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How economics can help mitigate climate change - a critical review and conceptual analysis of economic paradigms

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Abstract
In economic research about climate change mitigation, there is a tension between the objectives to ensure scientific rigor (focusing on orthodox theory) and to illuminate blind spots of relevance (drawing on different "heterodox" theories). Our aim is to develop an economic perspective on climate change mitigation which considers both objectives.

We conduct a critical literature review, searching for coherent economic theory lattices, which meet the requirements of research programs, i.e. contain a pre-analytic vision, an analytical core including a concept of rationality, and examples of applications in empirical research. We develop a framework structuring these research programs and associated research fields and search for examples illustrating their applicability to climate change mitigation.

We identify several research fields within four major research programs that perceive economic phenomena as (1) individual optimization decisions (neoclassical analysis of efficient and of inefficient equilibria and behavioral economics); (2) a set of institutions (New and Original institutional economics); (3) a complex evolutionary system (Biophysical and Evolutionary economics); and (4) an objective function (which can guide research focusing on the content or the distribution of the normatively defined units of interest). For each research program and its subdivisions, we present theoretical

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elements and illustrate how they can improve our understanding of how economic activity contributes to climate change and how these impacts can be alleviated.

There is a need for more systematic evidence synthesis to validate the contributions of the different economic research fields and to improve their selection and application to climate change.

Keywords

Climate change; neoclassical economics; behavioral economics; economic heterodoxies; evolutionary economics; institutional economics; objective functions; research programs; policy implications.

JEL Classifications
A11, A12, B5, H41, Q54.

1. Introduction: Economic analysis and climate change

Accounting for the increasingly obvious planetary boundaries (Rockstrom, Steffen et al. 2009), e.g. by mitigating climate change, is a core challenge of the 21st century (Lenton, Rockstrom et al. 2019). Anthropogenic climate change is a phenomenon which is largely associated with human economic activity (Wiedmann, Lenzen et al. 2020). Therefore, how to mitigate climate change also is an economic problem.

However, for many observers it is unclear, whether the discipline of economics addresses this problem adequately. Some would even consider mainstream, "orthodox" theory and teaching of economics a contributor to the problem rather than a societal resource of tackling it. It has been associated with various limitations like a bias towards material growth, ignoring the boundaries of the ecological system within which the economy is embedded; with a bias towards favoring more de-regulated "market" solutions and believing in "market equilibration" in situations where real-world markets in fact fail; a mindset favoring individual utility and business profitability in problems where collective action towards global common goods is needed; or a biased focus on (potential) Pareto efficiency which implies ignoring the pestering questions of equity in a context of increasing economic inequality (see e.g. Blaug 2002; Brodbeck 2009; Hill and Myatt 2010; Coscieme, Sutton et al. 2019).

On the other side, there is plenty of dissenting, "heterodox" economic theories, which promise some cure to that problem (Jo, D'Ippoliti et al. 2018), but which are constantly ignored by the economic and political mainstream, implying that these approaches are not considered relevant and allegedly characterized by methodological handicaps (Backhouse 1998, p. 134ff.; Graebner and Strunk 2020). Following heterodox critics, this is determined by the scientific community politics of the majority of orthodox economists (Grimm, Pühringer et al. 2018).

The aim of this paper is to contribute to the scientific discourse about economic perspectives on how to mitigate climate change by identifying economic research programs, which respond, first, to the heterodox call for dealing with the blind spots of mainstream theory; and, second, to the orthodox concern of scientific rigor.

To do so, we follow the method of a critical review (Grant and Booth 2009). We search the economic literature for fully developed economic research programs (Lakatos 1978), understood as "theory lattices" (Schurz 2014, p. 354) for which (1) an analytic core (Schurz 2014, p. 355); (2) pre-analytic visions of the central features of economic phenomena which are represented in this analytic core (Schumpeter 1954, p. 38f.); (3) a concept of rationality (Hahn 2017, p. 324); (4) examples of empirical methods used to test statements based on this theory; and (5) examples of applications to economic problems could be identified. We synthesize our results narratively, distinguishing major

research programs, and complementary fields of research in terms of theory sub-lattices within these research programs. For each field of research, we assess, based on sample applications, how the knowledge it generates can help understanding how to mitigate climate change.

Further detail on these concepts is provided in the next section against some epistemological background. In the following four sections, we present the four major research programs and nine fields of research that we identify. They are displayed in Fig 1. Bold letters indicate the fields of research which best describe the analytic core of the research program. For each field of research, we provide some information on items (1) to (5) above and exemplify which insights can be provided for climate change mitigation (see Table 1 for a summary). In the discussion section, we interpret our results and discuss remaining limitations of this study. We conclude that a broad economic perspective of complementary research programs is best suited to help understanding climate change and its mitigation. However, there is a need for more structured evidence synthesis to validate and compare the contributions of the different research fields.

2. Epistemological considerations

Assessing possible contributions and limitations of economics as a scientific discipline involves epistemological (i.e. theory of science) issues, which are briefly addressed in the following.

The discipline of “Economics” can be defined differently. Most economics textbooks are consistent with the idea that “the economic” is a specific form of human wanting and acting related to the problem of handling scarcity (Trautnitz 2008, p. 246ff.) and follow some form of Lionel Robbins’ definition of economics as “a science which studies human behavior as a relationship between ends and scarce means which have alternative uses” (Robbins 1932). Also other definitions have been proposed like the definition as a social science that studies the production, distribution, and consumption of goods and services (e.g. Krugman and Wells 2009: 9), the social provisioning process (Cumbers, Davis et al. 2015), or the generation of wealth (Blaug 1999). For compatibility with the economic literature and to facilitate distinction from other scientific disciplines like psychology or sociology we follow a definition of economics as a science which analyzes the rational allocation of scarce resources. Facing planetary boundaries, this problem also appears to gain rather than to lose importance. However, this definition requires further specification of the rationality criterion.

Following Hahn (Hahn 2017, p. 324), six forms of purpose- or rule based rationality need to be distinguished. These include the following:

1) Purpose-based rationality

a) Acting in a *subjective instrumentally rational* manner involves acting to pursue an aim individually deemed suited to achieve a goal. This weakest form of rationality includes acts such as, e.g., avoiding unfamiliar food on a Friday, the 13th, to prevent obesity (Hahn 2017, p. 324ff.).
b) Acting in a *validated instrumentally rational* manner involves pursuing an aim which is rational, i.e. consistent with other aims of the acting person. This involves, for example, avoiding to eat a third hamburger to prevent abdominal fullness in a person who pursues a healthy life style (Hahn 2017, p. 353ff.).
c) Acting in a *robust instrumentally rational* manner involves pursuing stable aims which are held beyond a specific situation. As an example, consider avoiding meat consumption to reduce one's own impact on climate change (Hahn 2017, p. 356ff.).

2) Rule-based rationality
a) Acting in an *individually rule-rational* manner involves following individually set rules to pursue middle-or long-term goals. This includes rewarding oneself with buying an ice cream for every 500km gone by bike to motivate oneself to substitute personal car by bike travel (Hahn 2017, p. 361ff.).
b) Acting in a *superindividually rule-rational* manner involves following a rule set by an entity which reaches beyond the acting individual (for pursuing a goal adopted by the acting individual). This includes following a tempo limit in a residential area set up to reduce noise and particulate matter emission by an individual who shares these aims (Hahn 2017, p. 364ff.).
c) Acting in a *rule of thumb-rational* manner involves following a different kind of rules which connect types of situations with types of actions which have been (or have appeared) successful in similar situations in the past. This includes satisficing behavior (Simon 1955; Gigerenzer and Selten 2002), rather than optimizing, in decisions dealing with complex situations with limited information available or limited information processing capacity of individual agents (Simon 1955; Hahn 2017, p. 367).

For 1b)-2c), subjective and objective types of rationality can be further distinguished. The objective types involve that there is empirical evidence that the action is suited to pursue the given goal while in the subjective type, the agent is only subjectively convinced that this is the case (Hahn 2017, p. 356). An act can be rational in one concept of rationality and irrational in another simultaneously. Understanding "economics" as science analyzing rational allocation of scarce resources thus requires specifying the concept of rationality it draws upon and does not involve limiting the analysis to individual subjective rationality (short-run optimizing) as in the neoclassical standard (textbook) case.

Given that economics refers to empirical data about economic activity, it could be classified as empirical science (Schurz 2014, p. 70). Following Schurz' proposal for a unified theory of science, the aim of an (empirical) science is "to find true and content-rich statements, laws, or theories relating to a given domain of phenomena" (Schurz 2014, p. 50). Scientific theories and resulting statements should be formulated in a way

that can be falsified and conflicts between different theoretical views should be resolved by empirical testing rather than science politics (Popper 1994).

However, given the complexities of continuing purposeful human interactions among many and heterogeneous agents, economic theory is less rigid and compelling than its natural science counterparts so that it is less susceptible to falsification (Kuhn 1962; Coats 1969; Harding 1976; Elsner 1986). Economics addresses heterogeneous and complex phenomena and there is more than one set of theories which have been developed in parallel (Blaug 2006). And as these theory systems can be partly substituting and partly complementary (Schurz 2014, p. 285f.), it is unlikely that "the one" correct economic theory can be identified and selected. Therefore, an alternative standard for selecting theories could be that the set of theories has reached a sufficient stage of elaboration.

Scientific research proceeds by generating systems of causal statements which display globality and unification power. This means that quite different phenomena can be explained by the same theoretical set of presumptions and mechanisms (Schurz 2014, p. 260). Well-developed theory systems are organized in the form of hierarchical theory lattices. They include some general core laws at the top, which then get enriched by more specific laws for specific applications (Schurz 2014, p. 259). In the following, we refer to them under Lakatos' term "research program" (Lakatos 1978). They may contain complementary fields of research, i.e. sub-sets of theories which address specific aspects within a research program.

Given that various types of quantitative data on economic activity are collected and used and that the standard textbook uses relatively many algebraic models and equations, economics is frequently considered a quantitative social science. On the one hand, the core of a research program within a quantitative science should consist of analytical axioms. On the other hand, following Schumpeter, its development is necessarily preceded by the pre-analytic cognitive act "to visualize a distinct set of coherent phenomena as a worthwhile object of our analytic efforts", a qualitative description which he calls "pre-analytic vision" (Schumpeter 1954, p. 38f.). We thus focus on fully developed economic research programs which contain hierarchical theory lattices with both an analytic core and a pre-analytic vision.

Besides generic theoretical statements at a theoretical core and more specific statements at the periphery of a theory lattice, research programs require empirical methods which are applied to testing the phenomena explained or predicted by a theory. As a complement to defining elements of economic theory, we therefore search for empirical methods and their applications. Given the topic of this study, mitigation of climate change, we search for applications which provide examples of how the research program and its fields of research can provide insights into this topic (see also Figure 1).

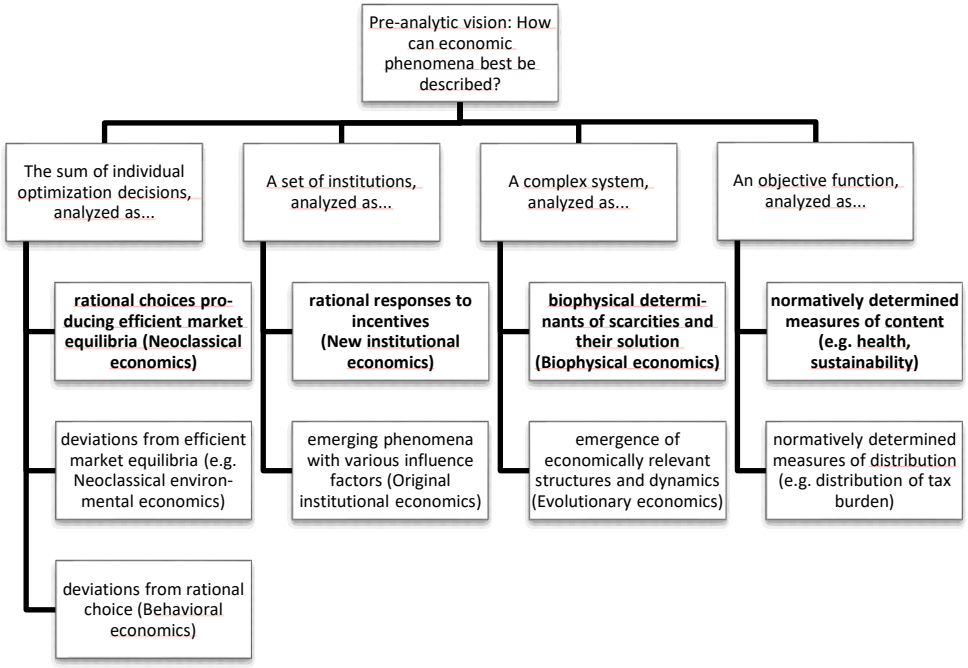

Figure 1: Overview of the major economic research programs

3. The Economy as a result of individual optimization decisions

Traditionally, economics analyzes rational allocation of scarce resources in terms of individuals who pursue individual objectives in a rational manner. “The economy” is seen as the sum of these optimization decisions. The core within this research program centers around the idea that the aggregate of individual choices lead to socially optimal market equilibria (Walras 1874; Arrow and Debreu 1954). However, it also includes a research field that analyzes systematic deviations from societal optima on an aggregate level. Furthermore, an additional field of research challenges some of the ambitious assumptions about the rationality of these decisions (but stays within its individualist approach).

a) Neoclassical economics analyzing efficient market equilibria

The analytic core of neoclassical microeconomics consists of equilibrium models which are largely borrowed from thermodynamic equilibrium models in physics (Aßländer 2011, p. 43ff.). They describe both the output of producing a good as well as the benefit from consuming it as functions with decreasing marginal productivity and benefit, respectively. They represent the idea that the price of an input factor or good expresses information on relevant relative scarcities. Lead by an invisible hand (Smith 1776, Ch.

2), price-establishing markets tend to move towards an equilibrium of market clearance which leads to maximization of overall welfare (Breyer 2015).

The default model of consumers' utility and producers' profit maximization leading to market equilibria can be (mis)understood as a blueprint of purely market-based economic policy and a justification for companies to ignore all concerns which go beyond short-term profit maximization and has heavily been criticized by advocates of more sustainable economic practices (see e.g. Hill and Myatt 2010; Coscieme, Sutton et al. 2019). However, neoclassical microeconomic theory can also be seen as a tool which can assist sustainability initiatives.

This is because it provides a structured framework to analyze how the success of sustainable product is determined in a competitive environment. Environmental issues can, first, be analyzed as costs of production inputs to be minimized. From a neoclassical logistics perspective, the production of a good can be described as the difference of customer value creation less the sum of all material and labor inputs. Proper logistics involves tracking resource flows, first in physical units, and second in terms of costs which can then be compared to the prices that can be realized for the (intermediate) products. The principal of lean management requires avoiding waste – i.e. optimizing this production process by systematically detecting and minimizing any unnecessary over-production, defective goods, transports, or processing steps (Balsliemke 2015). This can decrease both factor costs and environmental impact.

Second, sustainability can be analyzed as a dimension of benefit for consumers and source of product innovation. Neoclassical economic theory provides a theoretical basis for developing methods for analyzing consumers' willingness to pay. As an example, discrete-choice experiments (Hensher, Rose et al. 2015) can be used to estimate which price markup consumers are willing to pay for products which are characterized by a lower carbon footprint or which satisfy certain other dimensions of sustainability to a higher extent, e.g. in the field of greener transport (Ozaki and Sevastyanova 2011; Costa, Montemurro et al. 2019).

b) Environmental economics analyzing deviations from efficient market equilibria

A price-based mechanism can only lead to an efficient allocation of scarce resources if the relative prices correspond with relative scarcities. However, it is established for more than a century that this is not the case for many environmental goods like the atmosphere's absorptive capacity for greenhouse gases – emitting carbon dioxide incurs costs which are external to companies' profit calculations (Pigou 1920). Markets only induce efficient resource allocation if conditions hold such as that customers are fully informed about product characteristics and products are of

homogenous quality; market entry is free; there are no price-distorting taxes and subsidies; and there are no external costs and benefits (Sturm and Vogt 2018).

However, consumers may be not fully informed about the environmental damage caused by the products they acquire (Kapp 1978); seemingly homogeneous products may differ substantially regarding unobservable ecological characteristics (Witt 2017); or incumbent players may lobby against free market entry to prevent competition like in the case of energy corporations preventing citizens' initiatives to prosume carbon-neutral electricity (Horstink, Wittmayer et al. 2020). Finally, a core problem is that the prices which currently guide market behavior are misleading – first, because they do not account for the external costs of carbon emissions. And, second, because rather than taxing the over-use of natural resources which are not priced, existing tax system frequently do the contrary: for example, in Germany, about 64% of tax payments are born by labor, and only 4% by natural resources (Mahler, Runkel et al. 2017) which is unlikely to be efficient given the current ecological crisis.

Even if the neoclassical theory is a theory of market interaction, analyzing the economy as a result of individual optimization decisions does not necessarily imply a call for laisser-faire economic policies. Instead, this research program also contains a field of research which analyzes how rational individual optimization decision may lead to inefficient market equilibria and how market failures can be overcome by more (or different), rather than less regulation. For example, like mandatory information on calories, fat and sugar on food products, also information on climate and other environmental impact may be necessary (Kapp 1965), or environmental standards may be needed to achieve homogenous product quality. Furthermore, external costs may be internalized by ecological taxes (Pigou 1920) or certificates (Coase 1960; Crocker 1966; Dales 1986). Neoclassical theory then provides an established framework to compare the strengths and weaknesses of the different instruments.

c) Behavioral economics analyzing "irrational" decisions

Besides undistorted prices, perfect competition leading to efficient market equilibria also requires rational behavior. However, both consumers and producers have been identified to deviate substantially from neoclassical assumptions. Analyzing systematic biases in perception, cognition and behavior of choosing in the face of scarcity is the remit of behavioral economics.

Behavioral economics was strongly influenced by individuals like Kahnemann and Tversky (Kahneman and Tversky 1979) and their distinction between positive and normative (Heukelom 2014, p. 170f.): As a positive theory, it diagnoses behavioral anomalies (Thaler 2015) / deviation from norm of homo oeconomicus following neoclassical theory of games and economic behavior (Von Neumann and Morgenstern

1944). As a normative theory, it develops remedies, e.g. nudging (Thaler and Sunstein 2012) or different cognitive modes of decision making like satisficing (Gigerenzer, Todd et al. 1999). The behavioral economics perspective thus modifies the economic perspective on rationality: validated instrumentally rational choice requires evidence that choices indeed correspond with preferences (Hahn 2017, p. 324), and rule of the thumb rationality involves using cognitively less demanding approaches to decision making (see: Hahn 2017, p. 367 and Appendix 1).

Also this perspective can provide valuable insights into the questions of, first, which are the sources of irrational choices regarding climate change mitigation; and, second, how individual rational choice can be supported to appropriately handle abstract problems of sustainability like those arising in climate change mitigation. There are various factors which mediate sustainability behaviors (Stankuniene, Streimikiene et al. 2020) as well as various types of interventions available to encourage pro-environmental behaviors which are not always equally effective in different contexts (Grilli and Curtis 2021). For example, comparing different nudges (priming, mental accounting, framing, decoy, social norms, or default) in terms of their effectiveness in promoting the choice of renewable energy in one original survey experiment, only a default nudge had an effect and increased the share of individuals who chose renewable energy by 45% (Momsen and Stoerk 2014).

4. The Economy as a set of institutions

Next to the atomistic analysis of the economy as a sum of individualistic choices, there is a research program which centers on direct interdependencies and resulting interactions of many individual agents which is guided by institutions (Milgrom and Roberts 1992). Institutions can be defined as “humanly devised constraints that structure political, economic and social interactions” (North 1991) which enable individuals to solve collective problems and social dilemmas (Axelrod 1984; Erlei, Leschke et al. 2016). However, in a circular way, human interactions and prior institutions also determine the emergence of new institutions (Schotter 1981; Schotter 2008).

The research program therefore contains, first, the research field of New institutional economics (NIE), which evolved from works of economists like R. Coase (Coase 1937) and O. Williamson (Williamson 1975) and centers around the assumption of individual rational choice. Second, it contains a research field, which analyzes the historical emergence and ongoing evolutionary change and adaption of social institutions without this assumption and which is termed “Original institutional economics” (OIE). Like in the origins of institutional thought, it is frequently inspired by methods and concepts of other disciplines like psychology, anthropology, sociology, history, or biology (Elsner 1986; Elsner 2018).

a) New institutional economics analyzing rational choice of rules

Institution economics draws upon the insight that in economics, success evolves from cooperation rather than atomistic choices – and that this can be analyzed without abandoning the assumption of individual rational choice. The prisoner's dilemma, a game theoretic concept formalized by Albert Tucker in 1950 (Poundstone 1992, p. 18) provides an analytic representation of this insight: individuals willing to cooperate get caught in unintended self-damage as a consequence of their intentional behavior. And they can overcome this situation if they implement a mutually binding rule which changes the pay-offs of the strategies available to them. In this research program, economics analyses rules which guide self-interested rational behavior (Tullock 1985; Buchanan 1987; Buchanan, Tullock et al. 1999; Homann and Suchanek 2005), addressing the question of how institutions need to be shaped to facilitate successful cooperation (Buchanan 1964; Homann and Suchanek 2005). Assessing rules on a societal level, NIE analysis can expand the concept of rationality in economics to superindividual rule-rationality: even if idiosyncratic real-world situations may always leave incentives for individuals to deviate from regulation, NIE still helps identifying rules which can in principle overcome incentive problems (Hahn 2017, p. 364ff.).

Analyzing questions of sustainability as un-intended self-damage arising from social dilemmas can be a fruitful approach to guide consensus-finding for revisions of regulatory frameworks (Rogowski and Lange 2020). Particularly in the case of external costs and tax systems which inhibit competing companies' choice of climate-friendly procurement and production, it can guide the search for new (self-binding) institutional arrangements which provide win-win situations, e.g. international treaties which enforce CO2 certificate trading (Pies 2002).

Besides the generic prisoner's dilemma concept, more specific theories of detrimental incentives and their effects have been developed. The three major ones are principal agent theory (Jensen and Meckling 1976) which can help, for example, overcoming problems of information and motivation in environmental reporting in the face of greenwashing (Yu, Luu et al. 2020); property rights theory (Demsetz 1967) which can assist developing efficient arrangements of ownership and control in dealing with shared resources like CO2 absorptive capacity (Salminah, Alviya et al. 2020); and transaction cost theory (Williamson 1981) which can enhance the diffusion and commercialization of low-carbon technologies (Mundaca, Mansoz et al. 2013).

b) Original institutional economics analyzing emergence and change of social institutions

Given that it seems so obvious that climate change mitigation is hampered by social dilemmas, it is puzzling why institutions to overcome these dilemmas have not yet

been identified and implemented. OIE is a 130 years old field of economic research (Rutherford 2011), which can help addressing this puzzle. OIE is oriented, e.g., towards the emergence, ongoing change and cumulative circular causation (Berger and Elsner 2007) of institutions in real, historical time, rather than static analysis of decision structures. It includes the influence of the social context, such as the interaction environment and existing social rules as norms, on preference construction (rather than preferences taken as exogenous), recurrent direct interactions between agents (rather than isolated individuals) under different potential motivation structures and a continuum of genes, "instincts", prosocial and antisocial cultural traits, habits, deliberations and preferences to determine individual decision and behavior (rather than just a self-oriented short-run maximization rationality). Systems of institutions are typically assumed to emerge at "meso"-sized arenas and to constitute carrier groups and networks of "meso"-size which are in between the level of individuals and "macro" (national or other) levels, which are conventionally addressed by economic analysis (Veblen 1898; Veblen 1899; Adkisson 2010; Elsner 2018).

Current research in OIE is closely linked to neo-institutionalism, a field also adopted by neighboring disciplines like sociology, anthropology, psychology, management or political science (e.g. Brodocz and Schaal 2016; Walgenbach, Meyer et al. 2019). It also shares similarities with social economics or socioeconomics, a research strategy which analyzes economic phenomena and their social embeddedness in a multidisciplinary manner (Davis and Dolfsma 2015). Rather than a single set of core axioms and presumed general laws, OIE is characterized by a breadth and pluralism of approaches and applied fields with some common threads, such as ongoing interaction, institutionalized behavior, and ongoing change (Hodgson, Samuels et al. 1994, pp. 375, 401).

Recent examples of research which assessed the emergence of climate friendly (or harmful) institutions include the work of Elinor Ostrom on common-pool resources, related interaction processes and factors that facilitate self-organization (namely the size of the relevant group with a minimum accountability of individual behavior, recognized interdependence and feedback, e.g. punishment for individualistic non-cooperative opportunistic maximizing behavior). Policy orientations then relate towards the set of critical factors of successful cooperation (Ostrom 1990; Ostrom 2009).

Such work on social-dilemma theory provides an empirically richer framework to analyze societal conflicts as well as richer policy orientations than a static rational-choice based interpretation of a prisoners' dilemma (Liebrand, Messick et al. 1992; Rogowski and Lange 2020). Ostrom's and other contemporary institutionalists' multi-facetted frameworks of assessing institutions and institutional change have successfully been applied, for example, to climate change adaption strategies, e.g. in the Baltic Sea (Van Well and Lange Scherbenske 2014). Reviewing the literature on institutional inertia, Rosenschold *et al.* identify costs, uncertainty, path dependency, power and legitimacy

as key impediments that prohibit regulatory innovation towards better climate change mitigation (af Rosenschold, Rozema et al. 2014).

5. The Economy as a complex, dynamic system

OIE stresses the interplay of multiple factors in the emergence of economic phenomena. Formalizing this thought leads to a research program which emanated from works like the General Systems Theory developed by the biologist Ludwig von Bertalanffy (Bertalanffy 1950) or Cybernetics developed by the mathematician Norbert Wiener (Wiener 1948). They inspired a scientific worldview dedicated to describing, explaining and shaping complex dynamic systems (Schwaninger 2020).

Rather than analyzing static objects like individual optimization decisions or given formal institutions, economics inspired by the complex-systems approach puts the systems' dynamic interplay of various factors at its center. In the following, we call this research program complexity economics and distinguish two research fields within this program, following the distinction between first and second order cybernetics (Von Foerster 1984). Following Sherwood *et al.*, we label the first biophysical economics (Sherwood, Carbajales-Dale et al. 2020). It takes a more natural-science oriented perspective and analyzes economic phenomena as an observed system of human activities within the biological or physical conditions that determine needs and wants or their satisfaction in the face of scarcity (see also: Kapp 1965; Luzzati 2009). The second takes a more social-science oriented perspective and analyses economic phenomena as an evolutionary change process emerging in a complex adaptive system. Corresponding with Dopfer's definition of evolutionary economics (Dopfer 2007), this research field accounts for the role of economic decision makers as part of the system and analyzes economic phenomena as emergence of economically relevant knowledge and habits.

a) Biophysical economics analyzing biological and physical determinants of scarcity

In the history of economic thought, biophysical considerations played an important role early on (see e.g. Cantillon 1756). Building upon this tradition, biophysical economics analyzes the rational allocation of scarce resources in terms of inputs and outputs of economic activity with relation to human needs and wants and the natural capacities of production and absorption (Henrich, Boyd et al. 2004; Sherwood, Carbajales-Dale et al. 2020). This perspective changes the concept of rationality from subjective to objectively validated instrumentally rational: it assesses whether economic activities meet longer-run objective criteria of rationality like those of sustainability. This involves that the extraction of renewable resources must not exceed their natural

capacity of regeneration; the extraction of non-renewable resources not the rate of substitution of non-renewable to renewable resources; and emissions not the natural capacity of absorption (Daly 1990).

A methodology which is well suited to analyze these conditions is system dynamics, which was initially developed by, e.g., Jay W. Forrester (Forrester 1961). It models systems as networks of stocks, flows, and positive or negative feedback loops. Mathematically, a system dynamics computer simulation model is a system of nonlinear, coupled, differential (or integral) equations (Richardson 2020). Even if biophysical economics can encompass a rich variety of methodologies (Sherwood, Carbajales-Dale et al. 2020), in our view, the mathematics of system dynamics is best suited to represent the axiomatic core of this research field. Given its high level of theoretical and empirical elaboration (Schwaninger 2020), and its application not only in the field of environment, energy and climate change (Ford 2020) and economics (Radzicki 2020), but also in various other fields, it could even be seen as a research program on its own.

The seminal application of this approach to analyze economic activity is the report on limits to growth (Meadows, Meadows et al. 1972). It was based on the system dynamic "world 3" model which has recently been updated to a "world 6" model to provide more detail on the flow of metals, other materials and fossil fuel (Sverdrup and Koca 2018). An example of a recent model assessing the impact of drivers like population growth, economic growth and energy production on climate change is provided by Fiddaman (Fiddaman 2002).

b) Evolutionary economics analyzing emergence of economically relevant knowledge and habits

Besides system dynamics, the systems approach includes other areas of multidisciplinary research dedicated to the analysis of complex adaptive evolving systems such as chaos theory, information theory and catastrophe theory (Schwaninger 2020). These have inspired an economic field of research which models the economic phenomena as dynamic, path dependent, evolutionary process (Nelson and Winter 1982). Viewing economic agents as constantly searching and learning to adapt to new situations, learning rules to coordinate agents in more simple coordination problems and institutions to make agents regularly cooperate in more intricate collective dilemma problems, become a central element of economic analysis. Like variation of genotypes in evolution biology, routines, rules and institutions (Nelson and Winter 1982) are varied by economic agents trying new things. Successful ways of solving allocation problems under fundamental uncertainty and bounded rationality may be retained and may, under favorable conditions, be learned by other agents. In contrast to the neoclassical view of individualistic short-run maximization and market equilibration, economic phenomena become a dynamic process of generating and applying adopted knowledge, which is

deeply interlinked by mutual perceptions and learning (Nelson, Dosi et al. 2018; Hodgson 2019). Important concepts include emergence, self-organization, path-dependence, non-ergodicity or lock-ins in favorable or unfavorable system attractors (Elsner 2017). Methodological approaches include analysis of large data sets of systems' dynamics (physical statistics) to identify critical factors and develop appropriate agent-based models (Dawid 2018), also to simulate decisions addressed to those factors. Rather than rational choice in terms of maximization, evolutionary approaches typically follow the concepts of bounded rationality in complex environments and, thus, only satisficing behavior (Simon 1955; Gigerenzer and Selten 2002), a form of rule-of the thumb rationality (Hahn 2017, p. 324).

A central theme in evolutionary economics has been innovation – studying the ways how new kinds of technologies, products, industries, markets and organizations come into existence. Beyond the forces of market supply and demand, multiple other determinants like political, social, and cultural aspects are assumed to interact in innovation systems and shape economic activity in a manner which is not fully predictable but which consists of elements and their interactions that can be modeled and influenced (Nelson, Dosi et al. 2018, cf. p. 24; Elsner 2020).

A methodology successfully used also to analyze complex systems with regard to the generation and diffusion of green technological and institutional innovation is, again, agent-based modeling and related complex computer simulation experiments (Muller, Bohn et al. 2013). For example, a large number of agent-based models has assessed various policy measures to reduce emissions, promote the diffusion of green innovations, or of energy saving behavior and provided insights on various aspects like potential effectiveness, limitations, or adverse side-effects of some climate mitigation policies (Castro, Drews et al. 2020).

6. The Economy as an objective function

Sometimes, in discussions about alternative economic policies, assumptions about the most influential elements or causalities differ; different proposals are consistent with one or more economic theories; or the effects and costs of alternative policies are unknown. In such cases, there is a need for economic analysis assessing how decision alternatives affect specific policy objectives, agnostic about underlying causalities.

Promoting evidence-based policy, economic analysis then involves representing the policy objectives by some objective function to facilitate prospective trials or retrospective evaluation of policies (Bowers and Testa 2019). Rather than individuals' subjective instrumentality which can easily be mislead in such political questions, the concept of rationality in this research program is oriented at robust aims (Hahn 2017, p. 356ff.), i.e. aims which are sufficiently stable to make the development of objective

functions for further empirical research worthwhile. Additionally, rather than subjective validation of means-ends-relationships, the economic analysis provides objective evidence on whether certain policies meet these objectives. For example, in health economics, a frequent question is how to make coverage decisions in a way to optimize health care delivery of the population covered by this payer (Drummond 2007).

A rich normative literature addresses questions of how different policy objectives can be theoretically reflected and specified as functions (Boadway and Bruce 1984; Sen 1999). Besides welfarist ethical theories which play a dominant role in economics, also extra-welfarist concepts of value may play a role (Brouwer, Culyer et al. 2008). And besides quantity of resources and outcomes, also their allocation and distribution can play an important role in economic analysis (Cowell 2011; Fleurbaey and Schokkaert 2012).

a) Analyzing the objective function's content

The most important outcome of interest to economic analysis is wealth, measured, for example, as gross national income in purchasing power parity to correct for price level differences (Krugman, Obstfeld et al. 2018). However, there are different alternative performance measures for (economic) policies.

These measures have been developed particularly well in health economics, operationalizing the concept of health and its generation by economic or health policies (Brazier, Ratcliffe et al. 2017). Also, they can involve more than one single attribute like the disability-adjusted life year which is a health measure used by the World Health Organization (Salomon, Vos et al. 2012). They can be used in other fields of economics, such as the Human Development Index (Dervis and Klugman 2011) in development economics. Decision analysis provides an established analytic framework to guide the theoretical development and empirical measurement of such objective functions (Von Winterfeldt, Miles et al. 2007; Parnell, Bresnick et al. 2013).

Indices for providing comparative evidence of how environmental goals are met by different economies are, for example, the Environmental Performance Index (Esty 2001), or the Ecological Footprint (Rees and Wackernagel 1994; Lin, Hanscom et al. 2018). Possible objective functions can cover large numbers of decision criteria as is the case for the Sustainable Development Goals Index which includes a large number of indicators associated with the 17 Sustainable Development Goals (Schmidt-Traub, Kroll et al. 2017). Also, they can focus on a single indicator for a specified entity like the carbon footprint of products (Plath, Dziggel et al.).

b) Analyzing the objective function's distribution

Living conditions of individuals differ within and across societies and so do the quantities of resources to handle scarcity or the quantity of outcomes from economic activity. Typically, these values are not randomly distributed but display certain patterns of distribution. Even if, generally, differences are unavoidable, some of them can be affected by economic or social policies. The higher the spread of economic outcomes such as income or health, the more important are thus their distributions. Such analyses may be motivated, on the one hand, by a generic aversion against a certain degree of inequality, for example, as inequality may destabilize democracy or diminish economic growth (van der Hoeven 2009). On the other hand, the analysis of (in)equality can be motivated by legal requirements or moral theories according to which certain types of inequality (e.g., income inequality by ethnicity or gender) conflict with certain equity norms. Besides normative questions of which inequality is problematic and which reference standard of equality measurement should be chosen (Cowell 2011, p. 1), such discussions also require positive analyses about the extent of (in)equality and its mediating factors.

Economic analyses of equality, can, first, chart inequality by diagrams, inequality measures, or rankings (Cowell 2011). These descriptions include measures like percentile ratios, e.g. the one between top and bottom 1% of income or wealth (Atkinson and Piketty 2007). Also, specific measures for distributions of economically relevant objects like income have been developed like the Lorenz curve which describes the distribution of these objects relative to proportions of the population, or the GINI index which compares this distribution to equality (Cowell 2011, ch. 2). There are also indices comparing different GINI indexes like the KAKWANI index which compares the tax burden to the distribution of income to measure how progressive (i.e. borne to larger extent by higher income groups) a tax is. These measures can then be compared across jurisdictions or in the course of time (Kakwani 1977).

Second, economic analyses of inequality can assess determinants of specific (in)equalities of resources (e.g. education) or outcomes (e.g. income or health). For example, regression analysis can be used to decompose factors associated with inequalities into those which can be considered reasonable predictors of inequality (e.g. productivity in wage gaps or health need in different public healthcare expenditure spending) and those which can be considered problematic based on some legal or ethical justification (e.g. ethnicity or gender in wage gaps or wealth in different public healthcare expenditure spending). Also, evidence can be collected about the impact on different policies on different inequalities (Wagstaff 2000; van der Hoeven 2009).

Table 1: Comparison of the major economic research programs

Res. Prog.:	**Neoclassical economics**			**Institutional economics**		**Complexity economics**		**Decision theoretic economics**	
Research field	Neoclassical economics	Neoclassical environm. economics	Behavioral economics	New institutional economics	Original institutional economics	Biophysical economics	Evolutionary economics	Content of objective function	Distribution of objective function
Concept of economy	Multiple, individual, homogeneous, rational optimization decisions		[see left, but challenging "rationality"]	Formal rules to constrain maximizing choices	Historically emerging, social rules & institutions	Elements driving system dynamics like stocks, flows, feedback loops	Emerging patterns in complex systems	(Dependent on research question or not defined)	
Analytic core	Neoclassical general equilibrium theory			Game theory / prisoners' dilemma		System dynamics		Decision theory	
Main concept of rationality	Subjective instrumentally rational		E.g. validated instrumentally rational	Supra-individually, rule-rational		Robust instrumentally, objectively rat.	E.g. rule of thumb subjectively rat.	Robust instrumentally, objectively rational	
Methods (example)	Econometric estimation of price-de-mand funct.	Theoretic analysis of effects of carbon tax	Lab experiment of framing effects	Econometric analysis of incentive effects	Qualitative case studies on emergence ecological tax	World 3-model by Club of Rome	Agent-based modeling of technology diffusions	Cost-effectiveness analysis	Estimation of tax progression by KAKWANI index
Contribution to climate change mitigation	Willingness to pay for sustainable product	Decision be-tween stan-dard, tax and certificates	Effectiveness of specific climate nudges	Transaction cost for climate rule negotiations	Aspects which prevent effective Pigou tax by now	Ecological impacts of different policy options	Lock-in phe-nomena that deter green innovation	Economic evaluation of climate policies	Analysis of distributive effects of new carbon tax

And, third, inequality can be integrated into the indices of objectives presented in the section above. This can be done by correcting index values for distribution like the inequality-adjusted Human Development index (UNDP 2020, p. 351) which is corrected by the Atkinson Index (Atkinson 1970). Or, based on accepted measures of policies suited to reduce inequality, inequality analysis can compare different entities like country by their performance for reducing undesirable inequality. For example, Oxfam recently published "The Commitment to Reducing Inequality Index" which measures and compares public spending, progressivity of taxes and labor rights and minimum wages across countries (Lawson and Martin 2017).

The discussion about climate change mitigation is frequently framed as call for "climate justice" (Rouf and Wainwright 2020; Pearson, Tsai et al. 2021) and many of these equality measures are also relevant for the field of climate change mitigation. For example, the (over)use of the scarce resource of GHG absorption capacity is highly unequal, with the top 10% of emitters accounting for 45% or global CO2 emissions while the bottom 50% account for 13%. Likewise, both exposure and vulnerability to the impact of unmitigated climate change is unequal (UNDP 2019, p. 179). Also, in the discussion about monetary incentives for climate change mitigation, particularly by carbon taxes or certificates (see section on neoclassical environmental economics), the progressivity of financial burdens like increasing housing costs due to higher energy prices plays an important role in the political debate.

7. Discussion

7.1 Interpretation

This study illustrated that economic analysis which accounts for the breadth and variety of economic research programs can provide valuable insights into many aspects of how climate change is conditioned and can be mitigated. Oriented at the ideal of value-neutral science, economic analysis as a whole does not lean toward specific ethical or political positions as would be the case if the remit of economics was limited to neoclassical equilibrium modelling. Instead, it provides a rich source of theoretical insights, which can be implemented in various proposals for reform that then can be evaluated ex-ante and ex-post in a more evidence-based policy (Bowers and Testa 2019).

Mitigating climate change is a grand societal challenge which requires broad minimum consensus on economic policies to facilitate the transition to a net zero-emission economy. Therefore, opposing "mainstream economics" and calling for heterodox approaches instead does not appear fruitful to us. Instead, they provide complementary views. We see a surge in economic pluralism and believe that systematic

search and structured comparison of theories and their results for specific phenomena are more fruitful to advance economic science than sheer opposition.

7.2 Limitations

Mapping thoughts that evolved within a scientific discourse of many thousands of minds over centuries is necessarily difficult – concepts are fuzzy, there is haze at their edges, and there are multiple and different links between the concepts. For example, neoclassical markets could be interpreted as institutions (Homann and Suchanek 2005), institutions could be analyzed as emerging from complex system dynamics (Schotter 2008; Ostrom 2009), and system dynamics can be used to model neoclassical market equilibria (Radzicki 2020). Also, the fourth research program, i.e. economic analysis in terms of outcomes and their distribution, can be done in parallel to research within the other three. Nevertheless, we believe distinguishing the different research programs and fields helps understanding the economics toolbox as a whole as well as the often-complementary contributions its different perspectives can provide. This is also, because some integrated view could not replace the specific contributions each research program can provide – interpreting the market as an institution does not answer an empirical question like the price elasticity of demand for different products subject to a new carbon tax.

Furthermore, the history of economic thought yielded a multitude of theoretical and empirical approaches, like research from a Veblenian, Schumpeterian, or Hayekian perspective. Any attempt to provide a manageable overview of a science which emanated over centuries may be criticized for not capturing the complete variety of this history. Therefore, we do not claim that the framework presented here is exhaustive or fully selective. Like a subway map which gains its usefulness from its abstraction, we restricted it to two levels, research programs and their subfields, leaving single authors aside. We hope that the framework provides a reasonably broad overview which is well suited to identify the most important research programs in the field and which can guide further exploration.

Not all fields of research covered within heterodox economics have been addressed here. This is also because not all of them have been sufficiently developed to meet the standards of a fully developed research program. Further work is needed to explore these and establish whether and how this further development can be achieved.

Our assumptions about the analytic core of research programs which excludes verbally descriptive research (e.g. historical analysis or hermeneutic analysis). This value judgment is based on the observation that economics is typically practiced as a quantitative science and on the notion that economics should use existing data to

scrutinize its hypotheses and predict the effect of economic policies on research topics such as climate change.

Also, our study only addressed "positive" economics; however, economics also involves normative choices. How to deal with them in a scientifically reflected manner is a highly relevant complementary question, but it was beyond the scope of this study.

Finally, using a standard textbook definition of economics, we left aside scientific endeavors from other disciplines like anthropology, biology, sociology, psychology or political science (at least in the descriptions of the research programs' cores) which can also provide highly relevant insights about the economy. This was done for the purpose of obtaining a selective classification of this scientific discipline. The research fields of behavioral economics or OIE illustrate that interdisciplinary collaboration with other disciplines which are just as valuable and scientifically elaborated as economics is a highly worthwhile field of scientific activity.

7.3 Implications

In medicine and health sciences, for example, both evidence-based action (Straus, Glasziou et al. 2018) and the methods of evidence search and synthesis to support it are far developed (Liberati, Altman et al. 2009; Moher, Liberati et al. 2009). The EQUATOR network (see: https://www.equator-network.org/) provides standards for conducting structured evidence synthesis for very different types of decision problems and associated methodologies but, apart from studies reporting evidence about cost-effectiveness in terms of healthcare objective functions (Husereau, Drummond et al. 2013), unfortunately, hardly contains economic perspectives. The discipline of economics could gain if such method of structured-evidence synthesis could be applied to validate the hypotheses made by its research programs and fields of research.

Climate change mitigation policy could gain if economic advice was based on, first, a pluralist economic perspective which increases the scope of phenomena included into economic analysis; and, second, the use of systematic assessments of the evidence regarding causalities assumed in the (different) economic frameworks as well as desired effects and undesired side effects of climate change mitigation policies.

7.4 Conclusion

Mitigating climate change is the prime grand challenge of humankind in the 21st century, and thus also to the discipline of economics. We expect the framework of the four economic research programs discussed and compared above, alongside with the

research fields they contain, can provide some leverage to the economics discipline to better contribute to tackling this challenge with a rich toolbox at its hand.

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