Bioeconomic models for terrestrial social-ecological systems : a review

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In the context of species extinction and ecosystem collapse, designing paths for sustainable development appears crucial. Therefore, managing the interactions of complex social-ecological systems is key [1]. Non-renewable resources, such as fossil fuels, have extensively been studied in economics. However, renewable resources, whose rate of extraction and regeneration are commensurable, have only been studied later on, due to species extinction. Systematic reviews, that map the strengths and shortcomings of bioeconomic modeling are necessary for policy guidance [2]. Because bioeconomic modeling is relatively recent, such reviews are lacking.

We review 319 articles featuring bioeconomic models, based on a quantitative analysis of their methodological components, as well as a narrative analysis based on a quantitative assessment and an in depth reading

We aim at characterizing what methods are used for typical research questions in the literature over time as well as how the bioeconomic modeling framework can be of interest for policy guidance, especially compared with correlation-based, data-driven modeling endeavors.

DATA & METHODS

Article selection process

Scopus research : ≈1000 articles → Definition of model : mechanistic, equation-based, to map scenarios to expected social-ecological consequences (EXCLUDES statistical models, i.e, models whose results rely on correlative analysis) → Biological dynamics of wild and weakly managed terrestrial biodiversity (EXCLUDES agrobiodiversity and some forests and atmospheric and soil polution) → Decision process emerging from economic theory, i.e maximizing an objective function (EXCLUDES studies only valuing nature; descriptions rather than explanations of land-use change) → Integrating a linkage between ecological and economic models → **319 articles**

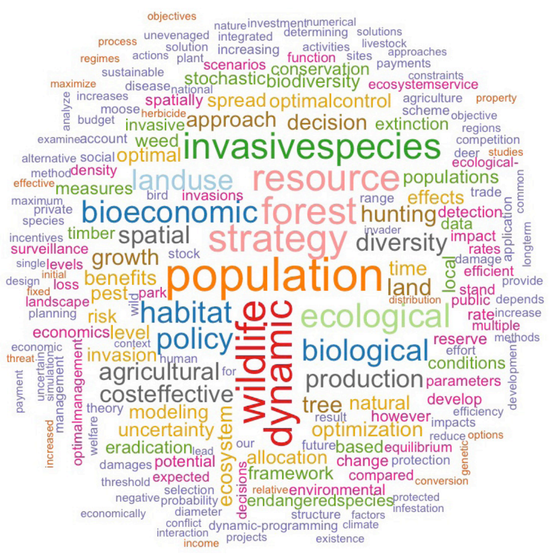
Methodological characterization

We use a set of methodological criteria to characterize the articles of the models we review :

- **HOW IS BIODIVERSITY CHARACTERIZED ?**
  How is it measured ? What is the contribution level ? What is the state variable ?
- **TECHNICAL ECOLOGICAL SPECIFICATIONS**
  Is the spatial component explicit ? Are there dynamics ? Is there uncertainty ?
- **HOW ARE THE ECONOMIC AND ECOLOGICAL MODELS LINKED ?**
  Is biodiveristy monetarized ? Are economic and ecological factors within a same objective function or separated?
- **TECHNICAL ECONOMIC SPECIFICATIONS**
  Is the spatial component explicit ? Are there dynamics ? Is there uncertainty ?
- **GENERAL CHARACTERISTICS**
  Are models solved numerically ? Is the model theoretical ? Is the equilibrium depicted general ?

In order to elicit groups, we perform a **Multiple Correspondence Analysis and K-modes clustering**

Narrative characterization

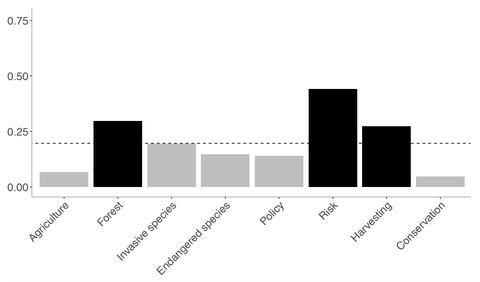


We get the words from titles, abstracts and keywords. After cleaning the database, we design 8 lexical groups from the data :

- **HABITATS :** agricultural, forest
- **SPECIES STATUS :** invasive and endangered species
- **MANAGEMENT SEMANTICS :** policy and risk
- **HUMAN-NATURE PARADIGMS :** conservation and harvesting

We use these **lexical groups to characterize the narratives deployed in the groups** elicited with the methodological characterization.

ANALYTICAL RESULTS

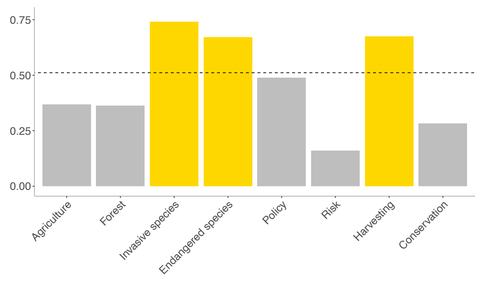


GROUP 2 : HARVESTING 2.0

- Population is the main variable
- Cost-benefit analysis
- Biodiversity is monetarized
- Theoretical solving
- Spatially explicit ecological model

ex. 1 : EPANCHIN NIELL et al. (1994) [3] : as bark beetles may invade forests, how large should surveillance and prevention efforts ?

ex. 2 : AUGERAUD-VÉRON et al. (2019) [4] investigate the value of biodiversity as an insurance device for agricultural production, as it decreases agricultural productivity volatility

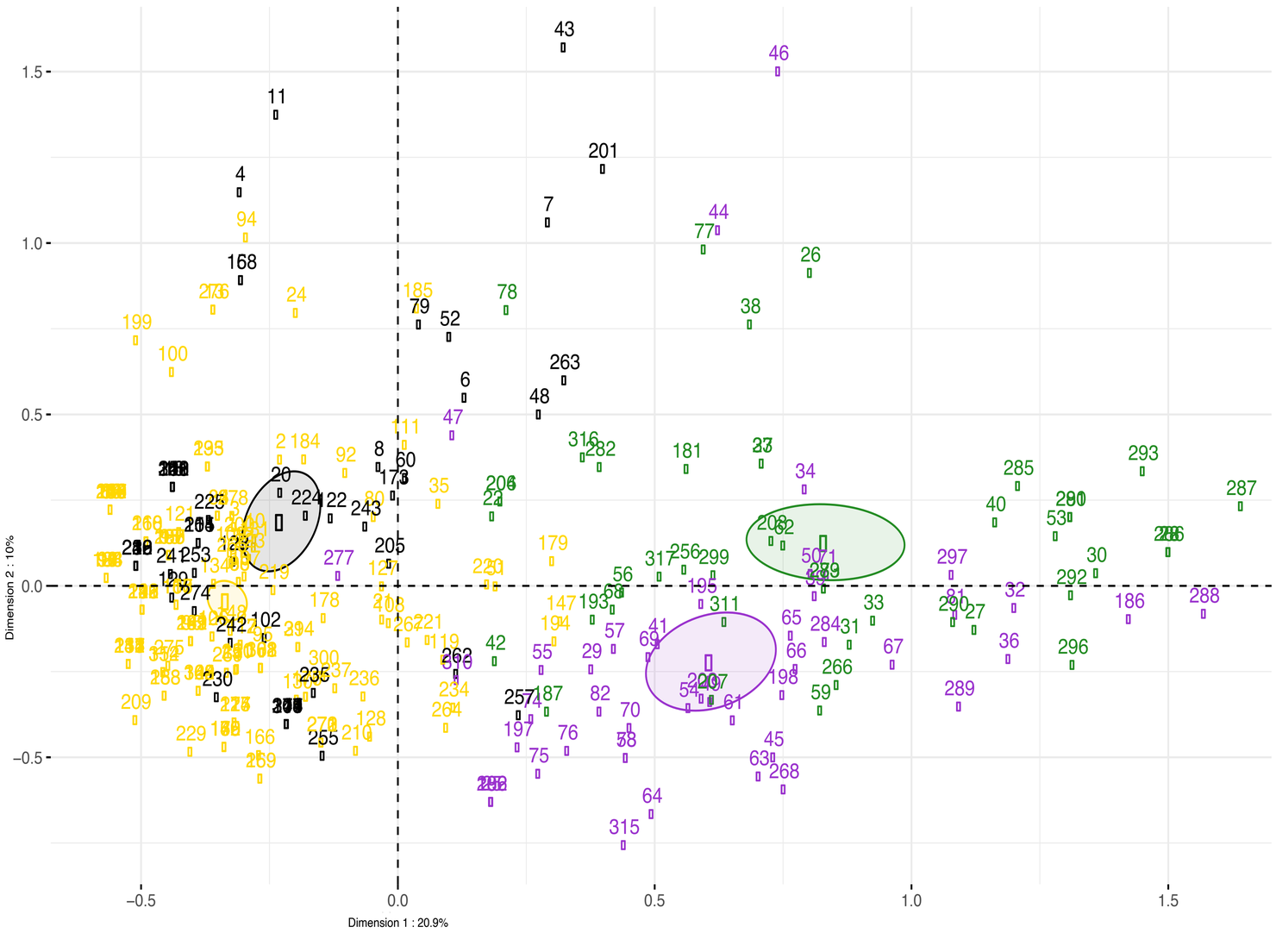


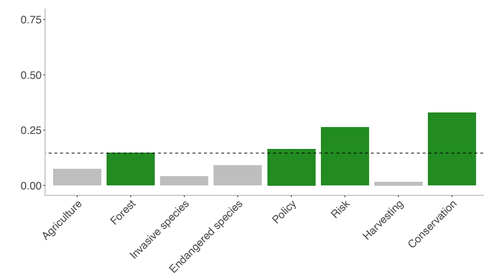
GROUP 1 : HARVESTING 1.0

- Population is the main variable
- Cost-benefit analysis
- Biodiversity is monetarized
- Numerical and theoretical solving
- No spatiality

ex. 1 : SKONHOFT (1999) [5] : optimal harvesting of large mammals in Africa, factoring non-consumptive values, land-use costs, harvesting profits and potential damages

ex. 2 : TAYLOR AND HASTINGS (2004) [6] : optimal removal of invasive species to promote ecological restoration



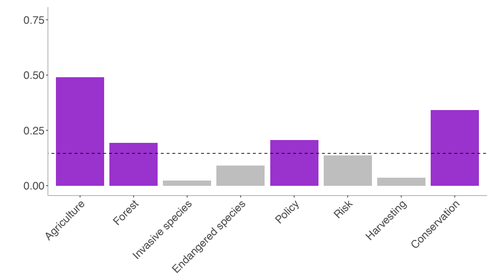


GROUP 4 : CONSERVATION REVISITED

- # of species is the main variable
- Cost-effective analysis
- Biodiversity is not monetarized
- Empirical and theoretical studies
- Stochastic in both models

ex. 1 : POLASKY et al. (2005) [7]: spatially explicit model in which vertebrates migrate across land patches as they compete for habitat with agriculture

ex. 2 : MOUYSSET et al. (2012) [8]: in a spatially explicit framework, farmers choose their land-use in an uncertain context and policies for farmland bird conservation are implemented.



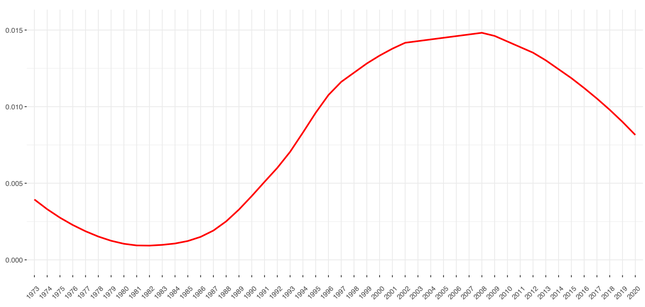
GROUP 3 : CONSERVATION

- # of species is the main variable
- Cost-effective analysis
- Biodiversity is not monetarized
- Empirical studies
- Spatially explicit ecological model

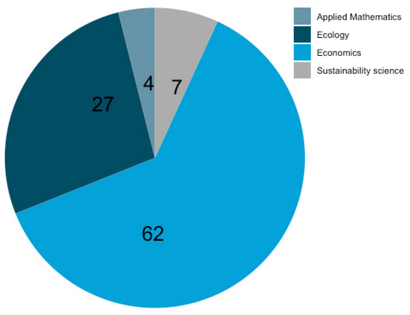
ex. 1 : WEITZMAN (1998) [9] : based on a measure of genetic similarity, how should budget be allocated to fill Noah's Ark?

ex. 2 : COSTELLO & POLASKY (2004) [10] : optimal combination of sites suitable for an array of species that need to be set aside from development, permanently or temporarily.

SOCIOLOGICAL RESULTS



The distribution shows an **overall decline of the method.** This is surprising, as bioeconomic modeling aims at helping to solve the ecological crisis, which is far from solved.



Bioeconomic modeling genuinely embraces an **interdisciplinary perspective.**

References

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DISCUSSION

WE HIGHLIGHT TWO HUMAN-NATURE PARADIGMS IN THIS REVIEW :

The harvesting paradigm in which biological elements are considered for what they directly bring to human welfare, without consideration for their intrisic value. It can be viewed as a modernization of the "conservationist" paradigm led by U.S Chief Forester Gifford Pinchot (1865-1946) and underlies institutions such as the WWF (1961) and emblematic public policies like the Endangered Species Act (1969)

The conservation paradigm, in which the existence and survival of biological elements are key. It is a modernization of the "preservationist" paradigm led by naturalist John Muir (1838-1914). It builds upon the concept of "biodiversity", brought about by the UN Earth Summit in Rio (1992), which encapsulates the diversity of living organisms and the growing threats to their survival.
It therefore appeals to a broader consideration of biological diversity and unambiguously calls for protection.

THE DECLINE IN THE USE OF BIOECONOMIC MODELING CAN BE PUT IN PERSPECTIVE WITH THE RISE OF OTHER METHODS, SUCH AS CORRELATIVE MODELS :

Using large datasets, they offer real-world analysis without emphasizing the centrality of mathematics, and seem appropriate for public policy design. Nonetheless, they often require proprietary data and softwares, and may fail at predicting events with no historical precedent. To this extent, bioeconomic modeling may offer solutions.

However, bioeconomic modeling faces several challenges.

1. Uncertainty and spatiality remain to be systematically integrated.
2. Ethical standpoints, especially arising from indigenous knowledge, need to be investigated
3. Advances from correlative methods should be integrated more systematicallyof biological diversity and unambiguously calls for protection.