power relationships during the process of building scenarios and linked them to the use of the product by decision makers.

The objective of this paper is to explore how qualitative and quantitative anticipatory methods are articulated, with a focus on power relations and the integration of discontinuities and unknowns, two key issues for anticipation that are hardly related to the modalities of the AQQAM (Garb et al., 2008; van Notten et al., 2005; Vervoort and Gupta, 2018).

This work draws material from a series of workshops organised between 2019 and 2022 where participants conducted a comparative analysis of their research projects that articulated qualitative and quantitative anticipatory methods to work on the future of social-ecological systems at various scales. We first clarify the terminology we use about anticipation, quantitative and qualitative methods and we introduce the two issues treated in this article, i.e. handling discontinuities and unknowns, and power relations. Then we give insights to differentiate between the various types of the AQQAM. We use these insights in the next section for exploring the different implications of the AQQAM on both issues of discontinuities and unknowns and power relations. Finally, we highlight several leverage points to ensure that projects developing an AQQAM could contribute to just and integral transformations of social-ecological systems.

2. Background, data & method

2.1. Clarifying the terminology

a. Anticipation

The word "anticipation" has been used since the 1950s when future-oriented thinking developed especially in the USA (in the army, in the Rand corporation, in universities) and in France (Berger, 1964; De Jouvenel, 1964; Berger et al., 2007). Godet (1994) insists on the importance of intellectual and emotional appropriation if anticipation is to crystallise into effective action. For Loveridge (2008) "*anticipation, or foresight, … is after all a political activity, related to agenda setting, that is why it is either 'care or provision for the future' or 'the muzzle sight of a gun'*".

Recently, an enlarged definition of anticipation has emerged, stating that "*all efforts to 'know the future' in the sense of thinking about and 'using-the-future' are forms of anticipation*" (Miller, 2018).

Anticipation uses several approaches: projections, i.e. the extension into the future of past developments using specific assumptions for the extrapolation or variations of trends (Godet, 1994), forecasting, i.e. the assessment, with a degree of confidence (probability) of a trend over a given period (Godet, 1994), and foresight, i.e. a systematic, participatory and multi-disciplinary approach to explore mid- to long-term futures and drivers of change (GFAR, 2014).

b. Qualitative anticipatory methods

Qualitative anticipatory methods use the future without considering numerical indicators. They usually provide representations of the future in the form of narratives, stories, and/or visual symbols. Common methods include among others scenario planning (Godet, 2001), visioning (Bezold, 2004), backcasting (Quist and Vergragt, 2006), causal layered analysis, Delphi (Gordon, 2004), the futures wheel and the futures triangle (Inayatullah, 2008). These methods are usually implemented in a participatory way; however, a single actor can also produce qualitative anticipatory models (Haegeman et al., 2013).

Qualitative anticipatory methods have the advantage of freeing imagination, boosting creativity and making it possible to integrate different disciplinary perspectives in a symmetrical way. Conversely, they may be considered less "scientific" as they are not always easily replicable and transparent (Alcamo, 2008) and entail a large part of subjectivity (Popper, 2008).

c. Quantitative anticipatory methods

Quantitative anticipatory methods generate numerical values and provide quantified representations of the future. Although analytical solutions can be determined for the simplest models, computational models are used in the vast majority of cases to generate numerical simulations. For biophysical processes, models are often based on mathematical formalisms traducing biophysical laws. Numerous quantitative models integrate human activities and the feedback of the environment, for instance agent-based models (Gilbert, 2008) or some land-use and land-cover change models. Purely quantitative methods concern mainly machine learning methods that predict response variables through functions qualifying relations from an input dataset. Other methods, such as analytical modelling, specify a qualitative conceptual model from a studied system and then implement it in a simulation model, justifying their final classification as "quantitative" approaches.

Although quantitative anticipatory methods are more associated with forecasting and projection (e.g. for several climate studies) than with foresight, a growing number of quantitative methods contribute to exploring alternative futures. This leads to the development of new tools for model exploration (Chérel et al., 2015; Kwakkel et al., 2013). The demand for quantifying beyond the present also arises from policy-makers who want to quantify ex-ante the expected outputs of a policy decision and therefore reduce uncertainty (Haegeman et al., 2013; Symstad et al., 2017). Participatory anticipatory approaches, such as companion modelling or group model building, also use quantitative tools (agent-based simulation, system dynamics model) to promote transformative learning (van Bruggen et al., 2019).

Quantitative anticipatory methods are often considered more explicit and transparent than qualitative approaches, as all rules and equations are written (Halbe et al., 2020). Yet, the way tools are developed can also be seen as an obstacle for transparency. Modelling choices, such as the modelling paradigm (agent based modelling, Bayesian network, etc.), the assumptions behind the conceptual model, the simplifications of the conceptual model, the source of the calibration parameters or even the computer implementation are not neutral. These choices shape the way the model represents the future (Alcamo, 2008). In addition, several authors point out the risk that quantitative anticipatory methods make the future seem less uncertain than it really is (Alcamo, 2008; Haegeman et al., 2013). Modelling choices are thus always partly subjective and arbitrary. Decision-making based on

quantitative model results requires opening the black box of the model and getting down to the assumptions to take the measure of the uncertainties on which decisions are made (Saltelli et al., 2020). This transparency can be particularly difficult to achieve when the quantitative models attempt to integrate many mechanisms (Sun et al., 2016).

Quantitative methods can be implemented in different ways, by a unique modeller, a group of modellers, or a range of stakeholders with modellers. They require at least one participant with specific technical skills.

d. Hybrid anticipatory methods

"Hybrid methods" refers here to the moving frontier between both categories, where qualitative and quantitative elements are often difficult to disentangle. Examples include fuzzy cognitive maps - also classified as semi-quantitative methods (van Vliet et al., 2010), role playing games as well as methods for bridging linguistic and epistemic uncertainties across narratives and simulations (Pedde et al., 2019).

e. Common terms but different meanings

Qualitative and quantitative anticipatory methods share some common terms, sometimes with different meanings. This ambivalence needs to be addressed in order to create a shared framework for reflecting on their articulation. While definitions of "business as usual", "predictability", "projection", "time horizon/time frame", "trend", "worldview", "driver/driving force", "variable", "anticipatory assumption", "hypothesis" are similar in both fields, other common words bear different meanings, depending on whether they refer to quantitative or qualitative anticipatory modelling, as shown in Table 1.

2.2. Discontinuities, unknowns and power relations

Before providing our insights (Section 3), we briefly present here how the existing literature addresses discontinuities and unknowns, and power relationships.

Table 1
Definition of words used in quantitative and qualitative anticipatory methods with a different meaning.

Terms	Qualitative anticipatory methods	Quantitative anticipatory methods
Scenario	A description of how the future may unfold according to an explicit, coherent and internally consistent set of assumptions about key relationships and driving forces.	A specific configuration of a model as given by parameters values, input data, activated modules.
Ruptures/ discontinuities	Abrupt, major changes in the nature or direction of a trend.	Manifestations of an underlying slow evolution. Determining this slow evolution requires, in general, the introduction of new dimensions, new parameters.
Emerging pattern	A novel situation/new trend created by unforeseen recurrent events.	The generation of novel properties or functionalities that can be described or specified without referring to their constituting elements.
Exploration	The investigation of a wide range of possible future developments, considered from a variety of perspectives.	A set of methods to investigate the input space of the model as well as the output space.
Plausible	Judged to be reasonable because of its underlying assumptions, internal consistency and logical connection to reality.	A term that is often implicit and rarely discussed.
Uncertainty	A state of having limited knowledge about the future.	The maximum possible deviations (with a typical probability of 95 %) of the calculated values of the output variables of the model from the values taken as reference.

a. Dealing with discontinuities and unknowns

Discontinuities and unknowns are extreme forms of uncertainty, which are inherent to the future. Integrating them in anticipation projects allows for a more open approach of the future and avoids the trap of working only on what we think is likely to happen. We understand discontinuities as changes producing a new order that is different from the existing one (Burt, 2007). They can be temporary or permanent, abrupt or gradual (van Notten et al., 2005). The unknown dimension of the future results explicitly from the absence of knowledge about a phenomenon. We consider as "unknowns" phenomena that we are not aware of in the present, therefore leading to difficulties including them in our representations of the future. Quantitative and qualitative methods have fundamentally different ways in approaching the notions of discontinuities and unknowns.

Qualitative anticipatory methods inherently entail the possibility of including discontinuities up to a certain limit through creativity and imagination. Indeed, change in the conditions of change (Popper, 1945) is a fundamental source of discontinuity, which is even often sought after. These methods also make it possible to approach and explore some unknowns and novelty, since it is not limited a priori by any tool. When we observe an event or an occurrence that we cannot explain, a qualitative anticipatory method can produce novel representations of the future through exploration, and help imagine how these representations can be connected to the present through abduction (Patokorpi and Ahvenainen, 2009). The main limit of qualitative approaches to think unknowns and discontinuities is the risk to stay in the same "system of thinking" or "certitude" that can hinder creativity.

For quantitative anticipatory methods, the possibility to incorporate discontinuities depends on their nature and the structure of the model. It is easy to integrate a discontinuity in the values of some parameters of the model. However, when discontinuities concern structural changes in the system, their integration will depend on the mathematical rules or algorithms that define the structure of the model. Such integration is easier when the quantitative model is flexible enough to be modified especially for the discontinuities, or when simulations entail time stops that enable incorporation of discontinuities. The same applies for the "unknowns". Anticipatory quantitative methods can hinder their integration, as these methods are more often based on the "knowns", for which they require a precise knowledge of the processes represented.

Hybrid anticipatory methods, such as role-playing games used in companion modelling (Barreteau, 2003), are more flexible for integrating discontinuities or exploring unknowns than quantitative anticipatory methods, through incorporating new features for example. Yet, they are still circumscribed by the game board and the basic rules of the game (such as time step, duration of a game, choice of represented elements and players).

b. Addressing power relationships

The future is a domain of power, freedom and will (De Jouvenel, 2004). The representations of the future in the present are subject to power struggles, which must be integrated into any anticipation activity (De Jouvenel, 2004). Of particular importance is the power related to the capacity to privatise the future, to transform the fundamental public good nature of the future, i.e. a resource the use of which is a priori neither a source of exclusion nor a source of rivalry, into a club or a private good (Bourgeois et al., 2022). The use of the future has witnessed a colonizing process (Sardar, 1993), where "existing power structures gain greater control over the future" (Dator, 2005). Power relations affecting the modalities of the AQQAM require particular attention as they can affect the effectiveness of scenario methods (Cairns and Wright, 2019) and lead certain actors to weigh more in imagining and using the future, and therefore to have more influence on the present (Vervoort and Gupta, 2018). Considering power issues in the AQQAM raises the question of "who gains and who loses; by which mechanisms of power?" (Cairns and Wright, 2019).

Nature of power relationships linked to the AQQAM

According to Avelino and Rotmans (2009) power is defined as "the

capacity of actors to mobilise resources to achieve a certain goal". Studying powers when using an AQQAM raises the question of the relation between power and knowledge. Using quantitative and qualitative anticipatory methods, seen here as "mental" resources (Mann, 2002), leads to constructing and communicating knowledge about the future. This makes it possible to exercise power in two ways: first by the mobilisation of these mental resources to reach a certain goal, second by influencing other actors in mobilising other types of resources according to the knowledge produced about the future (Avelino and Rotmans, 2009). We are particularly interested in the relational dimension of power, to understand the way in which the different mobilizations of these resources (the quantitative and qualitative methods) can change the power of certain actors and thus influence the relations between actors. Dahl's (1957) definition of power as a relation indicates that "A has power over B to the extent that he can get B to do something that B would not otherwise do". Arendt (1970) (cited by Cairns and Wright, 2019) develops another view of power relations, which can also lead to collaboration between actors.

Quantitative and qualitative methods can influence power relationships in different ways. First, they can confer a "technical" power to some actors (Crozier and Friedberg, 1977). Each method is generally associated with one or more actors who master the technique, for example a modeller or a facilitator (Tapio et al., 2011). The "technical experts" therefore hold a particular power, that of controlling a technique, a method or a knowledge, on which the success of the articulation process largely depends. The higher the level of technicality of the methods, the less substitutable the experts, and the greater the power of their expertise. Similarly, the more the people in charge present themself, or is seen, as a skilled "expert", the less easily their way of mediating between the tool/method and the group of users of the tool/method can be questioned. Knowledge of a computational language associated with quantitative models illustrates the power of mastery of technicity. A qualitative method expert with an expertise in facilitation can also dominate or even manipulate the participants in a "participatory" process.

Directly linked to the power of expertise is the power of nomination. The technical expertise or knowledge of certain actors linked to quantitative and qualitative methods is often put to the fore to justify their participation. The more we work with technologies that are difficult to understand and use, the greater the risk that some participants will be marginalised while others, who master the tool, appropriate it for themselves and take power from it (Chambers, 2006).

Another type of power relates to the nature of information quantitative and qualitative methods generate. The numerical information quantitative methods produce about the future is often associated in the collective imagination with objectivity. Quantitative anticipation methods claim objectivity, arguing that they construct and analyse the future in the most "neutral" way possible, based on numerical results derived from mathematical relationships stemming from common representations in the scientific literature. Although this claim for objectivity is questionable (cf. 2.1.c), it often confers a certain "scientific" legitimacy to actors using quantitative information, and it is often used as an argument of authority. Conversely, actors using qualitative methods claim subjectivity and seek creativity. They will also be able to use arguments of authority when they mobilise "expert" knowledge, particularly when dealing with non-quantifiable uncertainties.

Spheres of actors to be considered

Two spheres of actors matter when studying power relationships in a project of AQQAM.

The first sphere concerns the actors who are directly involved in the articulation project. These include the experts on the issue in question (anyone with knowledge of the problem), the "technicians" who master the tools and the facilitators. In each project, a core team is generally in charge of the strategic choices of methods. This team works usually with a group of participants who will often be associated with one or another of the quantitative or qualitative methods (Elsawah et al., 2020; Garb et al., 2008).

The second sphere to consider includes the actors who are external to the project and to the process of articulation. They belong to the socio-political context where power relations pre-exist (Garb et al., 2008; Vervoort and Gupta, 2018), and have the power to support, hinder, influence the project or use the results depending on their own interests and agendas (Cairns and Wright, 2019). They include decision makers at different levels, donors, the media, the civil society…

2.3. Data and method

We conducted an ex-post multiple-case comparative analysis to explore the implications of the AQQAM on handling discontinuities and unknowns, and on power relationships. It adopts a "project" entry because it is the level of organization where these articulations can best be observed (Lüdeke, 2013).

Several of the co-authors organised a two-day seminar of project presentations on "foresight modelling". It led to the identification of eleven projects of AQQAM and the associated researchers. We combined the following criteria for selecting suitable projects: i) future-oriented with at least one qualitative and one quantitative method, ii) related to the fields of environment and sustainable development, iii) the presence of at least one person who was deeply involved in the project to ensure intimate comprehension of each project, and iv) a balance between researchers working mainly with qualitative methods and researchers specialised in quantitative modelling, even if several participants had expertise in both methods. Table 2 displays some characteristics of the eleven case studies selected.

Based on first discussions on informal lessons learned in the projects, we inferred that the implications of the AQQAM on discontinuities and power relationships depended on the way the AQQAM was conducted within the projects. The first step consisted in proposing insights based on our case studies to differentiate the various types of AQQAM. We organised seven days of workshops and ten additional short meetings to conduct a comparative analysis of our projects. We developed an analytical grid based on classical descriptive indicators of anticipatory projects found in the literature (e.g. Vervoort and Gupta, 2018) and from our discussions: methods, scale, time horizon, time based articulation of the methods, actors involved, finalities, sectors concerned, input data and impacts reached. We filled the grid for each project. After an analysis of this grid, reinforced by elements found in the literature (e.g. Haegeman et al., 2013; Houet, 2015; van Notten et al., 2005), we selected two dimensions that seemed particularly relevant to categorise the different projects in relation to our research questions. The first dimension, the "why", is the purpose of the AQQAM, as stated (implicitly or explicitly) in the related projects. The second dimension, the "how", is the timing of the AQQAM. We described the different possible categories of the AQQAM for these two dimensions, based on our case studies and completed again by relevant external cases found in the literature.

We used the insights gained on purpose and timing to analyse how discontinuities, unknowns and power relationships were handled in the AQQAM. Through six additional meetings, we adopted an inductive approach starting with the observation of each case study about discontinuities and powers, from which we derived the identification of several points of attention. We completed this first in-depth analysis with a literature review of external cases. We then inferred the possible links between these points of attention and the categories of AQQAM.

In the following sections, we present in detail the cases from our corpus, and we provide external case references supporting the identified points of attention.

Table 2
Projects selected articulating quantitative and qualitative anticipatory methods.

Case number	Name	Main focus	Spatial and temporal horizon	Methods	References
1	Niayes	Exploring future scenarios of the social-ecological system of the Niayes in 2040.	Niayes region (Senegal) - 2040	Scenarios co-building; Spatial modelling	Camara et al., 2019; Jahel et al., 2021
2	Laos	Land-use planning in the uplands of northern Laos	Municipality of Vienkham (Laos) – 2030	Participatory mapping; Role-playing game; Socio-economic modelling	Bourgoin, 2012; Bourgoin et al., 2012
3	Agrimonde-Terra	Land use and food security at global and regional levels (13 world regions)	World - 2050	Scenarios co-building; Balance modelling	Le Mouël et al., 2018; Mora et al., 2020
4	NLU-PREDICTS	Exploring impacts of global scenarios of land-use on biodiversity	World - 2050	Scenarios building; Agricultural sector partial equilibrium modelling	(Prudhomme et al., 2020)
5	Domino	Exploring future scenarios of the Reunion Island in 2030.	Reunion Island (France) - 2030	Scenarios co-building; Agent based model	Botta et al., 2009; Daré et al., 2008; Lagabrielle et al., 2010
6	Paragominas	Exploring future scenarios of the municipality and role of the small-scale farming	Municipality of Paragominas (Brazil) - 2040	Scenario co-building; Spatial modelling	(Piraux et al., 2020)
7	Méjean	What future for Causse Méjean grasslands? Examining environmental and land management problems with stakeholders	Causse Méjean (France) - 2050	Agent-based model; Scenario development; Role-playing game	Étienne et al., 2003; Étienne and Le Page, 2004
8	Tuy	Exploring future patterns of forest clearances	Tuy province (Burkina Faso)-2040	Spatial modelling; Hypothesis on the future	(Jahel et al., 2018)
9	Viticulture	Exploring the influence of winegrowers' behaviour on the dynamics of vineyard landscapes	Two protected designations of origin (in France and in Italy) - 2025-2030	Agents based models; Structural analyses	(Delay, 2015; Delay et al., 2017; Delay et al., 2015; Delay and Chevallier, 2015)
10	Valensole	Collaborative modelling to stimulate the emergence of sustainable farming systems in Valensole plateau	Valensole plateau (France) - 2030	Farm simulation modelling; Scenario development	(Hossard et al., 2022)
11	Descartes	Territorial foresight and urban planning	Reunion island (France) - 2022	Participatory modelling; Scenario planning	(Lestrelin et al., 2017)

3. Insights for disentangling the diversity of AQQAM

3.1. Characterising purposes

Each project can be characterised by one or several specific purposes (or primary intention) regarding the AQQAM. We identified four categories of purpose (Fig. 1), which are not necessarily mutually exclusive.

i) Imagining new representation(s) of the future (case 7)

The primary intention is to produce representations of the future with qualitative and quantitative aspects that did not exist before the project.

In some cases, quantitative methods can be used to aid qualitative approaches by giving insights on the future. For example, the purpose of the Méjean project was to imagine several scenarios of the future of the social-ecological system of Méjean, depending on the dynamic of reforestation. An agent-based model was developed to simulate futures from different situations in the present based on the specific representations of the three types of stakeholders involved in the project (foresters, conservationists and sheep farmers). It served as a starting point for deriving several qualitative scenarios. Similarly, several projects rely on quantitative projections of variables (e.g. climate or demographic projections) to derive several qualitative scenarios of plausible futures of the social-ecological system (Kalt et al., 2021).

ii) Imagining and refining representation(s) of the future (cases 1, 2, 3, 4, 5, 6,10)

The primary intention is to provide more detailed information about one or several representations of the future developed in the project. It can consist in assessing different impacts of a narrative and their timing (Houet and Verburg, 2022; Symstad et al., 2017), identifying counter-intuitive effects (Symstad et al., 2017), exploring a wide variety of situations deriving from one narrative (Houet and Verburg, 2022). The refinement can then help to compare different scenarios with similar indicators, and make them more concrete and understandable (Tapio et al., 2011).

For instance, in the Valensole project, the aim of the AQQAM was to explore with a quantitative simulator the co-built qualitative scenarios. Similar cases can be found in Volkery et al. (2008) or Mason-D'Croz et al. (2016). Conversely, Maier et al. (2016) highlighted the usefulness of qualitative narratives to complement prior simulations of multiple plausible futures.

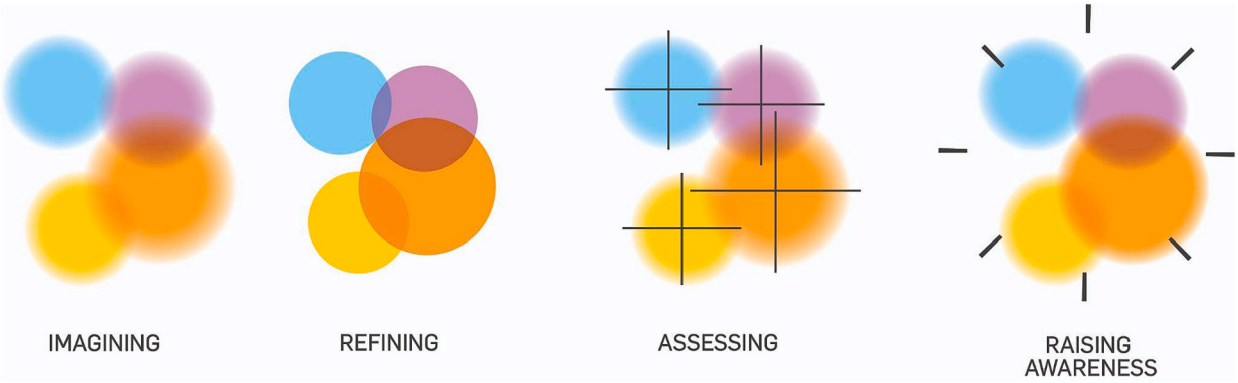

Fig. 1. Illustration of the four purposes of the AQQAM.

iii) Imagining and assessing the internal coherence of representation(s) of the future (cases 1, 3, 4, 5, 9,10)

The primary intention is to enhance the consistency of one or several representations of the future, i.e. the "validity of assumptions" (Symstad et al., 2017). Elsawah et al., 2020 distinguish the 'internal consistency' of a scenario defined as "freedom from internal contradictions" from the consistency between qualitative and quantitative parts of a scenario. They showed that issues of "internal consistency" concerned mainly qualitative scenarios, and that numerous quantitative tools have been developed to assess them. In this article, we assume that issues of internal consistency concern qualitative as well as quantitative methods.

One example is the Viticulture project, where the articulation was used to highlight points of views about variables of future and their interactions in order to assess the consistency of each point of view. The variables were identified qualitatively and with a simulator, and the results of both methods were then compared and discussed. In the Agrimonde-Terra project, quantification was also used to get a feel on the consistency of land-use change with the climate mitigation scenario hypotheses. Other similar cases are described in Palazzo et al. (2017) or Trutnevyte et al. (2014).

iv) Raising awareness about the future (case 11)

Looking into the future is a challenge that requires stepping out of the present, reconsidering our beliefs, changing our postures, imagining new alternatives. Using the future also requires taming the notions of uncertainty, plausibility, risk or unknown. The AQQAM can be used to raise awareness of the future, to help users to grasp scenarios.

It can be developed during the process of anticipation, to allow participants to put themselves in a "futuristic" posture before building scenarios. For example, the Descartes project started with simulations of trends of several variables in order to induce a reaction from the participants and help them to project themself into the future. The following qualitative scenario building method was not particularly linked to the results of the simulations, but participants were prepared and stimulated to work on the future. The AQQAM can also be used during the outreach phase, by touching more efficiently the external users, to raise their awareness and help them to re-think the present (Volkery et al., 2008; Mason-D'Croz et al., 2016). Trutnevyte et al. (2016) gives insight of quantitative methods developed to extract important information of a whole anticipatory project and van Pelt et al. (2015) used a serious game to communicate the dimension of uncertainty linked to climate scenarios. Wild Cards used after scenarios simulations can also raise awareness about the importance of evaluating policy choices in the light of possible extreme future events (Smith and Dubois, 2010). Endly, interfacing narratives and quantitative modelling is often put forward as a way to help decision-makers project into the future. In many studies this is assumed without clear justification, but some analyses of studies' outcomes showed some contributions to the debate and learning (van Ittersum et al., 1998). The AQQAM has also been used to explain models functioning, give more confidence in their results and help learning on their limits, as an intermediate step toward a better appropriation of the results (Leenhardt et al., 2012), or refinements on policies consistent with narratives and model results (Hauck et al., 2019).

3.2. Characterising time-based articulations

We developed a typology of time-based articulations entailing three categories: (i) successive, (ii) iterative and (iii) convergent (Fig. 2).

Fig. 2. The different types of time-based articulation. One colour designates one type of method (quantitative or qualitative); the other colour designates the other type.

i) Successive articulation (cases 1,8)

Successive articulation refers to projects where qualitative and quantitative phases occur only once and separately in two successive sequences, no matter the order (Fig. 3).

For example, the Niayes project started with a qualitative phase of scenarios co-building, followed by a quantitative phase of modelling to refine the scenarios with different indicators. The choice of the processes modelled, the variables and the parameters, was driven by the qualitative scenarios. Conversely, in the Tuy project, quantitative spatial simulations led to simple qualitative hypotheses on the future. Other examples include Finch et al. (2021), Palazzo et al. (2017) or Mason-D'Croz et al. (2016).

ii) Iterative articulation (cases 2, 7, 4, 11)

Iterative articulation alternates sequences of qualitative and quantitative phases, each one inducing changes in the next one (Fig. 4).

For example, the Laos project built on an initial modelling phase relating socio-economic and land use variables. Then, it involved local representatives in an iterative process of land use planning, articulating role-playing games and mapping on participatory 3D models. In the NLU-PREDICTS case, many elements of the scenarios already existed and were taken from the literature at the beginning of the project. Then, the additional qualitative scenarios selection and mitigation policies specification steps were scheduled when the modelling process needed them, and modified the way the model was parameterized and simulated.

More generally, the "story and simulation" (SAS) approach (Alcamo, 2008) is an iterative process, which usually starts with the production of narratives. These are used as a basis for modelling providing numerical values and checking consistency before being again discussed in loops between those in charge of the stories and those in charge of modelling. However, time and resource constraints may limit the iterative process to a single round of iterations (Volkery et al., 2008). Other examples can be found in Dong et al. (2013) or Provot et al. (2020).

iii) Convergent articulation (cases 3, 5, 6, 9, 10)

Convergent articulation occurs when quantitative and qualitative methods run in parallel, and interact at the end of the project (Fig. 5).

At the very beginning of the Agrimonde-Terra project, it was decided that a balance model would be used for the quantification. Work on data and model setup was done in parallel with the qualitative hypotheses and related scenarios building. Quantification of hypotheses, first, and of scenarios, later on, used information from the qualitative process, but did not feed back. In the Domino project, an agent-based model was built based on a diagnosis of past and present dynamics with representatives of the three main land-uses. In parallel, qualitative scenarios were created, outside of the project and by decision-makers at the regional level. The model was then used to simulate these scenarios. In the Paragominas project, the first phase was based on qualitative methods to build scenarios and backcasting firstly concerning the sector of familial farming, in relation with other sectors (including the agribusiness). With this specific sector and agribusiness, a quantitative model was then used to quantify the different options of micro-zonage in the future. As the model was already existing and developed by another team, we classified Paragominas in the convergent category.

Cases of convergent articulation can also be found elsewhere (Bode et al., 2017; Hurmekoski and Sjølie, 2018; Kok and van Delden, 2009).

4. Connecting the type of articulation, the integration of discontinuities/unknowns, and power relationships

In the following subsections we highlight and discuss the interrelations between the way the AQQAM is implemented and the integration of discontinuities and unknowns and on the power relationships. Concerning the integration of discontinuities and unknowns, these implications are separated in three types of challenges: a) generate or evict, b) explore or circumscribe and, c) assess or degrade.

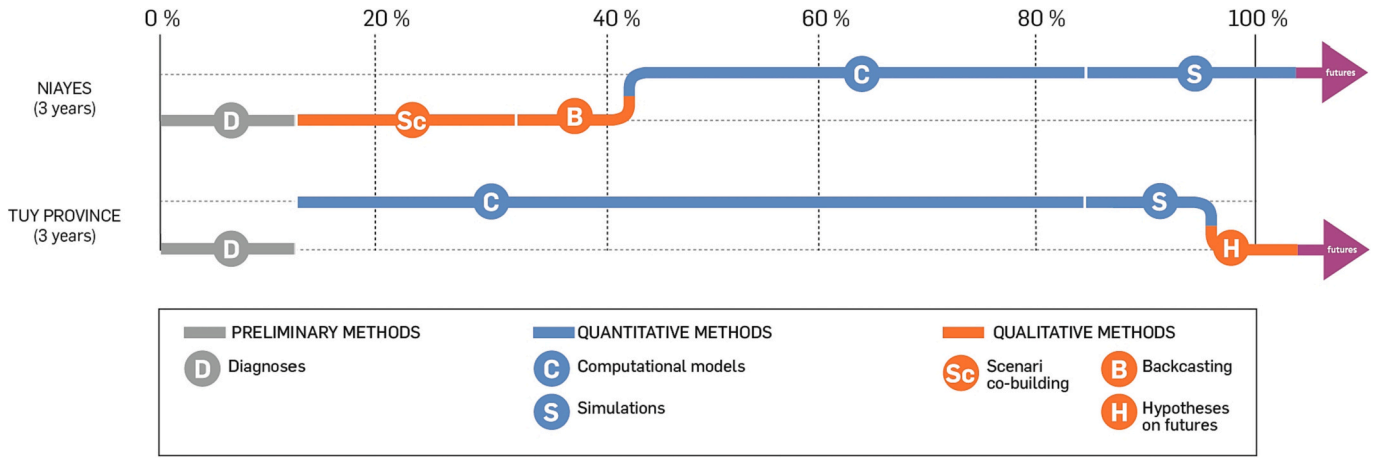

Fig. 3. Time line diagram of the different methods used in the successive projects of our sample.

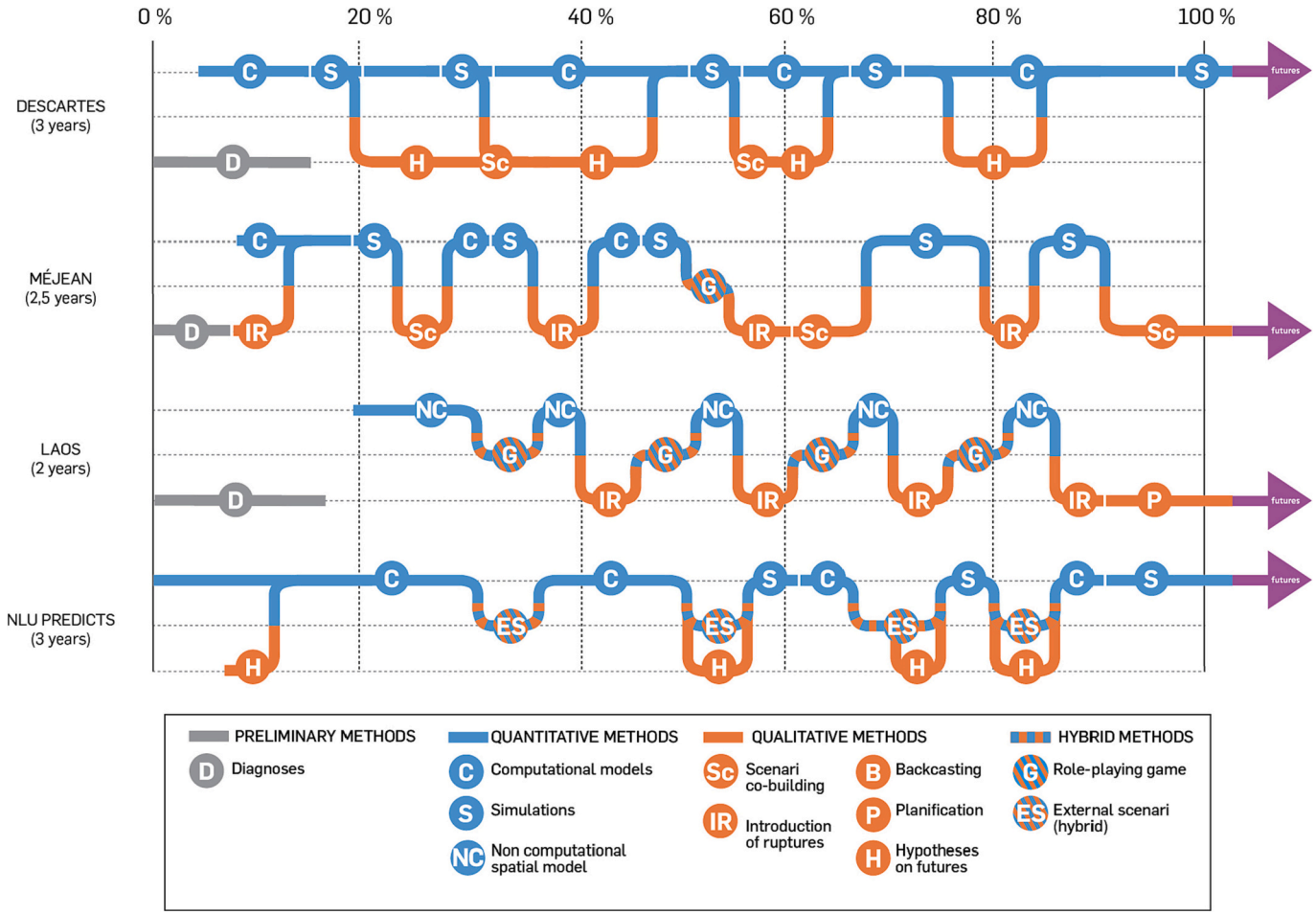

Fig. 4. Time line diagram of the different methods used in the iterative projects of our sample.

Concerning power relations, we identified different situations according to the phase of the project: a) before the project, b) during the process of articulation and, c) during the outreach phase. For each situation, we adopted an inductive approach to present the results, first describing the observed cases and then enunciating the more general implications.

4.1. Integrating discontinuities and unknowns: three challenges

a. Generate or evict

In the Méjean project, the quantitative model simulated several years of natural resources evolution indicating the limits of the system regarding both biodiversity conservation and livestock stocking rates. These limits were considered as sources of discontinuities, which were then integrated in qualitative methods so as to either imagine how to react to them or introduce earlier discontinuities before reaching these limits. Varho and Tapio (2013) developed an AQQAM (the Q2 scenario methodology) that led to produce discontinuities called "plausible unexpectedness". Other examples show how quantitative methods can be

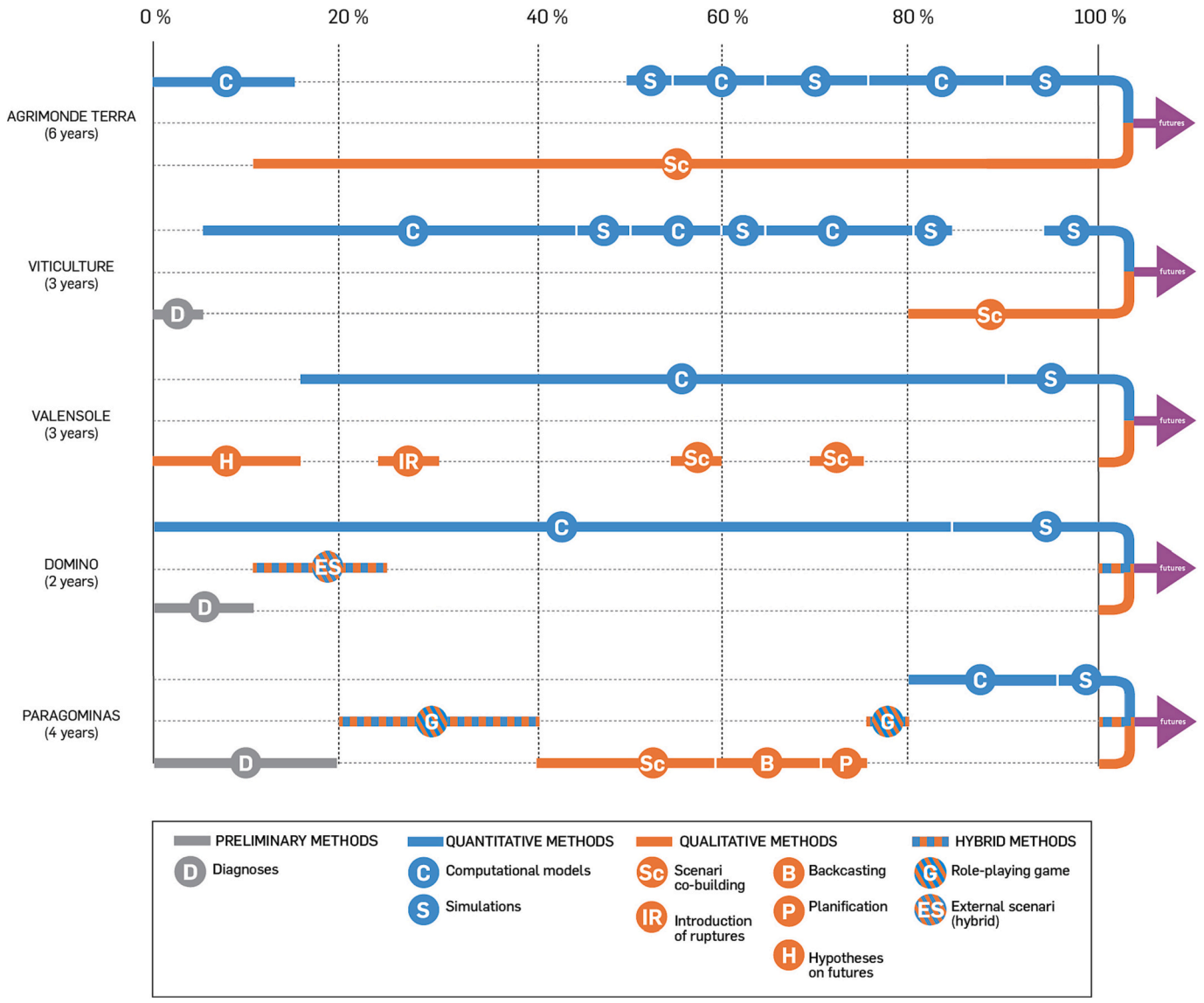

Fig. 5. Time line diagram of the different methods used in the convergent projects of our sample.

used as an input to better think about the discontinuities with qualitative methods (van Rij, 2013 cited by Elsawah et al., 2020; van Pelt et al., 2015). Quantitative methods can also be used after a qualitative phase of scenario building to "augment scenario thinking" with longer-term simulation unveiling new discontinuities arising from the scenarios (Elsawah et al., 2020). Similar examples concern the use of the AQQAM to generate unknowns. Models comparisons for a given narrative shows the range of uncertainty, seen as unknowns, embedded in the models hypotheses and the representation of mechanisms (Popp et al., 2017; Hauck et al., 2019; Mason-D'Croz et al., 2016).

These examples show how the AQQAM can be used to **generate discontinuities and unknowns**. They demonstrate that some computer models can simulate discontinuities or unveil unknowns, even if they do not integrate discontinuities and unknowns in their structure. This is particularly useful when the purpose is *imagining new representation(s) of the future, refining them* or *raising awareness* and can occur for *iterative* or *successive articulations*.

On the contrary, in the Domino project, one qualitative scenario imagined disruptions in the dynamics of transportation. However, the model already built could not represent the sector of transportation and thus did not integrate this discontinuity. In the case of the NLU-PREDICTS project, the combination of the NLU land use model, focusing only on land use of conventional agriculture, and the quantitative PREDICTS model, measuring very little agricultural biodiversity, explains the absence of both agroecology (a discontinuity in cropping practices) and agricultural biodiversity (unknown not represented because of lack of studies). It prevented thus any consideration of agroecology in global land use scenarios, because of the technical difficulty of representing ecological processes with quantitative methods, whereas conventional agriculture processes are more uniform and more data-qualified (Dorin and Joly, 2020).

These examples illustrate the risk of **evicting discontinuities or unknowns**, keeping only the quantifiable part of the future, based on past knowledge. This runs the risk of giving more weight to the short term and the simplistic than to the long term and the unknown. This risk mainly occurs for a purpose of *creation or refining*, and whatever the time-based articulation.

b. Explore or circumscribe

In the ESPON programme of spatialisation scenarios of the European territory, a first phase of scenario building and spatial impacts assessment led to several scenarios with limited disruptions. Wild cards were then used to introduce several types of disruptions that enabled testing the reactions of each scenario (Smith and Dubois, 2010). This case illustrates the possibility offered by the AQQAM **to explore**

discontinuities, in the sense of imagining how the system would react to a given disruption in the future.

An opposite example is given by the Tuy project. Simulations of plausible futures of Tuy province conducted to imagine qualitative discontinuities only on the two driving variables present in the model, the demography and the type of agricultural systems. The qualitative narratives of the possible futures based on the simulations were thus constrained by the quantitative choices. The circumscription of the representation of discontinuities can also stem from qualitative methods based on "two-axes approaches" that may hinder thinking about discontinuities and unknowns outside of the interplay of these drivers (Read (2014, p. 61) quoted by Elsawah et al., 2020) and then circumscribe the quantitative method. Other examples are described by De Cian et al. (2020). They illustrate the risk that one method bridges the other, resulting in the **representation of only a minor part of the possible discontinuities**.

This second implication of circumscribing or exploring discontinuities concerns mainly the AQQAM with the purpose of *creating* or *refining* the representations of the future, with *iterative* or *successive* sequences.

c. Assess or degrade

In the Laos case, the quantitative model was used as a safeguard to ensure that discontinuities designed by the participants were within reason. The quantitative model provided indicators (social, economic and environmental returns), but also indicated functional information such as required labour force that were constraining the consistency of some discontinuity scenarios. In the Niayes project, the quantitative model unveiled inconsistencies in qualitative assumptions that were based on general beliefs. For example, the discontinuity qualitative scenario of agroecology suggested a preservation of the groundwater level, however the simulations showed that even with the most water-efficient agroecological practices, maintaining the water level was not possible due to the related expansion of their cropping systems.

These examples show that the circumscription of the qualitative methods by quantitative methods is not necessarily a problem. When imagining discontinuities, qualitative methods can sometimes disconnect from unalterable biological or physical principles. Using quantitative approaches permits to **specify under what circumstances the qualitative discontinuities are possible**, and thus point inconsistencies in the proposed futures. The project Viticulture is an interesting example that shows the pertinence of both quantitative and qualitative methods to assess one another. It used a convergent approach to compare drivers of future dynamics obtained with two different methods: a computer model and a qualitative identification. Each method produced drivers with different weights that conducted to conclude on the importance of the convergence of both methodologies to lead a reflection on the future. This example showed that qualitative methods can also help **assess the soundness of quantitative discontinuities**. Computer models can lack transparency and may simulate some incorrect values due to errors in their structure or calibration. A control and assessment with qualitative methods (opinions of experts, validation by actors) is key to reinforce the consistency of the results. This use of the AQQAM for assessing the consistency of discontinuities is in line with the general purpose of *assessing the internal coherence of representation(s) of the future* and can be done with the three time-based types of articulations – *successive, iterative* or *convergent*.

Conversely, other examples show that the AQQAM may also have opposing implications when the purpose is to *refine the representations of the future*. In that case, one method is used to refine the outputs of the other method. It raises issues of translation between qualitative and quantitative methods and *vice versa*. Several methods exist (e.g. Booth et al., 2016; Fortes et al., 2015; Kemp-Benedict, 2010; Mallampalli et al., 2016; Pedde et al., 2019). However they often face limitations in treating issues of discontinuities and unknowns (Dorin and Joly, 2020). One way to "translate" a qualitative discontinuity within a quantitative model consists in modifying the quantitative model to relocate the discontinuities or unknowns in the exogenous processes, using proxies (Garb et al., 2008). For instance, in the NLU model the variable "diets" is an external driver, while in economic models diets are usually an internal variable that depends on food prices and income. This enables to simulate the effect of radical changes in diets (discontinuities) by changing the value of this exogenous parameter, but prevents from exploring how these radical changes in diets could occur. This exogenisation has the advantage of representing all aspects of the qualitative representation of the future, but questions the relevance and representativeness of the resulting simulations. The same goes for the Agrimonde-Terra project, the balance model chosen for the quantification had very few endogenous processes. As a consequence, it was possible to implement the qualitative discontinuities, by setting the efficiencies and demands evolution exogenously. Here again, such a simple model does not lead to a better understanding of the processes behind the discontinuities, as these processes are exogenous. It can illustrate the final result (purpose of *raising awareness*), but cannot refine the understanding of the transition nor be used as a basis for projections.

These two examples show how resorting to exogenisation can also **degrade the qualitative unknown or discontinuity**, in the sense of reducing its complexity, that is, *in fine*, in contradiction with the purpose of refinement. Maier et al. (2016) indicated that an alternative to the exogenisation consists in altering the model to integrate new processes linked to the discontinuity. This also runs the risk of inducing a form of **distortion of discontinuities** while seeking to represent them.

4.2. Power relationships between actors when articulating quantitative and qualitative methods

We analysed the power relations linked to the AQQAM for two spheres of actors (see 2.3.c): the level of the project itself, where the power relations take place between the participants of the project; and the level of the socio-political context of the project, and therefore of the actors external to the project, the users or decision makers, where power relations pre-exist in the social-ecological system. This explicit separation of both spheres is prevalent in scientific literature (e.g. Elsawah et al., 2020; Cairns and Wright, 2019). However, our cases showed permeability between them. In some projects, actors involved within the process can also have vested interests linked to their role within the social-ecological system (Garb et al., 2008). In the next sections we attempt to clarify this intertwining of spheres.

a. Challenges before starting

My future or our future

In the Tuy project, the plausible futures of the Tuy province stemmed from the model simulations constructed by a single actor, the modeller. The technical requirements for the quantitative method justified nominating one actor to create the future for all. A similar situation occurred within the NLU-PREDICTS project, whose model tried to fit into the construction of global scenarios supporting the IPBES Global Biodiversity and Ecosystem Services Assessment Report (IPBES, 2016). Participation in this type of international process requires significant human resources due to the high technicality of the global models developed. It also requires managing global models, leading to the exclusion of actors developing other models and forms of knowledge. van Beek et al. (2020) points to this system of exclusive mutual reinforcement: "Climate models have consistently represented climate change as a global phenomenon, rather than a local or national issue, and thus a problem to be governed on a global scale. (…) This global governance architecture in turn legitimises the use of global models". Actors managing global models are then more likely to obtain funding, and to participate in future building.

In the AgrimondeTerra foresight, the choice of a quantitative balance model was done by the institutions steering the process at the very beginning. This model could not refine the access dimension of food security and land use, although this dimension was found to be important early on in the analysis of the system.

These examples show the risk of **using the AQQAM before starting**

the project to justify the reinforcement of some actors over others, by nomination based on technical skills or unequal allocation of financial and human resources. This selection or reinforcement of actors participating in the construction of futures (and thus exclusion of other actors) can lead to a monopolisation of the future of a social-ecological system by a minority of actors, often non representative of all the point of views. This risk threatens particularly the projects whose finality is *imagining the future*, as it raises the question of who is legitimated to design the future of everybody?

b. Challenges while working together

Conflicts vs speaking the same language

Qualitative or quantitative communities do not always speak the same language. It can lead to **misunderstanding between communities during the process**. David et al. (2014) described how both communities behind quantitative and qualitative methods could not succeed to communicate and understand each other, leading to the blocking of the drafting process of the energy transition law in France. The phase of translation between qualitative and quantitative methods can be considered as "cumbersome", particularly when this is perceived by modellers as undermining the scientific credibility of their work (Volkery et al., 2008). It can also be perceived by the qualitative community as a reduction of their work when eviction or distortion occur (cf 4.1.b and c). Dong et al. (2013) underlined the problem of transparency that can occur when qualitative storylines are converted into quantitative models.

On the contrary, Tapio et al. (2011) showed that a Delphi exercise mixing quantitative and qualitative data allowed all participants to express themselves in the way they felt most comfortable, through numbers or qualitative descriptions. Similarly, Hauck et al. (2019) noted that the scenario and modelling framework allowed groups to work together without consensus, describing the approach as a boundary object-type. Several scholars identified the importance of having a well thought-out iterative approach with fluid communication for successful collaboration and trust building between actors linked to qualitative or quantitative methods (Volkery et al., 2008; Booth et al., 2016; Robertson et al., 2017). These cases show that the AQQAM can lead to **instaure a dialogue between a diversity of actors with different views**. This is the case when the articulation allows for the creation of a space for dialogue and thus helps to build mutual trust between the actors of both methods. The *iterative* articulations are particularly appropriate to build this space of dialogue. *Successive* or *convergent* iterations do not allow for as much dialogue between communities, except when all participants are involved in both quantitative and qualitative methods. Mason-D'Croz et al. (2016) gave the example of the phase of translation of qualitative scenarios into model inputs in a successive interaction. In this case the presence of the modellers during the qualitative scenario building helped them to better understand and include the spirit of the narratives. Reciprocally they were able to explain the specificities of the models.

The Laos project is an example of similar implication of the AQQAM on the power relations within the social-ecological system. Local authorities enforced the eradication of slash and burn practices, which they saw as archaic and unproductive. Local populations had to "officially" comply with official guidelines to avoid fines, leading to largely underestimated survey figures. As official census data was commonly the main input in quantitative models, with such figures, the exercise of land use planning was rendered inaccurate. The AQQAM led local authorities to openly acknowledge the impossibility for local farmers to comply with such restrictive slash and burn policies. Opening up this black box led local farmers to provide more precise land use figures with more confidence. The participatory process in place allowed participants to understand respective points of views, interests and objectives. This case showed that the use of an AQQAM can also induce a **dialogue between the different actors of the social-ecological system** (and not only between methodological communities) by fostering a new understanding of the other group, when the participants of the project are also representatives of vested interests. A similar example is the project ENCI-LowCarb, described in David et al. (2014).

Levelling the playing field vs power to the strongest

In the Valensole project, the articulation allowed a readjustment of the balance of powers between two groups of actors with different visions of the way certain actors would react facing a given future. Both groups, farmers and other local actors (technicians, representatives of cooperatives …) built scenarios. The two opposed scenarios were simulated at the end of the project, with the same quantitative indicators. The fact that the process was *convergent* also reinforced the "neutral" aspect of the quantitative tool to illustrate and evaluate the qualitative scenarios. Not associating a method with a particular stakeholder group allowed the two groups of actors to work on an equal footing. Another example of this situation of balance of power where each stakeholders group was equally considered with numerical methods is developed by Cairns and Wright (2019). Both cases show that the AQQAM, especially for *convergent* cases in a purpose of *creation and refinement* of futures, can help **put both methodological communities on an equal footing**.

In Paragominas, the *convergent* processes enabled to "separate" the communities, making them work independently before bringing them together. Qualitative anticipatory work gathering only the responsibles for family farming, a marginalised sector within the municipality marked with "weak personal capacities", led to a change in the posture of participants of the project. This separation allowed them to take the time to strengthen their power in order to be better equipped to exchange and more emancipated from potential power relations. This led them to build a plan and to negotiate it with the municipality (relational capacities), which increased their legitimacy. This case illustrates the possibility of using convergent AQQAM to **provide a safe space for the empowerment of powerless actors of the social-ecological system** in designing the future.

This same case provides at the same time an opposite example: during the process of AQQAM, the modeller decided to postpone the construction of the land use model because of institutional conditions that were deemed unsatisfactory. More qualitative approaches were then favoured. Here, a single actor, through the technical power derived from quantitative methods, influenced the entire process, which thus became convergent and not iterative as initially planned. The Domino project showed a similar risk. Initially, this project wanted to represent the different types of agriculture (small households, sugar cane, livestock farming systems). However, the choices made by participants during the modelling process delegitimized the knowledge of small farmers' representatives. These two examples show how the use of the AQQAM can **lead to an imbalance of powers related to the "technicality" or "needs" of one method**, either with the reinforcement of the power of the "technical expert" over other actors or with the weakening of power of some participants linked to the different levels of understanding of the tools. These two examples show that such risk can occur within the project sphere of actors (Paragominas project) as well as within the external sphere (Domino project) when the participants of the project are also key actors of the social-ecological system.

c. Challenges during the outreach phase

Who has got the final word?

In the Agrimonde-Terra foresight project, the final sequence of the qualitative method of imagining scenarios was followed and illustrated by the quantitative method, which thus came to end the project. It became the dominant part in the communication on the future, to the point of concealing the hypotheses that were not quantifiable. The actors linked to the quantitative methods had, in a way, the power to "decide" on the indicators to put forward to evaluate the scenarios, and thus the final futures to be told. The same situation was observed with the Niayes project.

This illustrates the risk of using the AQQAM to **give more weight to the group with the final word,** and will therefore have the final decision-making power on the product of the AQQAM. Elsawah et al.

(2020) warn of the possible tensions that may arise from this situation. This risk is particularly high in *successive* or *convergent* processes as the exchanges between communities are limited, when a method is used to *refine, assess* or *raise awareness* of the other. This situation may also happen in *iterative* processes (Volkery et al., 2008) but to a lesser extent.

Serving vested interests vs stronger together

In the Niayes project, the idea of linking quantitative and qualitative methods was proposed by researchers, originally for purely methodological purposes. Stakeholders' reactions to the proposed methods differed according to their roles and powers in the social-ecological system of the Niayes. The proposition to develop quantitative indicators for each scenario was supported by civil society actors, who saw them as an argument of authority in their pleas that would also reinforce their credibility in the power struggle with the public authorities. On the contrary, actors from structures assisting farmers in the field were more interested in qualitative media illustrating the scenarios in order to communicate them to the population. This shows the **possible instrumentalization of the methods to serve the interests of certain groups**. The Paragominas and Domino projects give examples on how this instrumentalization actually led to a **reinforcement of existing power imbalances**. In Paragominas, the quantification of different options for micro-zoning the social-ecological system gave more power to the political actors participating in the project, who were able to use these "resources" to justify their micro-zoning policy. In the Domino project, the transfer of the quantitative modelling tool from the researchers to the Region for the purpose of transferring competence actually led to a concentration of institutional (which the Region already had) and technical power.

On the contrary, the PRELUDE project (Volkery et al., 2008) showed that the combination of detailed qualitative stories, some of them being disruptive alternative representations of the future, and related quantitative land use maps, strengthened the plausibility of the scenarios in the outreach process. In the scenario approach of GIEC tested in 2014, quantitative and qualitative methods were articulated to give simultaneously to the decision maker elements of societal and policy choices (qualitative) as well as their costs and impacts (quantitative). Both methodologies were used in synergy to enlighten political decisions (David et al., 2014). Parker et al. (2015) showed the complementarity of qualitative intuitive logics scenarios and quantitative scenario discovery methods for the different parts of decision-making process. These examples show how the AQQAM can **gather the two methodological communities to have more impact on decisions**.

Get out of here

In Paragominas, the model was based primarily on a landscape approach designed to develop soil microzoning, an appropriate approach for agribusinesses with large cultivated areas. It was less relevant for family farming, particularly because of the small size of cultivated plots. The choice of indicators and model outputs excluded family farmers from quantitative modelling. The same goes for the Domino project, where the quantitative tool was unable to integrate the dynamics of family farming due to size and type of data constraints. This excluded the Chamber of Agriculture and some farmers organisations from discussions on the future of their social-ecological system in the modelling phase. This illustrates the risk that the AQQAM contributes to the **exclusion of certain actors of the social-ecological system from the discussion on their futures**, that can occur for all types of purpose or time based interaction.

4.3. General overview of the links between the way the AQQAM is implemented (purpose and timing) and discontinuities, unknowns and powers

As the number of our case studies does not allow us to obtain a generic picture of all possible configurations, we made logical hypotheses on the links between these implications and the different types of AQQAM. Some were based on direct observation of our case studies or external literature, others were logically extrapolated from the first one. Table 3 summarises the results.

5. Practical lessons learned and ways forward

In this conclusion, we would like to come back to two specific points: the limits of the study and the perspectives in terms of just and integral transformation of socio-ecological systems. This last point allows us to draw up concrete perspectives for our work.

5.1. Limits of the study

There seem to be as many ways of implementing the AQQAM as there are projects. Our work led us to observe the need for a formal framework to characterise the various ways in which quantitative and qualitative anticipation methods are articulated. We suggest and developed two dimensions in this framework: the timing of the articulation of the methods (successive, convergent or iterative) and the purpose given to the articulation (creation of new futures, illustration and refinement of futures, assessment of the internal consistency of futures, raising awareness of the future). Like any archetype, these categories have their limits, as some projects can take hybrid forms. We also illustrated some of the situations that can arise regarding the handling of discontinuities and power relations depending on the type of AQQAM. Here again, these situations depend on many other factors, and are not systematically and only associated with the choice of the time-based articulation or the purpose. However, this typology of AQQAM and the potential situations associated can give insights to better anticipate issues of power or discontinuities and unknowns when conceiving a project of AQQAM.

This study is based on our own experiences since it requires in-depth knowledge of certain aspects of the projects, which are often lacking in the literature. Some aspects of our analysis are rarely presented in the scientific articles associated with a project, as for example the purpose of the AQQAM or the evolution of power relations during the project. This approach allows analysing these unpublished elements, but limits the number of case studies, and therefore the generic scope of the results. Our aim was not to produce a generic painting but to indicate several points of attention when handling an AQQAM. However, we extended the corpus of analysis to several external case studies found in the literature, which allowed us to verify and complete our results when possible, without claiming to have achieved genericity. Through iterative cycles, we endeavoured to provide practical insights and to stress potential hurdles coming from an inside understanding, and reinforced and confirmed with external studies.

5.2. Developing an AQQAM toward just and integral transformations of social-ecological systems

Anticipation should contribute to a society being more informed in relation to the future, i.e. to think about the actions in the present in the light of the future. Thus, anticipation activities have a fundamental role to play in steering the transformations of social-ecological systems. We argue here that the AQQAM can be used to strengthen anticipation, but depending on the way it is conducted, it can significantly impact power relations and the handling of discontinuities and unknowns, which are two essential elements for a just and integral transformation.

First, incorporating unknowns and discontinuities allows for an integral approach to think transformations by providing a complete picture for the decision, not only based on the known and continuous (Trutnevyte et al., 2016; van Notten et al., 2005). It allows us to take into account a range of plausible situations that are currently impossible to know but which could influence transformations. It also permits to consider deep ruptures with the dominant model, so as to become more resilient (Kemp et al., 2022) or to find creative alternatives to current unsustainable systems (Stoddard et al., 2021). Secondly, considering power games in the construction of everyone's futures is essential for a

Table 3
General overview of the possible relations of both issues with the purposes and the time sequence of the AQQAM. Opportunities are in black, risks are in grey.

		SUCCESSIVE	ITERATIVE	CONVERGENT
IMAGINING	Discontinuities Unknowns	**Generate** **Explore** Evict Circumscribe	**Generate** **Explore** Evict Circumscribe	Evict
	Powers	Nomination of certain actors Misunderstanding Imbalance of powers related to the "technicality" of one method	**Dialogue** Nomination of certain actors Misunderstanding Imbalance of powers related to the "technicality" of one method	**Put communities on an equal footing** **Safe space for the empowerment** Nomination of certain actors
REFINING	Discontinuities Unknowns	**Generate** **Explore** Evict Circumscribe Degrade	**Generate** **Explore** Evict Circumscribe Degrade	Evict Degrade
	Powers	Misunderstanding Imbalance of powers related to the "technicality" of one method Give more weight to the group with the final word Exclusion of certain actors	**Dialogue** Misunderstanding Imbalance of powers related to the "technicality" of one method Exclusion of certain actors	**Put communities on an equal footing** **Safe space for the empowerment** Give more weight to the group with the final word Exclusion of certain actors
ASSESSING	Discontinuities Unknowns	**Point inconsistencies**	**Point inconsistencies**	**Point inconsistencies**
	Powers	Misunderstanding Imbalance of powers related to the "technicality" of one method Give more weight to the group with the final word	**Dialogue** Misunderstanding Imbalance of powers related to the "technicality" of one method	**Safe space for the empowerment** Give more weight to the group with the final word
RAISING AWARENESS	Discontinuities Unknowns	**Generate** Degrade	**Generate** Degrade	Degrade
	Powers	**Stronger impact** Give more weight to the group with the final word Serve vested interests Imbalance of powers related to the "technicality" of one method Exclusion of certain actors	**Dialogue** **Stronger impact** Serve vested interests Imbalance of powers related to the "technicality" of one method Exclusion of certain actors	**Stronger impact** Give more weight to the group with the final word Serve vested interests Imbalance of powers related to the "technicality" of one method Exclusion of certain actors

just transformation (Bennett et al., 2019). It enables recognition of all groups and interests and attempts at rebalancing power imbalances during the process of future co-building. In this sense, it contributes to both recognitional and procedural justice during the anticipatory process, two pillars of just transformations (Bennett et al., 2019; Abel, 2011). The integration of multiple views should also foster reflections and discussions about distributional justice (third pillar), when thinking or measuring how the different groups could be affected within the different future scenarios and which questions or challenges are put forward. Attaining socially just and power-balanced development pathways are some of the principles of territorial approaches in the development sector (Losch and May, 2023). Such approaches support public action by cross-cutting scales, stakeholders and resources in a geographical area appropriated by a community of actors or territory (Koop, 2014).

The question now is how can we ensure that the AQQAM can contribute to build a just and integral transformation? We derived three leverage points from our analysis.

Be aware of the potential implications of the AQQAM

Depending on how it is carried out, the AQQAM can have opposite implications, from unbalancing to rebalancing of powers and from exploration to eviction of discontinuities. If it appears difficult to control totally these implications, it is nevertheless important to question as early as possible the choices of articulation and to take into account their effects and potential biases on the results. Few studies develop a reflexive analysis of their results regarding the incorporation of discontinuities and the impact on power plays. Being aware of the potential implications of the AQQAM can help to take a step back on the results that have a direct impact on our understanding of the future produced and therefore on our actions in the present.

Incorporate questions of discontinuities and power at the beginning of the project

At the beginning of a project, the choice of methods and articulation is often guided by the tools or skills available within a project. We recommend to base this choice on the explicit consideration of the purpose we give to the articulation, the way we want to incorporate discontinuities and unknowns and the explicit consideration of power relations.

Most of the time, the general purpose of an anticipatory project is made explicit. It answers the following questions: why do we engage in such an endeavour? What are its aims and desired outcomes? (Vervoort and Gupta, 2018). However, the purpose of using the articulation is more rarely clarified. When starting an AQQAM, it is important to answer these questions: how does the AQQAM help to meet the general objective? What does it add to a purely qualitative or quantitative method? When answering these last questions, it is also important to

question the assumptions we have concerning the quantitative or qualitative methods. We showed that attributes given to one or other of the methods can sometimes be biased - Are quantitative methods really more neutral? Are qualitative methods always more relevant to explore the discontinuities?

Then, specific questions can help design the articulation taking into account the incorporation of discontinuities and unknowns: what place should be given to the discontinuities according to the general purpose of the anticipation process? How the selected methods and their articulation allows us to handle the discontinuity? What specific method could be introduced in the articulation to rectify the biases linked to the articulation?

Concerning power relationships, several authors advocate the need to incorporate them in the design of the anticipation project (Rutting et al., 2022), to diagnose the actors network in place in the study area, with a special attention to "third parties and beyond" (Cairns and Wright, 2019) to ensure a representation of all (Kok et al., 2007). We go further, assuming that we should choose the methods and the type of articulation according to power relationships, and explicitly make assumptions about how the chosen articulation can impact these power relationships, within the process and in the social-ecological system. The following questions may help in this reflection: do the communities associated with each method represent groups of actors in the social-ecological system? What are their power relations? Who would have an interest in promoting one method over another? How can the chosen AQQAM reinforce or weaken existing power games? How can we ensure to have a recognition of the legitimacy of all the points of view, both qualitative and quantitative (David et al., 2014)? How can we build mutual trust between methodological communities?

Develop an adaptive anticipation approach

It is difficult to totally anticipate the implications of the AQQAM on power relationships and discontinuities representation. New configurations of power relationships can arise during the process, as well as some neglect in the treatment of discontinuities and unknowns may appear. This means that a kind of monitoring process of these issues of discontinuities and power relations is needed.

Concerning power relationships, this monitoring can be realised by observing the posture of the participants, who speaks the most, where are the disagreements and whose ideas are retained? The outreach phase is a key moment as it will be decided which future will be shown. Surprises can arise, when for example unexpected actors use one method to promote their own interests. Concerning the discontinuities or unknowns, monitoring means to question, at each step of the process, how discontinuities have been taken into account. If some undesirable effects are noticed, several methods or readjustment can be adopted to correct them. This article gave several insights of such readjustment, for example separating the communities to enhance empowerment, or using wildcards at the end of the process to better consider discontinuities. Each project is unique and solutions have to be imagined "with the flow", depending on the context and the resources. It requires adopting a continuous reflexive approach and being creative.

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CRediT authorship contribution statement

Camille Jahel: Conceptualization, Methodology, Investigation, Project administration, Supervision, Writing - original draft, Writing - review & editing. **Robin Bourgeois:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Jérémy Bourgoin:** Conceptualization, Methodology, Investigation, Writing – review & editing. **William's Daré:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Marie De Lattre-Gasquet:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Etienne Delay:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Patrice Dumas:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Christophe Le Page:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Marc Piraux:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Rémi Prudhomme:** Conceptualization, Methodology, Investigation, Writing – review & editing.

Data availability

No data was used for the research described in the article.

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