REGULAR ARTICLE

# Integrated sustainability policy assessment – an agent-based ecological-economic model

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## Abstract

The paper proposes an agent-based evolutionary ecological-economic model that captures the link between the economy and the ecosystem in a more inclusive way than standard economic optimization models do. We argue that an evolutionary approach is required to understand the integrated dynamics of both systems, i.e. micro–macro feedbacks. In the paper, we illustrate that claim by analyzing the non-triviality of finding a sustainability policy mix as a use case for such a coupled system. The model has three characteristics distinguishing it from traditional environmental and resource economic models: (1) it implements a multi-dimensional link between the economic and the ecological system, considering side effects of production, and thus combines the analyses of environmental and resource economics; (2) following literature from biology, it uses a discrete time approach for the biological resource allowing for the whole range of stability regimes instead of artificially stabilizing the system, and (3) it links this resource system to an evolving, agent-based economy (on the basis of a Nelson-Winter model) with bounded rational decision makers instead of the standard optimization model. The policy case illustrates the relevance of the proposed integrated assessment as it delivers some surprising results on the effects of combined and consecutively introduced policies that would go unnoticed in standard models.

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## 1 Introduction

The discussion around sustainability is lacking an adequate consideration of complexity within and between the ecology and the economy (Faber and Frenken 2009; Foxon et al. 2013). Standard environmental and resource economic models typically depict the link between nature and the economy in a very simplified manner and separate between resource exploitation and problems of environmental damages while assuming optimization on the economic side. This partial-analytical approach of environmental or resource economic models (1) ignores the complex dynamics of the natural system, (2) fails to account for the feedbacks between resource exploitation, production, and waste or emissions resulting from them, and (3) does not consider the effects of non-optimizing, bounded rational economic agents in these processes.

According to van den Bergh and Nijkamp (1991) or Perrings (2006), integrated ecological economic models could provide a deeper insight than the partial-analytic optimization approach in economics or conventional ecological models, since they depict both the ecological and the economic system as well as the interdependencies at an adequate level of complexity. However, the potential of ecological-economic modelling as an analytical tool is not much explored as only few of them exist. The purpose of this paper is thus to introduce an integrated ecological-economic model that (1) depicts the economic system as a complex evolving system based on Nelson-Winter dynamics (Nelson and Winter 1982), (2) depicts the ecological system on the basis of literature from biology, and (3) integrates both systems in more than just one aspect.

A literature review by Anderson and M'Gonigle (2012) shows that the majority of published climate-economic models in Ecological Economics between 2007 and 2012 applied neoclassical economic theories and methods. These models explicitly consider aspects of the complex dynamics of ecological systems but combine it with the standard economic optimization approach which only captures a low level of economic complexity and denies bounded rationality of economic actors.

We argue that this field can benefit from an evolutionary approach (Costanza 1991; Witt 2003) where an evolving, innovating economy is coupled with a natural resource system. The concept of perfect rationality as applied in standard environmental and resource economics assumes instant utility or profit maximisation, even in complex situations. This approach overestimates the knowledge and abilities of economic agents and has been heavily criticized since it lacks empirical evidence (Simon 1982; van den Bergh et al. 2000). Human beings suffer from a multitude of cognitive limitations. Economic actors, therefore, rather search for options that at least satisfy some aspiration level than jump on optima (Simon 1997). This is what innovation, the ultimate drive of economic growth, is all about. If optimal behaviour would be an option – as in the maximization of present values in climate or resource economics over long time spans – no innovation would be needed or even possible. Real economic actors are different, their selected options may have unexpected effects which they try to correct, they interact and learn from each other and adapt

their aspirations (Simon, 1982; Witt 1993; Brenner 1998; Geisendorf 2011). This bounded rationality leads to a heterogeneity between economic actors and explains the presence of innovation (Simon 1997; Wall 1993; Selten 1993).

In 2009, Faber and Frenken coined the phrase 'evolutionary environmental economics' to subsume models applying evolutionary economic modelling in environmental policy assessment. There is a number of models contributing to this research field. Brouillat (2009) lets industries, consumers and recycling companies interact with each other to assess how the amount of waste can be reduced. The approach focuses on the environmental dimension of the product, measured by two performance variables, i.e. recyclability and life-time. Saint-Jean (2008) examines the impact of emission standards on trajectories of clean technologies implemented by firms subject to competitive selection and supply chain pressure. The paper provides guidance on the conditions of the dynamic efficiency of emissions standards, by taking into account the co-evolution of technology, user requirements and market structure. Beckenbach and Briegel (2010) propose a multi-agent model to explain economic dynamics due to innovation. They show the link between economic growth and $CO_2$ emissions and analyse how emmisions may be reduced through policy. Desmarchellier and Gallouj (2013) developed an evolutionary model with endogenous growth and structural change in order to test the hypothesis that environmental problems and environmental taxes negatively affect the economy. In their model capital goods produce emissions that are priced with a tax. More examples are Buenstorf and Cordes (2008), Bing et al. (2010), Brouillat and Oltra (2012), Liu and Ye (2012) or Hassani-Mahmooei and Parris (2013). However, while contributing to the field of evolutionary environmental economics and accounting for more of the complexity of the economic system, these models work without an explicit depiction of the ecological system or its multi-facetted link with the economy. The potential of ecological-economic modelling is thus not fully explored.

Only few models try to meet the needs of a more integrated ecological-economic modelling. Nannen and van den Bergh (2010), for example, apply an evolutionary agent-based model to evaluate climate policies and explicitly consider both subsystems. However, although the climate system is explicitly modelled it consists of only one equation and the dynamics follow a linear approach. In Janssen and de Vries' (1998) 'battle of perspectives model', an evolutionary agent-based economic model is coupled with a complex climate system. Agents try to understand the climate system's dynamics and adopt new worldviews modelled by genetic-algorithms. Other models using genetic-algorithms to model the evolutionary dynamics in climate-economics are Janssen et al. (2004) or Janssen et al. (2000). The original 'battle of perspectives' model has been updated and extended to include more agent types or a different understanding of climate expenditures as green investments by Geisendorf (2016, 2017) and Geisendorf and Klippert (2017). Another climate-economic model addressing policies for an endogenous climate change resulting from heterogeneous agent behaviour is by Nannen et al. (2013). Little and McDonald (2007) propose a model on uncertainty about harvest behaviour where agents learn to correct their mental representations of resource dynamics. Noailly (2008) proposes a co-evolutionary model to analyse the interaction between bounded rational agents and a pest population as an extension to a model by Munro (1997).

Economic evolution is only present in the form of adjustments of pesticide strategies to economic or ecological changes. The model by Lamperti et al. (2018) captures co-evolutionary features of the economy and potential feedbacks from climate change. By focusing on endogenous growth emerging from different types of incremental innovation the authors analyse how different policies affect the probability of a green transition. Increased production, however, often leads to higher resource extraction and damaging side effects on the natural system which are not part of the analyses.

This latter aspect is a general problem of most ecological-economic models thus far. While either one or the other side of the coupled systems is often under-complex in its representation, a crucial point we also want to address in this paper is the lack of integration of multiple links between both systems.

The model we propose contributes to the field of evolutionary environmental but also resource economics – whilst we would rather call it "evolutionary ecological-economic modelling" – and seeks to depict the co-dynamics and interactions between a stylized renewable resource system, based on population dynamics, and a stylized evolutionary economic system. The economy is modelled as a competitive industrial sector in which firms compete for market shares. The evolution of the economic system is characterised by an endogenous growth dynamic, realized through productivity increasing innovations, following the approach of Nelson and Winter (1982). Based on Beckenbach (1998), we enhance the economic system with (1) the opportunity to choose between productivity increasing innovations – as in the seminal Nelson-Winter model – and various eco-efficiency innovations and (2) a procedure of decision making under bounded rationality suggested by Wall (1993).

Thus, our model (1) puts an emphasis on the endogenous growth dynamics of innovations and (2) bases the formalization of the ecological system on insights from biology. Such an integrated model allows to analyse how the availability of the natural resource determines economic output, as well as how this output affects future availability of the resource.

In order to analyse if and how the link between a growing economy and a regenerative resource system can be managed by policy in a sustainable way, we calibrate our model leading to a breakdown of the coupled system. To assess the effects of different policies, i.e. taxes on emissions, resource extraction and pollution, on this instable coupled system, we propose several model internal indicators including thresholds covering the three sustainability dimensions, i.e. ecological, economic and social, in a stylised manner. Consequently, environmental and resource policy is faced with the challenge to design political instruments that allow companies to develop while protecting the natural basis for production by directing part of the innovative activity in resource efficiency and emissions reduction.

In sections two and three the ecological and then the economic model parts are described. In section four they are combined and calibrated to create a case requiring political regulation to protect an overused environmental system. Section five exemplifies the kind of political analysis such an integrated model allows. This is followed by conclusions and implications for political regulation as well as for further research in section six.

## 2 Modelling ecological dynamics

### 2.1 Purpose & design

The ecological model part is designed to fit with insights from population biology and to include multiple links with the economic system, going further than the standard resource economics´ extraction term. In particular, next to extraction, we study polluting and overshooting influences. The model thus allows a combined analysis of questions otherwise considered separately by environmental or resource economics. We argue that such an integrated assessment of extraction and damages allows more insights on the complex link between the economy and nature.

### 2.2 Formalizing the ecological model component

Resource economics usually employs continuous time models, allowing for the analytical maximization of benefits from resource exploitation over time.[1] Biologists, however, argue that discrete time models are a better description of population dynamics as individuals reproduce at given points in time (Domokos and Szász 2003; Domokos and Scheuring 2004). The dynamics for time discrete models are fundamentally different (May 1973; Domokos and Szász 2003). By varying the reproduction parameter in a logistic growth function, a single difference equation shows all behavioural regimes observable in ecological systems, from stable fixed points, over cyclical behaviour to deterministic chaos while at least three coupled differential equations are necessary to generate this spectrum of dynamic solutions with differential calculus (Vance 1978; Gilpin 1979). The choice of single differential equations in resource economic models is thus relevant for the results to be expected. We argue that this choice unduly stabilises the resource dynamics by e.g. not allowing for overshooting (i.e. an increase beyond the carrying capacity) and a subsequent decline of the population which could lead to a chaotic dynamic.

Following the pioneering work of May (1974) a multitude of population models allowing for chaos have been developed (Ellner 1991; Vandermeer 1993; McCann and Yodzis 1994 or Huisman and Weissing 2001). Others argued that chaos only emerges in these models because of an over-simplification of the equation, disregarding facts like sexual reproduction, the population´s age structure or spatial dispersal which have stabilizing effects (Scheuring 2001). However, although rarely featuring in nature by itself, biologists discuss the possibility of chaos being induced by economic influences (Berryman and Millstein 1989). If the economic impact on a biological population increases its growth rate, induces delays in the regulatory negative feedback or inhibits it, an otherwise stable system can be pushed over the edge to chaotic behaviour. Even more importantly, it needs to be pointed out that way before entering that mode, the system leaves the smooth growth path of a differential

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[1] Cf. Ricker (1954) or Beverton-Holt (1957) and their numerous applications in resource economics (Clark 1990).

equation to exhibit cyclical and multi-periodic behaviour which is very common in nature. Standard resource economics models do not include such fluctuations in their analysis.

An exemption is Xepapadeas (2009) introducing a second influence on the natural system besides extraction which affects the growth rate and carrying capacity. We adopt the idea and use it in the sense proposed by Berryman and Millstein (1989) as an influence leading to overshooting of the population over its carrying capacity ($\alpha_t$). Xepapadeas (2009) further points out that such influence may come from a different part of the economic system than the one extracting the resource. In this sense the economy of the interlinked systems has to be interpreted as a complex entity in itself which extracts resources and exerts intended or unintended side effects on the ecological system through emissions, pest control, fertilization or other.

Population dynamics is typically depicted by logistic growth, first described by Verhulst (1838). All subsequent population models are derived from it and embark on different specifications to account for particular assumptions. The Beverton-Holt (1957) model for fisheries approximates logistic growth. The Hassell (1975) model is a generalization of Beverton-Holt, and the Ricker (1954) model for fisheries is a limiting case of Hassell (Geritz and Kisdi 2004). Differences between the models concern their assumptions on inner species competition and the way population levels affect growth. Such features are species specific. Furthermore, as Gotelli (2001) points out, it is usually not possible to distinguish which model fits best with a given time series because the small differences in model dynamics are superimposed by the stochasticity of the data. Following this argument and taking into account that logistic growth exhibits medium values between the other two more specific models, we decided to use logistic growth as a stylized representation of the dynamics of the natural system.

Resource economics mostly employs single-species models (Clark 1990). We investigated the need to work with a multi-species model to account for the inner-ecological complexity but, again following biological literature, decided against it. First, even more refined models in biology address only some aspects of interaction (Hollowed et al. 2000) and second, Murdoch et al. (2002) conclude from their extended analysis of time series that single-species models in a periodic regime (which our discrete time model allows for) are in fact a good approximation of multi-species dynamics.

Population dynamics with $N$ as stock, growth parameter $r$, carrying capacity $M$ thus reads

$$N_{t+1} = N_t + rN_t\left(1 - \frac{N_t}{M}\right) \tag{1}$$

In a standard resource economics model, the only link to the economy would be a harvest factor $H_t$. We consider two further links, pollution and influences increasing population numbers over the carrying capacity of the natural system.

Pollution typically is dealt with in a different sub-discipline, environmental economics, where the models optimize between emissions or waste and the benefits of production allowing for them (Tahvonen and Kuuluvainen 1993). Contrary to that, we are interested in how pollution affects the resource, and thus, subsequently, its
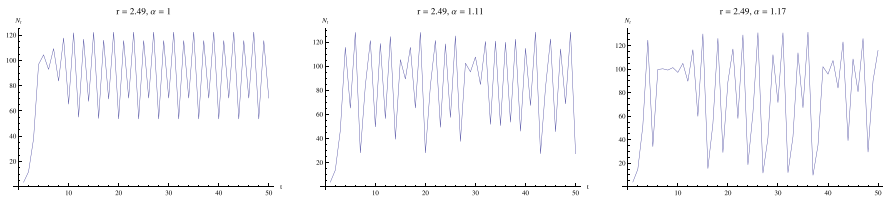
**Fig. 1** Effect of a change of a overshooting influence (α) from the economic system on the stability of the resource

availability for the economic systems. Following Hussen (2004), pollution can be assimilated to some extent, but nature´s capacity to do so declines with accumulating waste disposal. "Pollution reduces the capacity of an environment to withstand further pollution" Hussen (2004: 47). This nonlinear effect is modelled by a logistic damage function $\beta$, depending on the amount of accumulated waste ($W_t$).[2] For low levels of $W_t$ only minor damages occur, reflecting the assimilation capacity. The impact accelerates, ending with 100% damage ($\beta=1$).

A third link to include are influences increasing population numbers over the long term carrying capacity of the natural system. This can result from deliberate interventions such as fertilizers in agriculture or high stock numbers of animals, leading to a potentially unexpected degeneration of soil or overgrazing of habitats. The overshooting influences can also result less directly, for example from pest control which unduly favours a formerly limited species or through the deterioration of a habitat, for example from eutrophication which drastically reduces its carrying capacity for species living in it. Such influences can lead to an overshooting and subsequent breakdown of population numbers. They are least in the focus of environmental or resource economic models. If they are considered, some are treated similar to emissions, but their 'overheating effect' can only be made visible in the difference equation form proposed here.

Including all three links to the economy, $H_t$, $\beta$ and $\alpha_t$, Eq. (1) is thus enhanced to

$$N_{t+1} = \left(1 - \beta_t\right) \left[ N_t + \alpha_t r N_t \left(1 - \frac{(1 - \beta_t)N_t}{M}\right) - H_t \right] \qquad (2)$$

with $\beta_t = \frac{v}{1 + Ve^{-sW_t}}$ with $v = 1$, $V > 0$, and s [0, 1][3]

## 2.3 Simulating ecological dynamics

In the absence of $\alpha_t$, $\beta_t$ and $H_t$ the dynamics is the one of undisturbed logistic growth. Figure 1, however, illustrates how the economic influence of $\alpha_t$ can destabilize an

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[2] $W_t$ will be explained in Sect. 4.1.

[3] Higher $V$ increase the level of pollution tolerated without major effects. Higher $s$ increases the gradient. $v = 1$ to normalize the impact to the range [0, 1].

otherwise periodic natural system and shift it to unstable behaviour, making the availability of the resource unpredictable.

## 3 Modelling economic dynamics

### 3.1 Purpose and design

The economic sub-model follows suggestions of the seminal work of Nelson and Winter (1982) and specifications by Andersen (1994). We apply this formal model because it is well equipped to illustrate the endogenous growth dynamics of economies which, in turn, is an important determinant of ecological impacts from firms. Its focus on innovations allows us to introduce additional forms of innovation which then allow us to assess the effects of policies designed to strengthen more sustainable innovation activities.

The model consists of heterogeneous firms producing a homogeneous good. Firms compete for market shares and try to increase their share by reducing production costs. The cost competition triggers innovations, i.e. firms search for new production technologies with higher productivity leading to lower production costs. A better technology enables them to increase output. Firms consist of three different modules offering the opportunity to analyse effects and processes within themselves[4]: a market module, a search module and an investment module. A higher output due to a better technology, c.p. increases the firm's profit (market module) which leads to higher investments increasing the capital stock (investment module). The search process for new technologies is modelled as a two-step lottery where the probability of finding a new and better technology increases with R&D expenses (search module). Whether a new technology is sufficient or not to increase market share is manifested during the market process. Firms might face a drop of profits although a better technology has been found if another firm has found an even better one. Due to the selection pressure of the market, firms are thus constantly urged to search for better technologies in order to stay ahead. The search space is limited and depicts the path dependency of technological progress (Arthur 1994; Liebowitz and Margolis 1995).

### 3.2 Formalizing the economic model component

A firm's state is determined by its investments and search rules together with the probability of finding a new production technology. In the *market module* output $Q$ of firm $i$ in time $t$ is determined by capital productivity $A_{i,t}$ and capital stock $K_{i,t}$:

$$Q_{i,t} = A_{i,t} \cdot K_{i,t} \tag{3}$$

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[4] The model description is based on Nelson and Winter (1982) and specifications by Andersen (1994, 1996).

The total output is the sum of single outputs:

$$Q_t = \sum_{i=1}^{n} Q_{i,t} \tag{4}$$

To cancel out income or population effects, the aggregated output meets a fixed monetary demand $D$ which leads to a market clearing price[5]:

$$P_t = \frac{D}{Q_t} \tag{5}$$

Within the *search module* firms' innovation processes take place. Firms can invest in R&D to innovate or imitate other firms' technologies. In order to do so, each firm first allocates its R&D expenses. In the original model, R&D only aims at increasing capital productivity $A_{i,t}$. After having decided how much R&D money is placed, the firms are subject to a two-step lottery to determine the actual success. Investing in R&D is risky and might fail. First, the access lottery decides whether the firm finds a new technology at all. The probability of success follows a Poisson distribution depending on the R&D expenses, i.e. probability increases with R&D expenses. The total amount of R&D expenses in the standard Nelson and Winter model is a fixed proportion $r^{in}$ of the firm's capital stock $K_{i,t}$ ($K_{i,t}^{in} = r^{in} \cdot K_{i,t}$). To better account for bounded rationality as described in Sect. 1 an algorithm of adaptive behaviour which combines bounded rationality, satisficing and learning decides on the share of capital stock used for R&D expenses $r^{in}$ in every time step following a procedure of decision making under bounded rationality suggested by Wall (1993):

$$r_{i,t}^{in} = r_{i,t-1}^{in} + R_{i,t} \tag{6}$$

$$R_{i,t} = \frac{AL_{i,t} - \pi_{i,t-1}}{\left( \frac{\pi_{i,t-1} - \pi_{i,t-2}}{r_{i,t-1}^{in} - r_{i,t-2}^{in}} \right)} \tag{7}$$

The numerator of Eq. (7) shows the discrepancy between the aspiration level and realized profit $\pi_{i,t}$. The fraction in the denominator shows whether an increase (decrease) of R&D expenses leads to an increase (decrease) of profit. Depending on this information the firm decides on its R&D expenses in the next time step, i.e. learning. Thus, the aspiration level $AL_{i,t}$ plays an important role as it is responsible for the change of $r^{in}$. If the aspiration level is reached, i.e. the firm is satisfied, the firm stops searching and enters routine behaviour. Otherwise, it will continue searching. The aspiration level is modelled as follows:

$$AL_{i,t} = (1 - \vartheta) \cdot AL_{i,t-1} + B_{i,t} \tag{8}$$

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[5] This 'neoclassical' assumption has been criticized for a long time (e.g. Mirowski 1983). Abandoning this assumption would require complications in terms of differential prices and inventory management. Both are not essential for our focus on ecological-economic interdependencies and have thus been left out to not overlay the results.

where parameter $\vartheta$ defines the influence of $AL_{i,t-1}$ for determining the new aspiration level and can be seen as a factor of inertia. $B_{i,t}$ consists of two components defining the change of the aspiration level over time:

$$B_{i,t} = B_{i,t}^{I} + B_{i,t}^{II} \tag{9}$$

with

$$B_{i,t}^{I} = \vartheta \left[ (1 - \varphi) \cdot \sum_{j=1}^{m} \left( \frac{\pi_{i,t-j}}{m} \right) + \varphi \cdot \pi_{i,t-1} \right] \tag{10}$$

$$B_{i,t}^{II} = \gamma \left[ (1 - \omega) \cdot \sum_{j=1}^{m-1} \left( \frac{\pi_{i,t-j-1}}{(m-1)} + \omega \cdot \left( \pi_{i,t-1} - \pi_{i,t-2} \right) \right) \right] \tag{11}$$

where $m$ is the range of memory. The parameters $\varphi$ and $\omega$ determine how big the influence of recent profits or changes in profits on the aspiration level is, $\gamma$ determines the weight of profit changes. These two equations take into account that the aspiration level depends on past values of profits, both in absolute values ($B^{I}$) and changes between two proximate time steps ($B^{II}$). In both cases, not only the most recent experience (t-1) is taken into account but also the average of past $m$ values. Both, the limited amount of memory and the special importance of recent operations correspond to findings in cognitive psychology (Anderson 2000).

A firm being successful in the access lottery enters a second lottery to determine whether the new technology is better than the current one in terms of capital productivity. The possible results are depicted as random values within a limited range. The random values for capital productivities are normally distributed. Thus, incremental innovations are more likely than radical ones. The means of the distributions are exponentially increasing (decreasing) over time.

The imitation process consists only of the access lottery. In case of a success the firm gets access to a competitor's technology which is better than the currently applied one. Again, the probability of success increases with the amount of R&D expenses dedicated to imitation. The amount of imitation expenses evolves analogously to the innovation expenses (c.f. Equations (6) – (11)). Depending on their strategy firms either focus on innovation, imitation or both.

In the *investment module* the change of the capital stock is determined. The desired investment depends on the ratio of the current price $P_t$ and next period's unit costs $\rho_{i,t}$ which in turn depends on the result of the innovation process, and a markup factor based on the market share $s_{i,t}$. The price-unit cost ratio has a positive effect on the desired investment, whereas the market share has a negative one[6]:

$$I_{i,t}^{des} = \delta \cdot K_{i,t} + 1 - \left( \frac{\eta}{(\eta - s_{i,t})} \cdot \frac{1}{\rho_{i,t}} \right) \tag{12}$$

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[6] This indicates that the supposed firm strategy is mainly focussed on profits and not on conquering the market. Hence, there is an in-built smoothing governing the firm behaviour.

with $s_{i,t} = \frac{Q_{i,t}}{Q_t}$ and $\rho_{i,t} = \frac{P_t \cdot A_{i,t+1}}{c}$

where $\delta$ is the depreciation rate, $\eta$ the expected price elasticity and, according to Andersen (1994) and Nelson and Winter (1982), $c$ stands for unit costs and interest and is constant over time. The maximally possible investment depends on the profit $\pi_{i,t}$, external financing $l_i$ and the depreciation rate $\delta$. Thus, there are financial constraints determined by internal and external funds:

$$I_{i,t}^{max} = \pi_{i,t} + l_i \tag{13}$$

with

$$\pi_{i,t} = P_t \cdot Q_{i,t} - \left( c + r^{in} + r^{im} \right) \cdot K_{i,t} \tag{14}$$

$$l_i = \begin{cases} 0, \pi_{i,t} \leq 0 \\ b \cdot \pi_{i,t}, \pi_{i,t} > 0 \end{cases} \tag{15}$$

where $b$ is the loan from banks as a fixed proportion of the firm's profits. The firms choose the smaller one of both investment options:

$$I_{i,t} = min\left( I_{i,t}^{des}, I_{i,t}^{max} \right) \tag{16}$$

The capital stock increases with investments:

$$K_{i,t+1} = \begin{cases} K_{i,t} \cdot (1 - \delta) \forall \pi_{i,t} \leq 0 \\ K_{i,t} \cdot (1 - \delta) + I_{i,t} \forall \pi_{i,t} > 0 \end{cases} \tag{17}$$

## 3.3 Simulating economic dynamics

In the following, we present a single run of the economic model without any link to the ecological model, i.e. no extraction or emission costs are considered. Therefore, firms invest all R&D expenses in capital productivity innovations as it is the case in the original model by Nelson and Winter (1982). The model is programmed in *Mathematica* and the standard configuration for the following simulation follows the methodological issue and is thus not empirically based but the result of a sensitivity analysis of the most important parameters (Table 1).

Results will be discussed along the state variables *profit (π)*, *productivity (A)* and *output quantity (Q)*. Figure 2 shows a growing economy, measured by output quantity. Aggregate growth is tantamount to growth in scale of the economy (Daly, 2013). However, Fig. 2 illustrates that not all firms are able to grow.

An explanation for the growing output quantity and the heterogeneity among firms can be seen in the development of capital productivities (Fig. 3).

The average capital productivity of the economy increases as a result of the innovation and imitation process. This results in a higher output. However, some firms are more successful than others in finding productivity increasing technologies

**Table 1** Parameter settings and start values for the reference run of the economic system

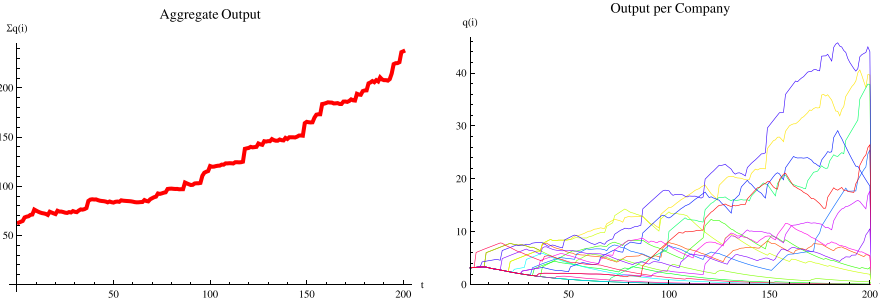| Parameter | Description | Justification |
|---|---|---|
| $b=1$ | Loan from banks as a fixed proportion of the firm's profits | Taken from Andersen (1994) |
| $c=0.16$ | Unit costs and interest per unit of capital | Taken from Andersen (1994) |
| $\delta=0.03$ | Depreciation rate | Taken from Andersen (1994) |
| $Dem=90$ | Fixed monetary demand | Calibrated to defined parameter values |
| $n=20$ | Number of firms | Calibrated to defined parameter values |
| $\eta=1$ | Expected price elasticity | We assume a fixed monetary demand leading to a market clearing price. Thus, expected price elasticity of demand is 1 |
| $\varphi=0.4$ | Influence of recent profits on aspiration level | We assume that firms are rather cumbersome since the aspiration level of the previous periods has a strong influence on the new aspiration level. Moreover, firms' learning behavior focuses on recent profits rather than on long term trends in profit development. Both, the limited amount of memory and the special importance of recent operations correspond to findings in cognitive psychology (Anderson 2000) |
| $\vartheta=0.2$ | Weight of recent profits for aspiration level | |
| $\omega=0.4$ | Influence of profit trend on aspiration level | |
| $\gamma=0.01$ | Weight of profit trend for aspiration level | |
| $m=3$ | Range of memory (time steps) | |
| $T=200$ | Number of time steps | In order to identify possible long term trends we run the model over a significant number of time steps |
| $K_{i,0}=19.7$ | Initial capital stock | Calibrated to defined parameter values |
| $A_{i,0}=0.16$ | Initial capital productivity | Taken from Andersen (1994) |
| $r^{in}_{i,0}=0.0223$ | Innovation intensity | We assume, that firms follow a innovation strategy rather than a imitation strategy. Thus, we assume a significantly lower imitation intensity compared to the innovation intensity |
| $r^{im}_{i,0}=0.00112$ | Imitation intensity | |
| $AL_{i,1-3}=\frac{\pi_{i,t}}{t}\forall t<3$ | Aspiration level | Relates to the range of memory $m=3$ |

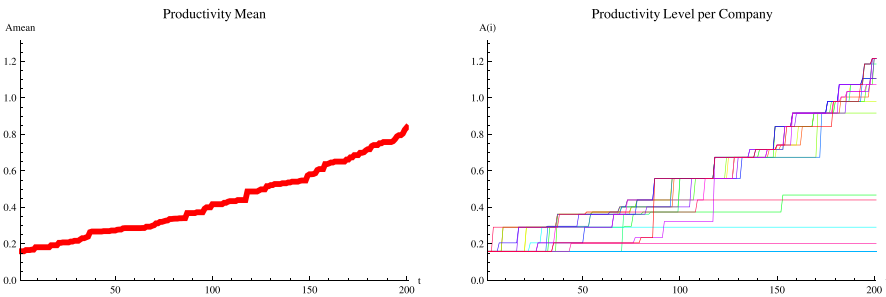**Fig. 2** Aggregate Output (left) and output per company (right)



**Fig. 3** Average Productivity (left) and productivity level per company (right)

(Fig. 3, right). Thus, some firms are able to increase their output whereas others stagnate. This heterogeneity can have different reasons. First, firms are individually fixing their aspiration level which implies different R&D expenses and thus different probabilities for finding better technologies. Second, even if aspiration level and R&D expenses are the same, some firms might be luckier than others in the innovation or imitation lottery. Those firms finding a better technology before others can realize higher profits and invest in their capital stock. This in turn enables them to increase their R&D efforts which positively influences the probability to find further better technologies.

The comparison of aggregate output (Fig. 2, left) and profit (Fig. 4, right) reveals that the economy faces a ruinous competition as a result of the interplay between innovations and investments. Due to the exogenously given fixed demand an increasing output leads to a decrease in price. Only few firms are thus able to translate higher productivities into higher profits. The majority suffers drops in profits. These differences also result from the fact that not all firms equally contribute to the output growth. For those not able to find better technologies in the beginning the lower price leads to lower profits or even losses. Those firms lucky enough to find better technologies in the beginning are able to compensate or even over-compensate the lower price with a higher output quantity.
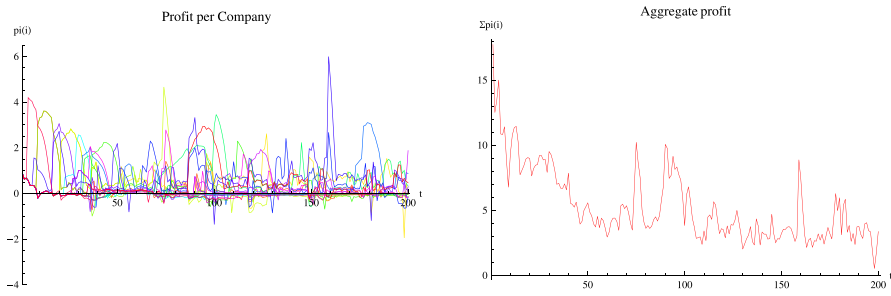
**Fig. 4** Profit per Company (left) and aggregate profit (right), coupled system

## 4 Coupling ecological and economic dynamics

### 4.1 Formalizing the links

As described in Sect. 1 we argue that integrated ecological economic models should depict the interdependencies between the ecological and the economic system at an adequate level of complexity and consider the basic idea of ecological economics that the economy critically depends on the ecology. The economy thus uses a natural resource as input ($H$), while at the same time polluting the natural system and influencing it through further interaction such as fertilizers or pest control which can trigger an overshooting over the carrying capacity. Integrating natural resources as a specific input, different from other forms of capital or input factors, is at the core of resource economics (Tietenberg and Lewis 2018) but also done in some macroeconomic growth models (Solow 1974). As the fractions of resource input vary between industries, we based them on empirical data from a global model by Nordhaus and Tobin (1972) who found partial elasticities of production of capital (20%), resource (5%), and labour (75%). Since we do not analyse labour as an individual input factor we allocate elasticity of labour between capital and resource while keeping the relation between the two, i.e. capital = 80% and resource = 20%:

$$Q_{i,t} = A_{i,t} \cdot K_{i,t}^{0.8} \cdot H_{i,t}^{0.2} \tag{18}$$

The amount of harvested resources per firm $H_{i,t}$ is determined by an individual harvest intensity $\varepsilon_{i,t}$ ($0 \leq \varepsilon_{i,t} \leq 1$) per unit of output $Q_{i,t}$, and the available amount of resources $N_t$:

$$H_{i,t} = Q_{i,t} \cdot \varepsilon_{i,t} \cdot N_t \tag{19}$$

This directly reduces the resource stock and enters its regeneration equation (see Eq. (2)).

Second, every unit of output produced generates a proportion $\varrho_{i,t}$ ($0 \leq \varrho_{i,t} \leq 1$) of (unspecified[7]) pollution or waste which negatively affects the ecological system.

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[7] Please note that the terms "pollution", "waste" or "emission" are therefore used interchangeably throughout the paper.

The total amount of waste generated by the economic system is the aggregate of all firms' pollution:

$$S_t = \sum_{i=1}^{n} Q_{i,t} \cdot \varrho_{i,t} \tag{20}$$

Pollution accumulates in a pollutant stock $W_t$ which enters the resource dynamics via the damage function $\beta_t$ (Eq. (2)). According to Xepapadeas (2009), we assume a self-cleaning capacity of the ecosystem ($\Pi$)[8]:

$$W_t = (1 - \Pi) \cdot W_{t-1} + S_t \tag{21}$$

Third, according to Berryman and Millstein (1989) we assume that economic activities can exert growth stipulating influences which might push the ecosystem into a multi-level stability regime once the carrying capacity has been overstepped (cf. Section 2 above). Thus, we consider an overshooting influence $\alpha_t$ linked to the production output $Q_t$ and determined by an individual factor $\Delta_{i,t}$:

$$\alpha_t = \sum_{i=1}^{n} Q_{i,t} \cdot \Delta_{i,t}. \tag{22}$$

Consequently, every combination of a production level with a given technology results in a specific reaction of the resource system and thus a changed availability of the resource and potentially changes of the resource dynamics.

Besides the influences of the economic system on the ecological system there are also feedbacks from the ecological system to the economy which affect the behaviour of firms. The use of resources causes costs, i.e. extraction costs. The scarcer the resource, the higher are the extraction costs as represented by the following equation ($0 < \zeta < 1$):

$$C_{i,t}^{h} = \zeta \left( \frac{M}{N_t} \right) \cdot H_{i,t} \tag{23}$$

The resource costs directly affect the profits of the firms and therefore the decision on investments and R&D effort:

$$\pi_{i,t} = P_t \cdot Q_{i,t} - (C_{i,t}^{h} + \left( c + r^{in} + r^{im} \right) \cdot K_{i,t}) \tag{24}$$

## 4.2 Calibrating the coupled ecological-economic model

For the following simulations we use the configuration of the model parts as described in Sects. 2 and 3 and calibrate the coupled model to lead to a collapse of the system (cf. Tables 2 and 3).[9] This generates a reference case for the testing of policies trying to prevent the breakdown in Sect. 5.

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[8] For the sake of simplicity it is assumed here that the assimilative capacity is proportional to the amount of waste.

[9] As shown in Sects. 2 and 3 the model parts, i.e. the resource and the economy, are stable if they are simulated separately. However, in order to analyse the meaning of policy instruments we calibrated the model leading to a collapse of the coupled system.

**Table 2** Parameter settings and start values of the ecological system

| Parameter | Description |
| --- | --- |
| $M = 100$ | Carrying capacity |
| $r = 2.49$ | Reproduction factor |
| $N_0 = 50$ | Resource stock |
| $v = 1$ | Pollution level for maximum damage |
| $V = 100$ | Rate of increase of damage |
| $s = 0.3$ | Normalizing factor |

**Table 3** Parameter settings and start values of the economic system

| Parameter | Description |
| --- | --- |
| $\varepsilon_{i,0} = 0.002$ | Harvest factor per unit output |
| $\varrho_{i,0} = 0.1$ | Emission factor per unit output |
| $\Delta_{i,0} = 0.015$ | Overshooting factor per unit output |
| $\zeta = 0.1$ | Weight of resource scarcity for resource costs |
| $\Pi = 0.4$ | Self-cleaning capacity of the ecology |
| $H_{i,0} = 0.1$ | Harvest |

A sensitivity analysis of the model parameters verified the structural validity of the model. Figure 5 shows the effects of a 10% variation of parameters $c$ (costs per unit of capital), $\Pi$ (self-cleaning capacity of the ecosystem) and *Dem* (fixed monetary demand). Increasing capital costs negatively affect production costs. Consequently, profits drop and firms are not able to increase production as fast as in the case of lower capital costs. A less strongly increasing production for higher values of $c$ goes along with less pressure on the resource. Thus, the coupled system breaks down later for higher values of $c$. A higher demand leads to a higher price of the product. Consequently, profits of firms are significantly higher for higher values of *Dem* at first. However, since firms generate higher profits they can invest more into more efficient technologies leading to an increasing production but increasing competition as well. Following from that, the initial advantage disappears quickly and does not change the pressure on the resource significantly. The higher the self-cleaning capacity of the ecosystem ($\Pi$) the longer the resource survives even for increasing pressure by the economy. However, this also does not prevent the breakdown of the system. Summing up, a variation of the chosen values does not change the dynamics significantly. The same is true for other defining variables of the system.

## 4.3 Analysing the benchmark simulation of the coupled ecological-economic model

The simulations of the combined effect of economic growth dynamics and potential ecological instability manifest four problems for ecological-economic reproduction:
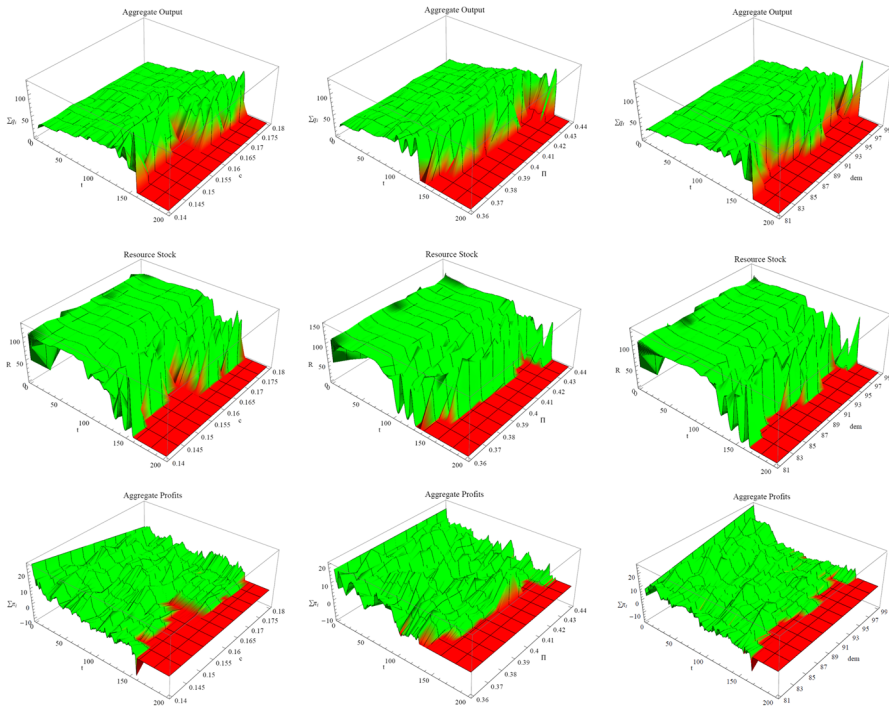
**Fig. 5** Sensitivity analysis for ± 10% variations of *Dem*, *c*, and *Π*

**The threat of extinguishing the ecological resource** The ecological system is influenced by the economy via extraction, emissions and overshooting effects, while the economy depends on the resource as input and has to pay an increasing price when the resource gets scarcer. In this reference case, no innovations in resource efficiency or reductions of emissions and overshooting influences are possible yet. The purpose of this baseline case is to show how two systems that are robust in their inner dynamics (cyclic behaviour for the ecology and internal, innovation driven growth of output for the economy) may destabilize each other through their interaction up to the point of collapse of both. The more goods are produced, the more resources are extracted and emissions are generated. The expansion of the economy is linked to an overshooting effect on the resource (through fertilizers, pest control or accidental overheating, e.g. eutrophication). Under the chosen constellations, the economy reaches an activity level (scale) where a further increase of resource extraction is not possible and the resource gets extinguished. Economic production consequently collapses.

According to Eq. (23) there is an increase in harvesting costs if the economic output increases. However, there is no guarantee that the market process generates a price-related scarcity signal in itself strong enough for the survival of the resource and hence of the economy. Exemplarily, this is shown in Fig. 6 displaying the stock of resources for several singular runs differing in the effectiveness of the market signal, i.e. the resource costs (indicated by the parameter in formula (23)). It can be

**Fig. 6** Resource stock for various values of resource costs (resKost)
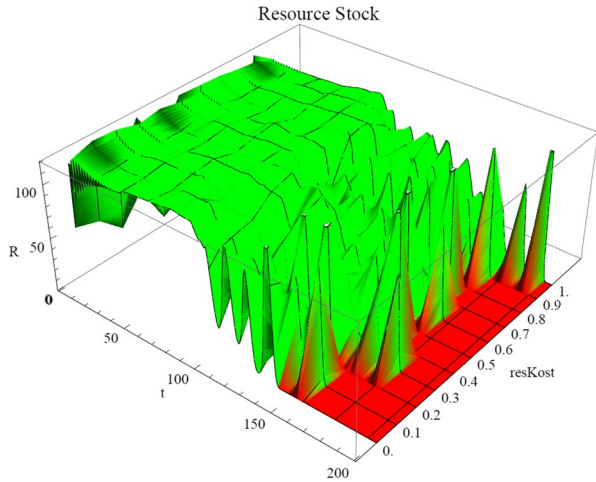


clearly seen that the price signal is not sufficient for maintaining the resource; even for high resource prices (red areas illustrate resource levels of $\leq 0$).

**The threat of a chaotic ecological regime provoked by inner economic growth dynamics** In their competition for market shares, firms enter an investment-innovation spiral leading to economic growth. Increased productivity creates higher output, which incites competitors to invest into their own growth, thus diminishing the advantage of an innovation and motivating companies for continuous further investments. However, as discussed above, this growth dynamics of the economy leads to an increasing pressure on the ecological system, i.e. extraction, emissions, and overheating influences. Especially the latter might lead to a structural uncertainty in terms of a variety of regimes including cycles with different periods or even chaotic behaviour of the natural resource system. A chaotic behavior of the resource system increases the uncertainty of the firms since unpredictable changes of the resource stock negatively affect the planning reliability with regard to necessary investments or planned output, and bear the risk of extinction.

**The threat of declining economic output** In economics, real GDP (per capita) can be considered a measure of welfare. Accordingly, a declining aggregate production level is related to a loss of welfare. Within the context of our model (constant monetary demand) a declining aggregate output leads to increasing consumer prices. Hence, keeping the living standard on the initial level ($Q_0$) requires at least a constant level of real GDP measured by aggregate output when considering a constant demand. Furthermore, periods of declining production in a broader focus than the one taken here hold the risk of increasing unemployment (Okun 1962) and a subsequent loss of confidence in the economy, resulting in declining investments and consumption (i.e. recession). The minimum requirement for economic policy is thus usually to prevent such a downshift.

**The threat of negative profits** In our model firms face a potentially ruinous competition for market shares. They try to increase their market shares by searching for new production technologies allowing for cheaper production. However, a cheaper production results in an increase of aggregate output which in turn reduces the price for the goods and only the ones ahead of other firms can benefit from this competition and increase their profits. Profits are thus competed away by the innovation race. The declining profitability becomes dangerous if a firm generates losses. Our model firms get access to external funding for capital investments only if they are profitable. A negative aggregate profit is thus a sign for recession of the entire model economy because it stops investment financing and results in a declining aggregate production capital. The short periods of losses in the end are reflecting the induced breakdown of the resource system which strangles the economy.

## 5 The difficulty of achieving a sustainability path

### 5.1 Defining sustainability criteria

In order to test the effect of different policies on the sustainability of the coupled system, we need to define sustainability criteria. As the model is only a rough sketch of a real economy or society, indicators for sustainability have to be defined in terms that are measurable by the model. In line with the common understanding of sustainability as a three dimensional concept (ecological, social, and economic, e.g. Strange and Bayley 2008) and in view of the problems sketched above in Sect. 4.2 we suggest to discuss the possibilities of sustainability paths within this model along the following minimum criteria:

(1) *Ecological dimension*: The ecological system should survive and be kept from critical fluctuations. This includes at least that an extinction of the ecological resource is avoided. Moreover, the economic use of the ecological component of the whole system should be confined to a range for which the variability of the ecological state variable remains within a regular regime (i.e. static or cyclic) not putting its survival at hazard (i.e. no chaotic fluctuations). The latter depends on growth parameter $r$ and variable $\alpha_t$ as well as on the counterbalancing effect of $\beta_t$ and the amount of harvest in Eq. (2) but no exact threshold can be defined for the different variables. The absolute minimum requirement for ecological sustainability thus is to prevent extinction and reads:

$$R_t > 0 \forall t < T$$

(2) *Social dimension*: In the model, a social dimension is only represented in the form of goods available for consumption. A minimum requirement for social sustainability should be that output ($Q_t$), i.e. the consumption level, stays above a critical threshold ($Q^*$). This lower limit is defined by the original consumption level of this model economy, i.e. $Q_0$. For a constant demand the minimum

requirement would thus be a non-reduction of the aggregate output in order to maintain the living standard and avoid social conflicts:

$$Q_t \geq Q_0 \forall t < T$$

(3)  *Economic dimension*: In the model context, a minimum requirement for the economic dimension is that aggregate profits are positive in order to create the basic condition for investments in production capacities in terms of capital stock:

$$\pi_t \geq 0 \forall t < T$$

However, further economic considerations should be made: There may be time series in which this non-loss criterion is violated but in which a higher average profit compared to other runs is generated which should be valued positively.[10] Thus, average aggregate profit ($\pi_{mean}$) will be taken as an additional criterion for the economic sustainability dimension. Furthermore, economic paths diverge in terms of their smoothness or volatility. The bigger the volatility, the higher the adaption requirement and therefore the threat of instability. Hence, a further criterion for the economic dimension may be seen in the volatility of the aggregate profit over all time steps as measured by the standard deviation ($\pi_\sigma$). A high standard deviation indicates a high level of volatility of aggregate profits. This may be seen as a problem for regulators and society and could thus be taken as an indicator for an unsustainable path. Together with periods of declining output it may even be a sign of recession.

If the criteria for all three dimensions are met, the corresponding path is considered as fulfilling the minimum requirements for sustainability within our model. We are aware that these criteria are strong simplifications of the ones to apply to a real society but have to keep them within the possibilities of the also simplified model.

## 5.2  Regulating the coupled system

In the above simulations, we calibrated the coupled dynamics with an initialization leading to a breakdown under economic exploitation. This will be our starting point for the analysis of conditions under which a collapse can be prevented. Since it cannot be excluded that market forces alone are insufficient to avoid overexploitation and extinction of the ecological resource, regulation is often necessary. The multitude of links between the economic and ecological systems suggests that a policy mix is required where each instrument sets adequate incentives for innovations in the respective area, i.e. resource efficiency, emission reductions, reductions of influences provoking overshooting. In principle, all kinds of policy instruments could be analysed with that model, i.e. limits or quota, certificates and taxes as well as subsidies. Limits on production or non-tradable quota usually lead to a macro-economic suboptimal result since they are inefficient in terms of firm specific technologies

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[10]  As we do not discount aggregate profit over time, which would correspond most closely to the standard present value maximization, we use average profit ($\pi_{mean}$) to compare results between scenarios.

(Tietenberg and Lewis 2018). Moreover, the relevant aspect we want to capture is the financial incentive for innovation and technological progress instead of a plain ban. Tradable quota are an efficient market based instrument, but would require the additional modelling of an exchange market for the certificates. We thus use taxes as a common market-based instrument with a high innovation potential (Stavins and Whitehead 1997).[11] Environmental taxes charge a price for utilizing the environment. In our model, production costs are thus composed of capital costs, resource costs (extraction costs as well as a potential harvest tax) and emission costs (in case of an emission tax or tax on overshooting influences).

$$
\pi_{i,t} = P_t \cdot Q_{i,t} - (C_{i,t}^h + T_{harv} \cdot C_{i,t}^h + S_t \cdot T_{emis} + \alpha_t \cdot T_{growth} + \left(c + r^{in} + r^{im}\right) \cdot K_{i,t})
$$

(25)

In this more integrated model we propose, there are four options to lower production costs: increase capital productivity, increase resource efficiency, reduce emissions and reduce overshooting influences. The allocation of R&D expenses happens according to the relative exceeding of the different production cost elements compared to the industry's average in the given time step.

The model is first used to simulate the consecutive introduction of instruments regulating critical activities in the order of their perceived relevance.[12] Judging from the growth dynamics of the economy as described above, the expansion of economic production requiring a growing amount of natural resources seems to be the main stress factor on the ecological system. We thus assume that our model regulator first considers a tax on harvests ($T_{harv}$) to incentivise innovations for higher resource efficiency.

## 5.3 Regulation by a resource tax

In the model, a resource tax increases production costs. We assume that this motivates firms to additionally search for more resource efficient technologies instead of just less costly production technologies, as before (cf. Clarke and Weyant 2002). The allocation of R&D expenditures follows the mechanisms explained in Sect. 3.

The results in Fig. 7 show that the additional cost factor "harvest tax" leads to an increase in resource efficiency, i.e. decreasing harvest and increasing output. The output seems to surpass a critical level around period 150 when the resource faces a dramatical drop which leads to a considerable increase of harvest costs, making firms unprofitable and forcing them to reduce their activity. The resource slightly recovers and the more resource efficient technologies developed after the first price increase allow a further expansion of the economy leading to the collapse of the

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[11] According to the main subject of this elaboration neither the internal determinants of the tax agency nor the effect of tax spending are taken into account.

[12] By introducing the policies sequentially, we tried to follow a realistic logic in case of an acknowledged overexploitation of a natural resource. Checking each individually (as we did later) would assume a rational decision process without a history in real time. Typically, once a policy limiting exploitation numbers is in place, it is not taken back but complemented by more policies when it becomes apparent that the resource also suffers from additional damages. Fish quota, e.g. are still employed (Tietenberg and Lewis 2018) even though fish also suffer from climate change and eutrophication. Such influences are regulated additionally, e.g. in climate or agricultural policy.
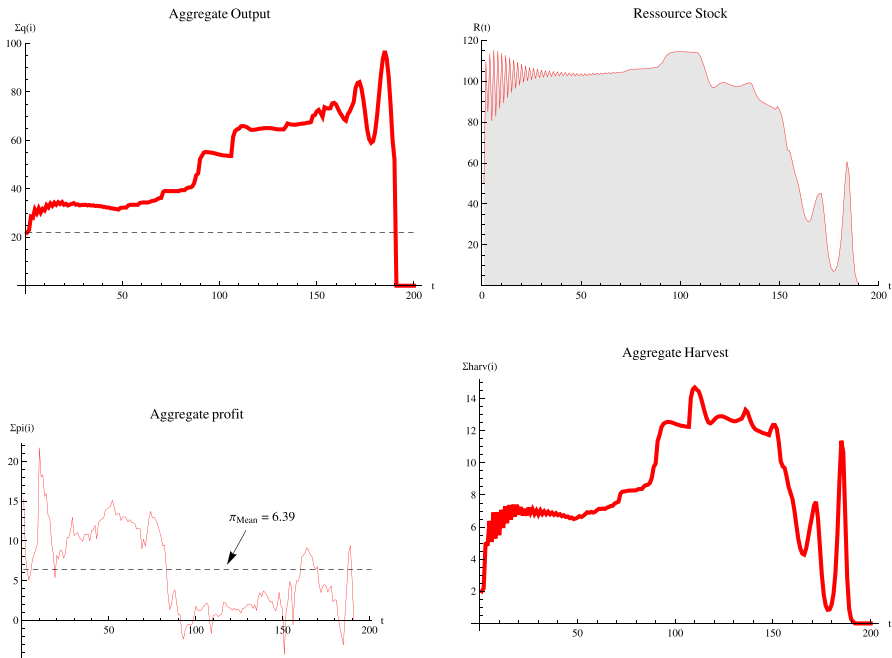
**Fig. 7** Aggregate Output, Resource Stock, aggregate harvest, aggregate profits and profit mean over time for harvest tax

resource. Thus, although the harvest tax increases resource efficiency per unit, the expansion of production allowed thereby ultimately lets the system crash. Concerning the economic sustainability dimension, apart from the final breakdown, there are periods where the non-loss criterion for aggregate profit is violated and average aggregate profit of 6.39 is slightly lower compared to the unregulated case (6.72). Moreover, the standard deviation of aggregate profit ($\pi_\sigma = 5.23$) is higher in the case of a harvest tax compared to the unregulated case (5.02), which indicates a higher volatility of aggregate profits with all the negative effects explained above, i.e. adaptation requirement and uncertainty (cf. Table 4).

## 5.4 Regulation by a resource plus emission tax

As the system could not yet be stabilised, we assume that a regulator would look for additional influences of the economy on the natural system that need to be ruled. As defined in Sect. 4.1, every unit of output generates a certain amount of emissions which negatively affect the resource. Thus, an additional tax on emissions will be implemented in the given model as a next step for assessing policy effects. The tax puts a charge on emissions and is thus an additional cost factor influencing the firms' profits. We assume that this additional factor will incite firms to allocate their R&D expenses to the search for low emission technologies.

**Table 4** Sustainability criteria for harvest tax

| Criterion | Fulfilled in time interval / value |
|---|---|
| Ecological dimension | |
| $R_t > 0$ | $t = [0, 190]$ |
| Social dimension | |
| $Q_t \geq Q_0$ | $t = [0, 190]$ |
| Economic dimension | |
| $\pi_t \geq 0$ | $t = [0, 91], [99, 107], [110, 150], [152, 155], [157, 182], [186, 190]$ |
| $\pi_{mean}$ | $= 6.39$ |
| $\pi_\sigma$ | $= 5.23$ |

Figure 8 shows the effect of an emission tax. The additional costs are significant and force firms to spend most of their R&D expenditures on the search for emission reducing technologies with the effect of a considerable reduction of emissions whilst output is further increasing. This decoupling allows for a faster growth of production which, however, destabilizes the resource even faster than before and leads to an earlier breakdown. Also, together with an erratic resource price we observe great fluctuations of aggregate profits ($\pi_\sigma = 4.01$). Thus, the additional emission tax helps to reduce emissions but leads to an even earlier collapse of the coupled systems.
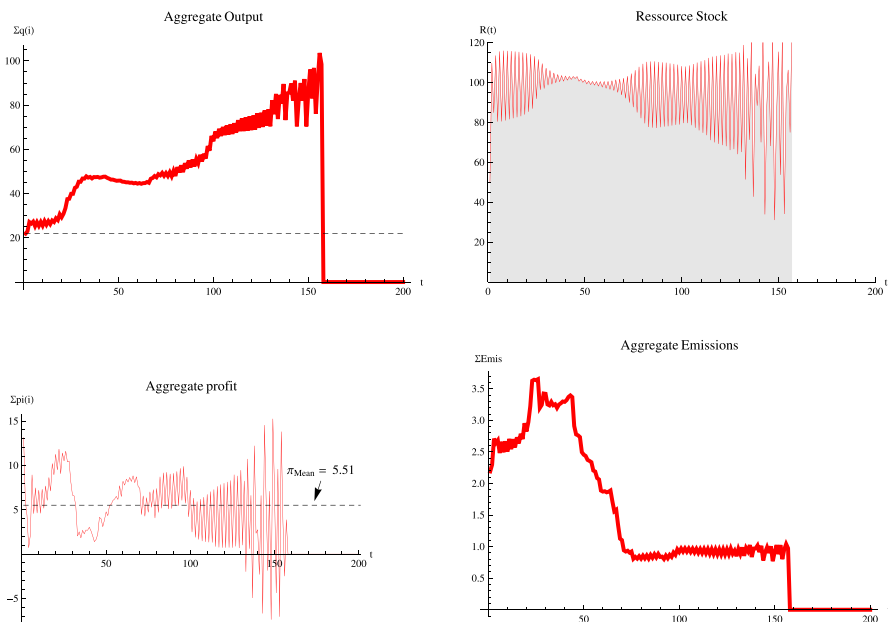


**Fig. 8** Aggregate Output, resource stock, aggregate emissions, aggregate profits and profit mean over time for emission tax

**Table 5** Sustainability criteria for harvest combined with emission tax

| Criterion | Fulfilled in time intervall / value |
|---|---|
| Ecological dimension | |
| $R_t > 0$ | $t = [0, 157]$ |
| Social dimension | |
| $Q_t \geq Q_0$ | $t = [0, 157]$ |
| Economic dimension | |
| $\pi_t \geq 0$ | $t = [0, 132], [134, 136], [138, 140], [142], [144, 145], [147], [149, 150], [152], [154, 155], [157]$ |
| $\pi_{Mean}$ | $= 5.51$ |
| $\pi_\sigma$ | $= 4.01$ |

According to our sustainability criteria, the combination of harvest tax and emission tax is thus worse than the single tax case in terms of the ecological and economic sustainability dimension (cf. Table 5).

## 5.5 Regulation by resource and emission tax plus tax on overshooting influences

The reasons for the regime shift of the ecological system from a cyclical to a chaotic regime in the previous simulation are overshooting influences on the resource provoked by increasing economic activity. Such influences are least in the focus of environmental policy because parts of them, such as fertilizers or pest control,
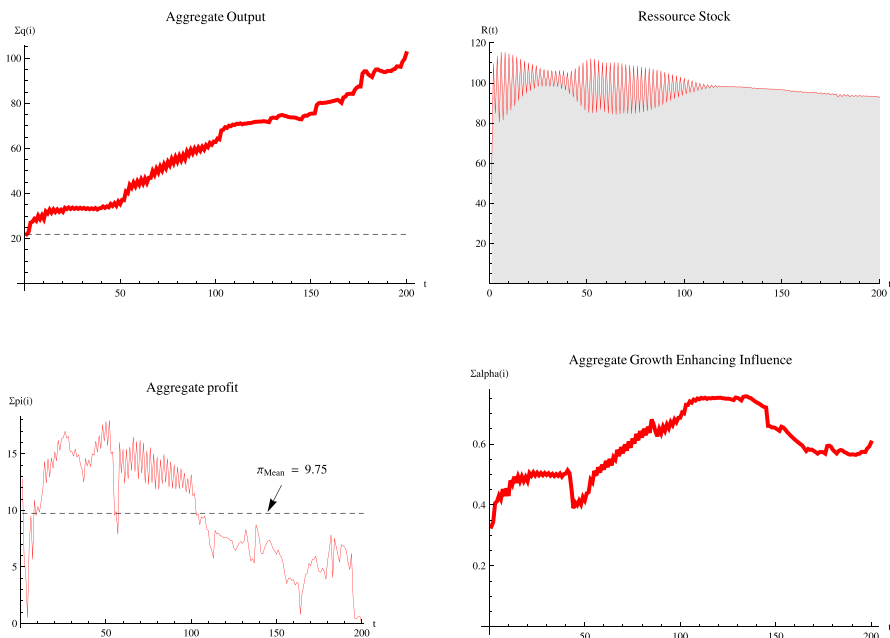


**Fig. 9** Aggregate output, resource stock, aggregate overshooting influences, aggregate profits and profit mean for tax on overshooting influences

**Table 6** Sustainability criteria for harvest tax combined with emission tax and tax on overshooting influences

| Criterion | Fulfilled in time intervall / value |
|---|---|
| Ecological dimension | |
| $R_t > 0$ | $t = [0, 200]$ |
| Social dimension | |
| $Q_t \geq Q_0$ | $t = [0, 200]$ |
| Economic dimension | |
| $\pi_t \geq 0$ | $t = [0, 199]$ |
| $\pi_{Mean}$ | $= 9.75$ |
| $\pi_\sigma$ | $= 4.53$ |

are promoted by farmers as favourable for the resources´ growth. This 'overheating effect' is still not controlled in our model and can destabilize the resource dynamics. Thus, a tax on such activities is implemented next. It works analogously to the former taxes and is again an additional cost for the firms. Figure 9 shows that this final tax is able to limit overshooting influences to an ecologically compatible level: the resource finally enters a cyclical regime followed by a stable period lasting longer than the period of observation (200 time-steps) as a longer run over 350 time-steps revealed (not depicted here).

In the present case of combined instruments, sustainability in all three dimensions can be realized (see Table 6). Moreover, average aggregate profit is higher ($\pi_{Mean} = 9.75$) compared to previous runs which compensates the higher volatility compared to the previous run ($\pi_\sigma = 4.53$).

## 5.6 Sensitivity analysis for regulation by single measures

The analysis of the above runs suggests the conclusion that there is a complementary regulatory effect of the considered taxes and that all three are needed to stabilize the system. The challenge now seems to be finding a valid calibration of the instruments. Therefore, we first look at the effect of parameter variations for all three taxes if they are employed as single instruments. Figure 10 shows the results of the tax variations in terms of aggregate output, resource stock and aggregate profits.[13] The red areas indicate a violation of our defined sustainability criteria, i.e. $R_t > 0, Q_t \geq Q_0, \pi_t \geq 0$.

Obviously, for single tax cases only a harvest tax of at least 2 is able to ensure sustainability in the ecological dimension while high levels of resource stock can only be maintained for taxes above 4 (cf. Figure 10). However, increasing levels of this tax negatively affect the amount of output and provoke repeated periods of negative aggregate profits. Additionally, most R&D effort is allocated to more resource efficiency. This money is lacking for production increasing innovations which is the reason why output declines. Alternatively, emission tax and tax on overshooting

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[13] For comparison, the variations have been normalized to a scale from 0 (no tax) to 10 (high tax) for all three taxes.
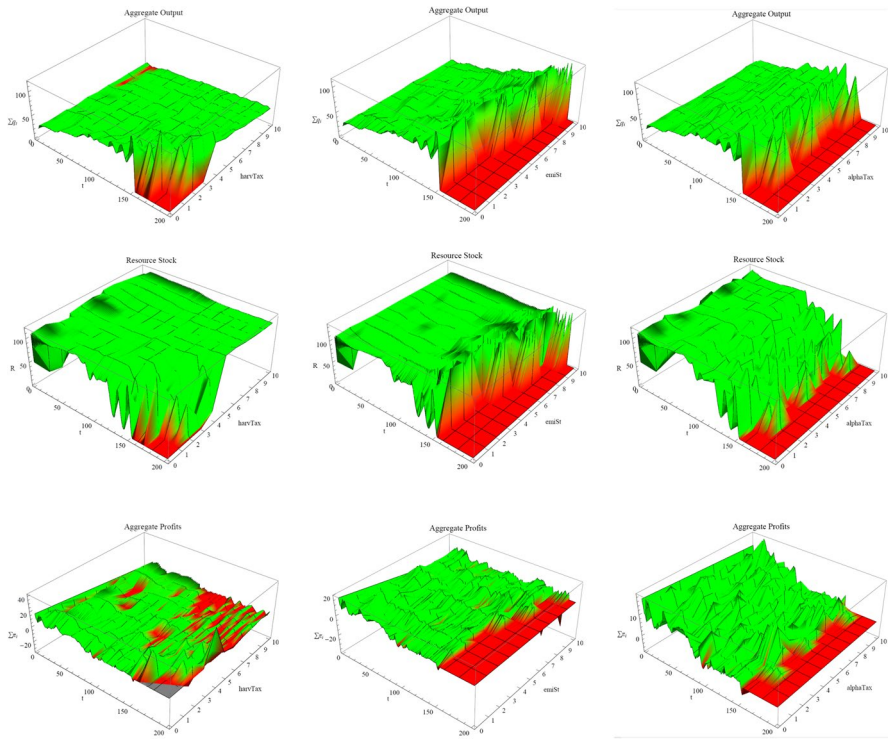
**Fig. 10** Aggregate output, resource stock and aggregate profit for parameter variations of harvest tax (left), emission tax (middle), and tax on overshooting influences (right) respectively

influences open the possibility for output growth, even for higher levels of the taxes. However, both taxes are not sufficient to prevent a breakdown of the resource system and thus the economy as the growing economy overexploits the resource. Moreover, firms are able to expand production, but an economically sustainable path is not achieved continuously, i.e. during some periods aggregate profit is negative. This illustrates why a sustainability policy is hard to optimize without considering the multi-criteria context.

## 5.7 Designing an instrument mix for sustainability

According to Fig. 10, neither an emission tax nor a tax on overshooting influences have a strong influence on the output. Instead, the system is rather sensitive to variations of the harvest tax. Therefore, we now compare aggregate output, resource stock and aggregate profits for a stepwise variation of the harvest tax while keeping taxes on emissions and overshooting influences on a low level. Based on a sensitivity analysis of the policy mix we set emisTax = 1 and alphaTax = 1.

As Fig. 11 suggests, all analysed harvest taxes between 0 and 10 now ensure sustainability in the ecological dimension and the tax on overshooting influences

helps to keep the resource system away from entering a chaotic regime. However, sustainability in the economic and social dimensions is achieved only for harvTax = {0, 1}. Additionally, average profits ($\pi_{Mean}$) show a downward trend with the implementation of a harvest tax after a positive peak at harvTax = {1}. Fluctuation of aggregate profits ($\pi_{\sigma}$) is increasing with higher values for harvTax with a jump between harvTax = {5} and {6}. Taking also the two supplement indicators mean profit and fluctuation of aggregate profit into account, a harvest tax of 0 or 1 turns out to be best.

Concluding, the most obvious political instrument in face of an overexploited resource has surprisingly to be handled with care in a policy mix for sustainable development in our model world. If it is implemented, it should only be on a very low level, i.e. harvTax = 1. Although it is the only instrument able to guarantee the survival of the ecological resource when employed as a single instrument, it can be a disturbing element in a policy mix, especially for the higher tax levels needed as a single instrument. Furthermore, the level allowing sustainable development of the system in a policy mix (harvTax = {0, 1}) leads to a breakdown of the system in the single tax case (cf. Figure 10, left). Thus, in case of a sequential implementation of different policy instruments, beginning with a high level of harvest tax to avoid overexploitation of the resource, the consequences are unfavourable if the instrument is later combined with the other taxes.

Let us again emphasize that the policy adjustment was just a test case for the integrated modelling we propose. We do thus not conclude that instruments addressing extraction would always be superfluous. What the model and somewhat surprising result of the policy analysis illustrates, however, is why a thorough analysis of the complexity
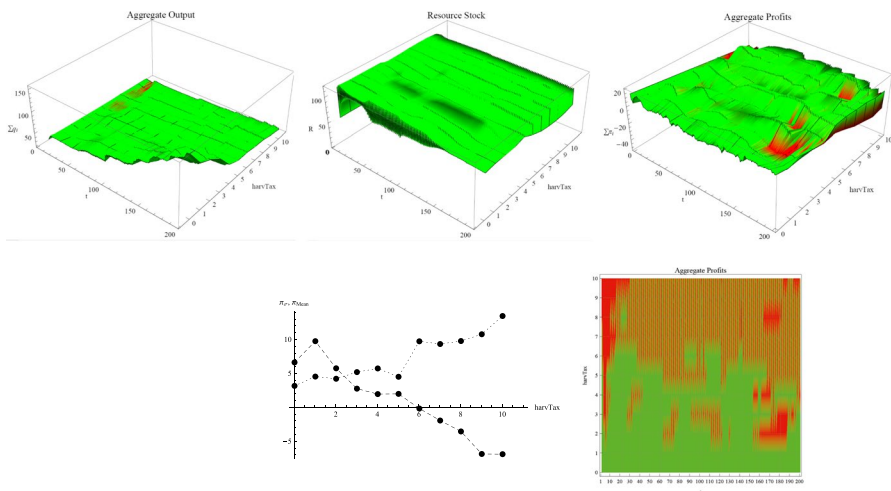


**Fig. 11** Aggregate output, resource stock, aggregate profits, profit mean (dashed) and standard deviation of aggregate profit (dotted) for different values of harvest tax but fixed emission tax (1) and fixed tax on overshooting influences (1)

of ecological-economic systems can lead to more insights than standard optimisation models.

## 6 Conclusions

The evolutionary ecological-economic model proposed in this paper accounts to a high degree for the complexity of the ecological as well as the economic system distinguishing it from standard environmental or resource economic models by (1) implementing a multi-dimensional link between the economic and the ecological system, considering side effects of production, (2) using a discrete time approach for the biological resource allowing for the whole range of stability regimes instead of artificially stabilizing the system, and (3) linking this resource system to an evolving, agent-based economy (on the basis of a Nelson-Winter model) instead of the standard optimization model. The model was used to analyze if and how sustainability of the evolutionary ecological-economic system can be ensured through innovation activities of firms incentivized by a set of sustainability policies. As the model represents a highly stylized economy and ecology, sustainability criteria had to be defined in a stylized way as well, i.e. avoiding extinction of the resource for the ecological dimension, positive aggregate profits for the economic dimension, and economic growth for the social dimension.

We created a link between both systems in which market forces alone are insufficient to avoid overexploitation and extinction of the resource. Regulation is thus required. We then used the test case of subsequentially introduced policies addressing the main influences of the economy on the natural system to illustrate the non-triviality of finding the right policy mix. As our model focuses on innovation activities we implemented taxes directed at the potentially harmful influences on the resource depicted by our model, i.e. harvest, emissions, and overshooting influences. These taxes affect the firms' cost structure and are supposed to stear firms' innovation activities in the respective directions in order to find better and more efficient technologies, i.e. less harvest, fewer emissions, less overshooting influences.

At first glance, the results suggested that only a combination of all three instruments is able to ensure sustainable development of the ecological-economic system. However, a sensitivity analysis of the policy mix' instruments showed that the system can only be sustainable in all three dimensions if the most obvious tax (i.e. harvest tax) is introduced on a very low level or even absent. This result was surprising as both, tax on emissions and tax on overshooting influences, lead to a breakdown of the system in the single tax case. While this result does not claim to represent an empirical case – we do not conclude that limitations of resource exploitation cannot be a valid solution to ensure the system's survival in any case – they illustrate the point we want to make. A thorough understanding of the dynamics of such coupled systems as well as an adequate policy analysis is only possible on the basis of an integrated evolutionary ecological-economic model.[14]

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[14]  As an example for a more in depth modelling of a specific case using similar methods cf. Beckenbach et al. (2017).

Two main conclusions can be drawn: (1) Environmental policies require an adaptation of firms. In competitive, evolving markets, firms are continuously innovating in order to gain advantage over each other. R&D expenditures have thus to be allocated between different kinds of innovations. (2) The mixture and calibration of instruments addressing the multiple links between the economy and the ecological system can only be analyzed if all influences are examined within the same, integrated model.

The policy case illustrates the relevance of the proposed integrated assessment as it delivers surprising results on the effects of combined and consecutively introduced policies that would go unnoticed in standard models. Understanding the co-evolutionary dynamics between policies, R&D development and their effects on the ecosystem thus requires evolutionary modelling.

We see the proposed evolutionary ecological-economic model as an important approach to enhance the discussion and analysis on whether and how an evolving economy can be guided towards a more sustainable development. The model allows for the analysis of the effect of different calibrations, various combinations and different implementation sequences of policy instruments.

We are convinced that evolutionary ecological-economic modelling is a valuable step to start a more thorough discussion about the need for an analysis of side effects and combined effects of policy instruments for sustainability that become only visible if more of the complexity of the ecological as well as the economic system and their multiple links are considered. In future research, this approach should be improved (1) by an endogenously determined demand, (2) by explicitly modelling the market dynamics without assuming market clearing and (3) by an empirical validation.

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

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