Asian Bioethics Review (2018) 10:295–312
https://doi.org/10.1007/s41649-018-0069-5

ORIGINAL PAPER

On the Ethics of Biodiversity Models, Forecasts and Scenarios

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Received: 28 March 2018 / Revised: 30 October 2018 / Accepted: 1 November 2018 /
Published online: 16 November 2018

Abstract
The development of numerical models to produce realistic prospective scenarios for the evolution of biological diversity is essential. Only integrative impact assessment models are able to take into account the diverse and complex interactions embedded in social-ecological systems. The knowledge used is objective, the procedure of their integration is rigorous and the data massive. Nevertheless, the technical choices (model ontology, treatment of scales and uncertainty, data choice and pre-processing, technique of representation, etc.) made at each stage of the development of models and scenarios are mostly circumstantial, depending on both the skills of modellers on a project and the means available to them. In the end, the scenarios selected and the way they are simulated limit the futures explored, and the options offered to decision makers and stakeholders to act. The ethical implications of these circumstantial choices are generally not documented, explained or even perceived by modellers. Applied ethics propose a coherent set of principles to guide a critical reflection on the social and environmental consequences of integrative modelling and simulation of biodiversity scenarios. Such reflection should be incorporated into the actual modelling process, in a broad participatory framework, and foster effective moral involvement of modellers, policy-makers and stakeholders, in preference to the application of fixed ethical rules.

Keywords Biodiversity · Data · Ethics · Model · Scenario · Ethical principles

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Introduction

Computer-assisted and machine-based systems not only proliferate and interfere in our everyday life (the ambient intelligence paradigm; Remagnino and Foresti 2005) in particular through the use of connective objects but also when it comes to facing "wicked" societal problems (Rittel and Webber 1973; Funtowicz and Ravetz 1993). It is remarkable that an integrative approach to biodiversity conservation must simultaneously take into account several of these wicked problems—such as the biodiversity loss (Sharman and Mlambo 2012), climate change (Lazarus 2009; Sun and Yang 2016), global sustainable development (Pryshlakivsky and Searcy 2013; Dugarova and Gülasan 2017) or the design and implementation of intersectoral policies (Head and Alford 2013)—particularly through their interdependence and interactions. Modelling is a socio-technical approach capable of representing and integrating into a coherent scientific framework data and knowledge. It entails a volume of knowledge required to mitigate issues as they arise. The activity of modelling also assimilates masses of data (UNSG-IEAG 2014) distributed on all kinds of devices and geographical sites, and processes them on computers within a time frame compatible with the transformations of socio-ecological systems. In particular, the use of models (Harfoot et al. 2014) and prospective analyses based on scenarios simulated in silico is one of the approaches promoted for the conservation of biodiversity (Pereira et al. 2010) by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES; https://www.ipbes.net/).

This study provides a view on the ethics of modelling and scenario building for biodiversity conservation (the *intrinsic* ethical issues following Tuana 2010). It should be noted that many considerations debated about the ethics of climate change modelling (see Beck and Krueger 2016 and references therein), using integrated impact assessment and modelling approaches (Jakeman et al. 2006; van Delden et al. 2011) straightforwardly apply. As a component of extrinsic ethics—which, in short, consists in applying scientific outcomes to policy (Tuana 2010)—the ethical questions raised by political assessments of projected changes in biodiversity (e.g. debates on the repartition of the historical responsibility of these changes or on the linkages between development level and social vulnerability to biodiversity loss) are outside of the scope of our contribution. We focus on the identification of ethical implications raised by the design and development of the model-artefact used to produce these scenarios and by the options they present or discard. We do not pretend to sketch answers to the ethical challenges raised, but simply to highlight them in the context of modelling for biodiversity conservation.

The ethics of modelling and scenario simulations are linked to the technical aspects of what we are to critically assess. Section 2 presents what we mean by *models*, *forecasts* and *scenarios*. In Section 3, we identify some key decisions that must be taken during the modelling process and underline the contextual and relative character of the objectivity of the simulations produced. Then (Section 4), we consider the contingencies accompanying the instantiation of the models for a particular social-ecological system on the basis of heterogeneous, incomplete and prone-to-error data sets. In Section 5, as long as it concerns the modellers, we are interested in the ethics of forecasts and scenarios. These projections are aimed at establishing and choosing measures favouring a desired trajectory of development in a given socio-ecological system (or a regional/global socio-environmental system). Section 6 draws some links between the activities of modelling, simulation and principles of applied ethics. Arguments are advanced so that ethical reflection is conducted in a framework of broad participation, through dialogues accompanying the very process of modelling and biodiversity scenario simulations, in the specific context of the social-ecological system considered. Such ethical practice, based on flexible research guidelines statements, still needs to be designed. It would encourage effective moral involvement of stakeholders in biodiversity conservation. Finally, salient conclusion of this paper is provided in Section 7.

Biodiversity Models, Forecasts and Scenarios

Let us first sketch the steps taken in the design of model artefacts used to assess global biodiversity changes. By *model* we mean a set of formal representations of the states of entities composing a system and of the processes at work in their interactions. These processes—represented as sets of equations or rules—are producing the evolution of the states simulated by the computation in a machine. At a given time, the values of the N state variables are represented as a point in an N-dimensional space. The evolution of these variables with time constitutes a possible trajectory of the system represented as a unique geometrical form in this space. The analysis of this form provides information on the system stability, on the states favourable to abrupt and little predictable changes or on the probability of occurrence of specific events. All the conditions of a numerical experiment (initial state of all the variables of the system, values on the spatial limits of the model, values of the parameters of the processes in mechanistic representations, etc.) being stipulated, the resolution of the equations or the execution of the algorithms (computer-interpretable series of formal instructions to solve a problem) constituting the model produces a unique evolutionary trajectory. It is possible to generate an indefinite number of evolution trajectories according to the specifications of the conditions of the use of the model.

The term *forecast* here does not mean a deterministic prediction as for example in meteorology, but rather a system trajectory (set of time series of all state variables) that is likely to happen in the future via nested interaction processes. In fact, several processes modify at the same time the same variables whose aggregated result can only be observed. The complexity and indeterminacy (see Section 3) of factors of evolution—especially when involving virtual entities representing human agents, social groups, arenas of collective decision (Ostrom 2010), etc. (see Mazzega et al. 2014, 2016, in the context of water management policy)—set intrinsic limits to the predictability of the evolution of the system. These forecasts show some likely evolution of the studied system, taking into account only the entities and processes represented in the model and the way in which they are represented. Through comparison with historical data on the previous states of the system, the simulation of past evolution makes it possible to check the more or less realistic and satisfactory behaviour of the model, or even to optimise some of its key inputs (initial state, parameters, code options) so that it fits the available empirical information. In this process, a statistical description of the data errors is taken into account in order to give less importance to least accurate data or to those data with less informational input.

At first, a *scenario* is usually a narrative of the experience one would like to achieve or of the hypothesis that one wishes to test with respect to a reference situation. Once translated in the model representation frame, a scenario is an exhaustive specification of the conditions for performing a numerical experiment that leads to the simulation of a single trajectory. It includes the characteristics of the state of the system (e.g. initial state of biodiversity) and of the processes involved (e.g. deforestation or urbanisation rate, uses of natural resources, demographic growth) about which it is interesting to know the impacts on the evolution of the complete social-ecological system. The business as usual (BAU) scenario consists of the specification corresponding to the maintenance of conditions observed empirically over a past reference time window. The resulting trajectory describes the possible evolution of the system, given steady conditions.

The integrated impact assessment modelling progressively accounts for a larger variety of interactions between society, the environment and biodiversity. In particular, specific scenarios can be designed to evaluate the impacts of implementing public policies (e.g. for biodiversity conservation) or of the degree of compliance of stakeholders with existing regulations (e.g. the Nagoya Protocol). Thus, a set of alternative impact assessment scenarios are to be compared, if necessary, at the request of decision makers, as is the case of studies coordinated by IPBES.

The socio-environmental consequences of these scenarios are then compared and interpreted, using indicators that summarise the most relevant information for policy-makers, stakeholders or scientists (Hammond et al. 1995; Surminski and Williamson 2014). The ranking of scenarios in descending order of desirability (a notion that may include risk aversion, social acceptability, simulation reliability, probability of occurrence, etc.) is then used to design and implement measures promoting the achievement of the scenario deemed most desirable. The values and principles—explicit or latent—of the community (human, artificial or mixed) underlying these choices are expressed in particular through this prioritisation of scenarios (see Section 5).

Ethical Issues in Knowledge Integration

Our purpose here is not to discuss the objectivity of scientific knowledge that we will consider as acquired. Nevertheless, we should note that modelling process is fraught with contingencies that affect choices about the knowledge used, their systemic organisation and the technological options implemented to produce the simulation platform. These options include in particular the modelling environment, the model, the data and their pre-processing, the visualisation tools and those of control and analysis of digital experiments, etc. As a result, the model should be considered as an integrative and contingent system of objective knowledge of which simulations depend on the context governing its design and development. The simulated trajectories cannot claim a radical objectivity. Being based on an explicit and limited body of knowledge, they constitute a particular set of diagnostics on biodiversity changes. Generally, the options present and the choices made during the modelling process are not explained. More precisely, the following points seem crucial to us.

Model Ontology The categorisation of the entities and processes represented in the model is based on an ontology that is a “formal, explicit specification of a shared conceptualisation" (Grüber 1995). In this sense, ontology gives the general form of the space of possibilities that the model can explore next. For example, the interpretation and use of the simulation results are directly constrained by and limited to the social or political categories distinguished in the model. Nevertheless, the ontology underlying models of global change is generally not explicit. Most of the time, it is not even perceived by modellers as the basis of determinative representations. In response to the epistemic questions raised by integrating representations of societal activities and practices in social-ecological system models, several ontologies have been proposed (Ostrom 2009; Binder et al. 2013). Thus, the same system is likely to be represented in various ways, all scientifically legitimate and all in accordance with the norms of good scientific conduct (a piece of "*procedural ethics*"; Tuana 2010). Moreover, there exists no objective method to categorise entities or to determine which entities and processes are *in* the model, kept out but interacting through information flow, or simply discarded (Sibertin-Blanc et al. 2018).

Scales and Patterns The choice of relevant scales of representation is also not trivial, though it conditions the emergence and observability of patterns (Levine 1992): spatial and temporal scales, of course, but also organisational scale of ecological interactions, aggregation of groups or communities (up to the option of representing individuals), jurisdictional, administrative or territorial scales. This choice is sometimes imposed by the resolution of available data or by the existence of a theory operating at a given level of representation. In fact, analyses of population dynamics models have shown that the scale of representation (e.g. population density versus set of individuals), modelling techniques (e.g. differential equations versus multi-agent system) and paradigms of analysis (e.g. deterministic versus stochastic approach) are interdependent (Pascual and Levin 1999). This conclusion is more broadly applicable to integrative models involving societal components.

Uncertainty and Indeterminacy The magnitude, time of occurrence and cascade of impacts of some fundamental dynamics are also very difficult to anticipate, like biodiversity tipping points (Leadley et al. 2010) of which, main mechanisms include feedback amplification, thresholds, time lagged effects and changes irreversibility. Their main drivers are habitat change (mainly through land use land cover changes), climate change, resource overexploitation, development of invasive species and pollution. The network of entities, processes, and activities involved in simultaneously propagating the multiple effects of an event is only partially known and understood. Moreover, the nature and intensity of the processes (including the actors' activities) that are actually triggered depend on the state of the entities affected. These weak or unpredictable network causal dynamics confer a character of indeterminacy (Wynne 1992) on possible future changes, which necessitates a redesign of policy analysis frameworks that are restricted to the consideration of well identified or potentially identifiable risks and uncertainties.

Modelling Techniques For the same dynamics, there are several modelling options like systems of equations, multi-agent systems, cellular automata, Bayesian networks, neural networks, stochastic time series, etc. The modelling technique imposes the basic semantics of the model and delineates its field of interpretability. The choice of the modelling technology, methods of solving the equations and the environment in the background of simulation platforms depends on the skills and preference of modellers involved in a project. It should be noted that understanding the conservation of biodiversity in a holistic framework relies also on qualitative data (e.g. survey results, interviews, legal or political texts). These data cannot be represented in a space endowed with a distance function (needed for example to evaluate how well a simulation fits the available data). However, a topological approach can extract some of the fundamental properties of the system from these data (Carlsson 2009; Mazzega et al. 2018). Finally, and without delving into the depth of an epistemological debate of substance, it must be admitted that the reproducibility of the results is not always guaranteed as shown by Edmonds and Hales (2003).

The main consequences of all these points are first that there is potentially as many objective and contingent models of a given SES as modellers or modelling teams. The agreement obtained about the various choices made during the modelling phase does not mean that other radically different models could not be also supported by a similar agreement. Modelling is a practice involving numerous arbitrations and compromises that are external to the modelled system (the reference social-ecological system) and to the solicited knowledge. These choices can be informed but their impacts on the forecasts and on the space of choice of the scenarios that can be envisaged are neither simulated nor evaluated by comparison with other simulations which would be based on different modelling techniques. Moreover, underlying assumptions—in particular those of an ontological nature—might be difficult to identify, and their associated impact remains undetected and therefore are not analysed. Indeed the simulations are likely to modify the perception or the understanding that the modellers have of the treated problem, in particular through the emergence of unexpected patterns in the results. However, because it is integrated in the design of the models, modellers' ontology does not seem revisable on the basis the analysis of the results. We reach the position that models are «social constructs», artefacts resulting from a delicate crafting, part of a culture (Seaver 2017) that in turn takes over the influence of various epistemic cultures (van Zundert et al. 2012).

Ethical Issues in Data Integration

The integration process is to connect several pieces of knowledge in a common representation (the model) and instantiated them with heterogeneous data sets. Models and scenarios (Alcamo 2009) of global or biodiversity changes are progressively integrating larger and more heterogeneous data sets. For example, in support to the CBD Strategic Plan 2011–2020 and some Aichi Targets, GEO BON (2015) is producing 1-km^2 resolution terrestrial indicators (on habitats, species protection, protected areas, human impacts, ecosystem restoration, information availability) mainly related to species distributions, taxonomic diversity and ecosystem extents by mixing open access data sets (in situ and remote-sensing, local to large scale) and results of model-based heterogeneous data integration. Indeed, to tackle a definite case, a formal abstract model must be instantiated with empirical data or data-derived products like land use maps derived from satellite imagery, for example. In situ or in vivo measurements, remote-sensing data (e.g. satellite imagery), surveys of the populations concerned and interviews (e.g. with key actors) and textual corpora (regulations, laws, policies) are informing the observed changes affecting various entities represented in the model. This step reduces the space of trajectories simulated by the model, to those that best correspond to the characteristics and history of the evolution of the analysed system. However, to be usable, the information produced by certain sensors (e.g. products of optical and radar imaging) requires the development of other models (like radiative transfer models) articulating this information and the state variables of the model. These additional models or model components themselves must be tested according to a variety of procedures and application conditions. Moreover, the available data are usually not directly interoperable. Their integration requires the design of heuristics which allow their use in a coherent scheme covering various scales and administrative divisions.

The instantiation of the model on a particular social-ecological system also presents some flexibility with regard to the choice concerning the data used, their pre-processing (removal of outliers, filtering ...), the objectives and methods of data integration (parameter identification, optimisation of initial or boundary conditions, etc.) and the representation and consideration of data errors. Therefore, there is no one-to-one correspondence between a couple {model, data} and the modelled system. As with the model construction process (Section 3), contingent choices are made whose effects are generally not evaluated or identified in relation to possible alternative choices. And if what data gives information on is known, how this information fits into the ontology of the model is often not explained. Accordingly, concept of particular information as “data” is a social construct.

The availability or lack of certain data, their accessibility and reliability also constrain the models that can be produced and tested, as well as the likelihood and representativeness of the forecasts and scenarios. As an example, the Secretariat of the Convention on Biological Diversity notes: “(...) we do not know if the limited number of local-scale measurements of species response to environmental impacts used in constructing the models can correctly capture trends at these large scales” (Leadley et al. 2010 15). The final uncertainties associated to the scenario depend in a nonlinear way on the data errors, simulated processes and system trajectory.

The legal issues related to the preliminary stages of production, dissemination and sharing of data (Casanovas et al. 2017) are not directly part of our analysis but concern us in two ways: (a) integrated impact assessment models use increasingly massive sets of data and (b) the intensive exploration of massive data (a practice well covered by the expression “deep learning”; LeCun et al. 2015; Schmidhuber 2015) is often presented as producing solutions to complex problems. A rich critical literature on big data analytics (Wise and Shaffer 2015; Coveney et al. 2016) warns against this drastic view, on the basis of epistemological and ethical considerations. It is also already apparent that the practical exploitation of the opportunities offered by the diversification of data sources (e.g. via connective objects) and by massive data mining techniques is beyond the current legal frameworks of the IPR (Costa 2016). Today, no ethical framework exists that could efficiently apply to the production and use of these data.

Here, we only insist on the fact that data is a valued resource. Its management is embedded in complex governance frameworks (Ruppert et al. 2017) whose interactions among agents are crudely expressing often diverging and even conflicting values and interests (Boyd and Crawford 2012; Hansen and Porter 2017). A precondition for modellers, especially those free of conflicts of interest (a quality today subsumed as publication ethics), to become more involved in these debates, would be to recognise the pre-eminent political and sociological character of collective instruments (databases, models, simulation platforms, policy reports, etc.) that they develop, and of their uses.

All the preceding points show enough that the existence and the use of relevant data are not obvious, even less their integration into a model. Modellers' practices must be transparent, explaining each of the difficulties encountered, presenting the choices that have been made to overcome them, clarifying the possible consequences on reliability and diversity of the scenarios and forecasts produced, mentioning and describing the options of the scenarios that have been discarded. An even more demanding expectation is to identify values that have helped to shape their choices, a reflective exercise to be accompanied by the work of ethicists. Moreover, transparency requires that the data used and produced through simulations are made accessible publicly on open repositories.

Ethical Issues in Scenario Design

The values recognised and defended are most directly expressed in the choice of scenarios that are numerically simulated and in the nature of the scenarios discarded—intentionally, inadvertently or ignorantly (for example radical innovations cannot be foreseen). The governance pattern defines the group that decides the degree of desirability of this or that projected future, according to the group's own values. For example, influential economic factors may restrict the choice of scenarios to those seeking economic optimisation of incomes, regardless of biodiversity conservation, preservation of local community livelihoods, or environmental sustainability. The social acceptability of these choices results from other, often contingent, processes. Scenarios expressing or endorsing political, societal or cognitive choices or preconceptions should be accompanied by a critical examination, in particular by raising ethical concerns.

So far, the biodiversity models are mostly based on the representation of ecological processes or of the local to regional impacts of global changes. The increasing capabilities and reliance of impact assessment models make it possible now to include public policies, regulations and laws in the scenarios. Let us consider two examples: (1) Lajaunie et al. (2018) justify the importance of the integration of public policies and regulations in the models in the context of simulating prospective scenarios of the emergence of infectious diseases linked to biodiversity and environmental changes in Southeast Asia and (2) the modelling of the impacts of low-water policy on the aquatic ecosystems, on farm production and economic viability and on the water supply of the populations is used to evaluate scenarios of water resources sustainability at the hydrological basin scale in a context of climate change (Gaudou et al. 2014). Public policies or at least the main measures that they promote are formalised and integrated into the models in order to evaluate the expected (for which they are designed) and unexpected effects that appear dynamically in the short run of all interactions between society, environment and resources. This process alone does not resolve ethical disagreements: on the one hand, the way policies are formalised and the choice of the simulated policy options might be debated because they promote values; on the other hand, the simulations provide evidence for decision-making and socio-ecological development.

Some scenarios predict a negative impact of climate change mitigation or poverty alleviation measures on biological diversity. But precisely, this type of inference depends on the design of the simulated scenario: indeed, these conclusions stem from the fact that the climate change or poverty reduction measures envisaged involving the use of more land to produce resources like food, bio-fuels and water, in an unsustainable way. In fact, these scenarios primarily consider the options proposed in climate change studies and apply them to biodiversity thus concluding for example to poor species provisioning through reforestation. This could explain why the large differences between variables in the socio-economic scenarios only result in relatively small differences in the impacts on certain biodiversity variables.

Reversing the prevalence of climate change considerations over biodiversity concerns would lead to the identification and exploration of those scenarios that primarily affect life (in all its forms) on planet Earth, including scenarios that include realistic representations of social practices, public policies and effective regulations that favour the redeployment of biodiversity (limitation of meat consumption, low use of bio-fuels, extension of protected areas, limitation of population growth, etc. see Morand and Lajaunie 2018, chap.10). In the long term, it is necessary to defragment the points of view by integrating major global changes and exploring the co-benefits of appropriate measures (see, e.g. Ding and Nunes 2014 regarding the role of biodiversity as a nature-based policy solution for climate change mitigation). Achieving this goal supposes an extension of the pluralistic approach to problem solving (crossing the boundaries of domains and problem settings) and the implementation of working procedures fostering openness and fairness in knowledge building.

Considering the impacts of human societies only as drivers of impacts on biodiversity as is usually done is too limited. Socio-economic activities and biodiversity changes are linked through continuous feedbacks and interactions. Coupling dynamically in the models, all these social and nature-based processes would lead to better understand the adaptability of the whole system and opens the possibility to explore behavioural strategies, including the implementation of sound policies and regulations. This approach would also constitute a tool for locating actual responsibilities for changes in biodiversity. The first two points are particularly pertinent: if the public policies are conceived from the results of the scenarios, their direct and indirect effects will modify the conditions which prevailed at the simulation of a scenario, thus requiring completing a new full cycle of scenario design and simulation.

Scenario simulation also determines the framework in which next-generation scenarios will be designed. In this sense, it is likely to impose itself as a cognitive norm. There is reason to fear an effect of reinforcing more or less arbitrary options made in the past or present in the choice of scenarios or of their underlying assumptions. Maintaining public policies and regulations outside the models, setting human activities as drivers of environmental changes and not as one of their components or conceiving development as inseparable from economic growth, might be this kind "locking" by arbitrary assumptions or choices. Biodiversity conservation involves maintaining dialogues and taking into account a diversity of cultures and points of view, which should in turn be expressed in a variety of scenarios expressing a diversity of values, expectations and ethics. Thus, other development scenarios can and should be taken into consideration, bringing innovation and dialogue to the heart of the mainstream development and justice philosophy.

Biodiversity Models, Scenarios and Ethical Principles

Van den Hoven (2008, 51) notes that "human values, norms, moral considerations can be imparted to the things we make and use (technical artefacts, policy, laws and regulation, institutions, incentive structures, plans)", while Palmer (2017, 96) invites us to consider a model as an "ethically charged artefact". Indeed, seen from a consequentialist perspective, the consequences of policies developed from models determine the model's moral value (ethical/unethical). In this sense, the ethical evaluation of integrative impact assessment models and simulated biodiversity scenarios should focus on the social-ecological effects of four main items detailed in the previous sections: the choices made in the model design; the limitations (including uncertainty and indeterminacy) of the model representational capacities; the choices underlying the design of simulated scenarios; the potential impacts of use of the simulated scenarios on diverse communities (humans and non-human) and ecosystems.

This expectation goes beyond the framework established by the codes of professional conduct (Gotterbarn et al. 1999; Ören 2000; Ören et al. 2002). Admittedly, these codes present the principles of professional ethical behaviour like the principles of truth, honesty and trustworthiness, respect for human life and welfare, fairness, openness, competence and accountability (WFEO/FMOI-UNESCO 2001) but also principles of fair use of public funds, integrity and honesty in the reporting of research results, avoidance of conflicts of interest, fair treatment of subordinates and colleagues, privacy protection in computer ethics, etc. The concept of sustainability now enters some engineering society codes of ethics along with principles like protecting public health and safety, disclosure of all circumstances relating to the conflict of interest or objectivity, honesty and truthfulness (Schwartz 2017). But these codes do not encourage developing an ethical reflection on the formation of the formalised collective knowledge and its use to establish scenarios potentially having societal and ecological consequences.

Table 1 compares the most salient features of biodiversity modelling and scenarios with some principles of applied ethics. Interpreting and relying on ethical principles in a particular social-ecological context or scenario modelling are not self-evident. Moreover, the links between these principles are intertwined, each feature soliciting several principles and the principles not being independent of each other. Here, we only point out some of these links. Indeed, their precise analysis can only be carried out through a dialogue and the participation of stakeholders involved in all changes affecting biodiversity. It must articulate the diversity of values (particularly ethical ones), with the implementation of modelling and simulation practices in the specific context constituted by the social-ecological reference system.

A coherent set of ethical guidelines to frame the biodiversity scenario modelling and simulation does not exist yet. Promoting the importance of critical reflection on modelling activity and the use of simulated biodiversity scenarios is a preliminary step. It involves a diversity of applied ethics (environmental ethics, computer science and artificial intelligence, development ethics).

Some of the expectations suggested in Table 1 are not easily achievable goals. Transparency supposes disclosure (“providing accurate information about the benefits and harms that is reasonably expected of the action under consideration”) and comprehension (“individual’s accurate interpretation of what is being disclosed”; both citations taken from Friedman et al. 2008). But software for the simulation of global changes can or will count thousands or millions of executable instructions (code lines), embed complex (e.g. adaptive) algorithms and allow the emergence of unexpected properties dependent on the system evolutionary trajectories. In

Table 1 Linking the salient features of biodiversity modelling and scenarios with principles of applied ethics

Salient features	Technical issue	Consideration of ethical principle
Collective endeavour	There is no one-to-one correspondence between individual modeller’s action or decision and impacts associated with model uses.	Collective responsible and accountable behaviour.
Participation	Not only scientists but also stakeholders, ethicists and policy-makers should be involved at the various stages of platform conception, development and use.	Promote a pluralistic approach.
Knowledge integration	A common framework for sharing and producing knowledge must be developed, adopted and used in a consensual manner.	Implement fairness and openness.
Reduction	Explain and disseminate the knowledge representation processes that include knowledge reduction, the enforcement of coherence between representations and the use of integrity constraints.	Strengthen the transparency and legitimacy of knowledge.
Categorisation	The model ontology is not a passive representation of some system. It also frames—and possibly reifies—social and ecological segmentation and categorisations.	Foster disclosure.
Scenario valuation	The definition of a scenario explicitly or latently expresses the interests and values of the group that conceives it. Obligations to involve the public in decision-making about these technical matters.	Assume accountability, foster comprehension and social acceptability of scenarios.
Differentiation of impacts	Scenarios are not only used to improve knowledge but also to take decisions that have differentiated impacts on different segments of society, biodiversity and ecosystems.	Integrate values of equity and justice.
Knowledge use	Simulation results can be used by policy-makers, governmental and non-governmental organisations, civil society, etc.	Strengthen the independence of end users and promote benefit-sharing.
Capacity	Obligation to promote public education regarding the most relevant aspects of model and scenario building and use for supporting policy and regulation.	Adhere to the transparency of modelling and scenario uses.
Data sharing	Make all data open access and available on public repositories	Build public trust and inclusivity.

See, e.g. CBD 2011

addition, the exhaustive documentation work is at least as important as that of software development without necessarily being financed or valued. The tendency towards a growing automation of the production of forecasts, but also in the near future of the design, interpretation and evaluation of the scenarios (with the final step of ranking them with regard to values) and political decision-making, already opens a more demanding and higher level of ethical issues (Bostrom and Yudkowsky 2014; van de Voort et al. 2015).

Participation of the public or stakeholders in the modelling process is more of a horizon than a fully achievable goal, because of the limited interest, availability, competence and integrity of the agents involved. Similarly, the legitimacy of the simulation tools and the acceptability of the recommendations produced are social constructs that break out over a long period of time and which, beyond the framework of research, depend on political cultures and power relations. On the other hand, there is nothing to oppose the open access of data on public repositories, which promotes public trust and the inclusion of all kinds of communities in the development of scientific knowledge (Soranno et al., 2015).

The possibility to establish ex ante standard ethical procedures to account for ethical issues in integrative impact assessment modelling is not guaranteed: how may it encompass all the possible ethical consequences of modelling choices and uses, on subjects that precisely are beyond the individual human understanding? Moreover, the limitations of the representational capacity of the model-artefact are not well known (in particular with regard to alternative models), the model and scenario uncertainties are difficult to estimate, and most indeterminacies are ignored. The establishment of such standard procedures also presents the risk of a kind of automation (perhaps even algorithmic in a near future) of ethical responses to the problems raised, without thinking, without effective moral implication of human stakeholders. Automated decision-making is already involved in many activities such as banking, taxation, staff recruitment, healthcare, etc. It has direct impacts on the society or individuals through profiling, (Article 29 DPWP, 2018) or is in a position to conquer entire domains of application (e.g. justice—Aletras et al. 2016; armed conflicts—Allenby 2014, 7). Its use in the field of biodiversity conservation—either to overcome tensions between personal and collective values (Primmer et al. 2017) or to make the best use of the mass of information and data (Bolam et al. 2018)—is a matter of time. Nevertheless, by delegating decision-making to machines whatever the ethical implications, we assume the risk to divest ourselves of our responsibilities.

Since the aim is to change practices, it is preferable to develop flexible "research guidance statements" that would incorporate, in dynamic interaction between stakeholders, ethical expectations in the process of modelling and scenarios development. Those guidance statements would contribute to the procedural equity that "refers to the fairness of the procedures used for policy and decision-making" here in the context of biodiversity conservation and aiming at the "determination of legitimate interests, the process by which they are considered, and the allocation of rights and responsibilities among relevant parties" (ISSC/UNESCO 2013). The value sensitive design approach seems particularly adapted to answer this challenge by showing in particular "(...) how a technology affects human values on both the individual and organisational levels, and how human values can continue to drive the technical investigations, including refining the simulation, data, and interaction model" (Friedman et al. 2008, 84).

Boden and McKendrcik (2017) provide modellers with a framework of ethical practices in constructing evidence for policy development. This framework is based on four general ethical criteria (independence: "Scientific evidence should be derived autonomously through objective, established methods and subject to scientific and ethical review", and supposes no conflict of interest; transparency: "clear documentation of the scientific approach so that methods are robust, repeatable, and reproducible, and outcomes are clearly communicated and understood"; beneficence/non-maleficence: "excellence in design but also aim to enhance welfare for participants and stakeholders"; justice: "obligation to consider the equitable and non-discriminatory distribution of benefits and burdens of research in light of the risks that may be undertaken by individuals") related to brief descriptions of the ethical risks carried by the models. This grid of analysis is very promising and should be developed.

But it also appears from the outset that the assessment of these risks may diverge on many technical points depending on the modeller's views, skills and experiences. It is realistic to assume that these differences of opinion will be even more significant with the effective participation of policy-makers, or other stakeholders (i.e. the model end users). This remark is in no way pessimistic: on the contrary, it underlines the importance and the urgency of the conduct of these collective reflections and the debates that they will provoke. This need is further reinforced given that the ethical principles mentioned have different definitions, and they depend on the context leading to modelling and the production of scenarios.

Conclusions

The pace of improvements of integrative impact assessment models and simulations and of data acquisition on large-scale biodiversity changes is comparable to high species extinction rates. Indeed, despite scientific warnings about environmental degradation and increasing depletion of resources (Ripple et al. 2017), erosion of biodiversity and massive extinction of species (Barnosky et al. 2011) continue to progress. The accumulation and publication of knowledge and data are not enough to slow down these phenomena, let alone reverse trends. In this respect, the ethical analysis of integrated impact assessment models and biodiversity scenarios is now appearing essential.

Clarification of the philosophical underpinnings of modelling ethics should be pursued insofar as simulated prospective scenarios have an impact on the development of our societies and their environment. The distribution and content of responsibilities attributable to the modellers and users of the models and scenarios must be specified. The effects that such imputations could induce should be considered. It is accepted that model and scenario design and uses must involve not only scientists but also other stakeholders of biodiversity changes as well (local communities, policy-makers, ethicists,...). However, it is up to scientists to explain the apparent paradox that models incorporate objective knowledge according to proven scientific protocols, but that modellers must at each stage make circumstantial choices that place constraints on the scenarios explored, thus limiting options for policy-makers and the public. Considering that the same system can be modelled in various ways, all legitimate, with different results, it is essential to document transparently the options presented, the reasons for the choices made and to detail the alternative scenarios that are or are not explored. However, the design of ways to endow models and the modelling process with transparency raises fundamental questions, especially about individual and collective cognitive abilities (including those of machines). Reflection on this specific point is in its infancy and for sure requires more research.

Ethical analysis must be conducted as a dynamic process through collective reflection and open dialogues in each context. It offers a unique opportunity to question the presuppositions and values conveyed by models, forecasts and scenarios (Risbey et al. 1996). Scenarios produce knowledge to guide the design and implementation of public policies, whereas these public policies and regulations should now be represented and integrated into models as active components of societal and ecological changes and their ongoing interactions. The development goals are to be considered in an environment where the uncertainty and indeterminacy associated with the evolution of socio-ecological systems are persistent facts, rather than imagining decisions relying on scenarios whose knowledge of the most powerful effects (tipping points, cascading negative effects, etc.) is not mastered. It is also the responsibility of modellers to describe both carefully and in-detail these ethical implications (Danaher et al. 2017; Lowrie 2017). This leads to transparency of models and the social acceptability of scenarios.

Further development of models and empirical observation is necessary; however, provisionally our common future depends critically on the ethical positions articulated at all levels of individual and collective behaviour and decision-making. Without compromising the efforts made to improve the biodiversity models and scenarios that are essential and irreplaceable tools, recognising the limits inherent to integrative knowledge and model artefacts should lead to more caution and restraint in our individual and collective relationships with the environment, resources, biodiversity and life.

Acknowledgments We are grateful to three anonymous reviewers who have made a significant contribution to improving this article. This study was presented at the International Symposium “Investigating biodiversity and health at the human/animal/environment interface in the Nagoya Protocol era” held at the Faculty of Veterinary Technology, Kasetsart University, Bangkok (12–13 December 2017). It is a contribution to the ANR Project (2017-2021) No. ANR-17-CE35-0003-02 FutureHealthSEA “Predictive scenarios of health in Southeast Asia: linking land use and climate changes to infectious diseases”.

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