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# Economics & Biology: The whole is something besides the parts – a complementary approach to a bioeconomy

Joshua Henkel*

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**Abstract**

This paper examines relations between economics and biology regarding the historical background of these disciplines. Though economics is a social science its emergence has strong links to the natural sciences, especially to physics. This methodological basis seems to be mostly forgotten in mainstream economics. Since this methodology is based on the same principles of universal natural laws, it should make the branches of economics and biology compatible. Merging biology and economics could have a strong impact on finding solutions to our modern world sustainability problems and avoiding the dangers of the entropic abyss. This is only possible if mainstream economics is more open to assimilate information from outside its own field. Unequivocally, the most straightforward impact of a collaboration of these disciplines would be a biobased economy, that would tackle many problems our resource intensive and unsustainable economic system is facing at the moment.

**Keywords**

Sustainability, Culture, Collapse, Bio-economy

**JEL Classifications**

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* University of Bremen, Max-von-Laue-Straße 1,
28359 Bremen, Germany
e-mail: joshua.henkel@uni-bremen.de

# 1. Introduction

Contemporary economics asks many questions, that are also investigated by other disciplines. Trade between countries is a hot topic for political scientists, the question why people behave in a specific way is researched by psychologists and the neurosciences, and ecologists want to find out how environmental degradation influences our health. All these topics are likewise researched by economists but the analytical frameworks and methodologies differ. A combination of these disciplines in an interdisciplinary approach, should, therefore, lead to a more productive discourse and a deeper understanding of the topics per se. In recent years, economic research, that draws on interdisciplinary ideas, like for example biology (Bedhard and Dhuey, 2006), psychology (Akerlof, 1982), neuroscience (Berns, Laibson, and Loewenstein, 2007), or demography (Chiteji and Hamilton, 2002), has substantially increased. Fields like evolutionary economics, economic growth, cognitive economics, consumer theory, and especially ecological and environmental economics can have significant outcomes from joint research (García Callejas, 2007). In mainstream economics, however, the acceptance to integrate ideas from other research fields is rather low. The methodological basis of economics in the natural sciences, seems to be mostly forgotten nowadays, most likely because it contradicts accepted traditional economic knowledge. And while even Alfred Marshall, one of the founders of neoclassical economics, was convinced that economics is a branch of biology, most researcher don't necessarily see a connection between these sciences (Hirshleifer, 1978). On the contrary, through the widespread thinking of neoclassical economics[1], economic students are yet instilled with a rather inward looking and limited view of traditional economics. After being shaped intellectually for multiple years and usually during the maturation phase of the human brain, it is very difficult to appreciate different perspectives and learn new methods afterwards (for more information on the maturation process of the brain, see Sowell, et al., 2003; Johnson, Blum, and Giedd, 2009; Arain, et al., 2013). Therefore, traditional economics is still shaping the landscape for economic processes and planning for the future, which decelerates new and innovative economic ideas like a circular economy or a bioeconomy. The goal of this paper is to show the origins of economics and biology, point out why it makes sense to integrate biological thinking into economic theories and what can possibly be achieved with this collaboration. To understand why these disciplines can build on each other, a deeper understanding of the emergence of these fields is necessary. Due to the fact, that one paper cannot shed light on all important ideas, persons of interest, and connections between different branches of science, chapter 2 takes only a brief look on the arguably most important and influential physical history of economic thinking and biological teachings, to show that these disciplines can

[1] Kim, Morse, and Zingales (2006) show that since 1970 American-driven neoclassical economics have an intellectual monopoly in the economic literature.

harmonize. Chapter 3 gives an example of the entropic problem we are facing, based on the works of Nicholas Georgescu-Roegen. Chapter 4 describes how a knowledge-based bio-economy can be a possible solution to these entropic problems. Finally, Chapter 5 concludes.

## 2. The Past - on the Origins and Compatibility of Physics, Economics and Biology

When we start talking about the compatibility of economics and biology in terms of sustainability, we have to start with a totally different natural science first, because physics is fundamentally important to understand the evolution of economic thinking (see for example Farmer, Shubik, & Smith, 2005). In the 4th century BC, the Greek philosopher Aristotle laid the foundation of a natural science that studies matter, with a written text just called "*Physics*" (meaning "knowledge of nature") in his *Corpus Aristotelicum* (see Aristotle (2018) for a translation of the original text). While Aristotelian physics are a wild mixture of many different scientific branches, and are largely disproven nowadays, the desire to find a general principle that governs all natural bodies hasn't changed and his work was to some extend empirically grounded (Rovelli, 2015). Another leading scientist in classical antiquity that later strongly influenced the scientists of the Renaissance was the Greek mathematician Archimedes of Syracuse (Leahy, 2018). The work of these classical polymaths is strongly linked to the evolution of physics and the concepts of economics. With this basic framework we can skip nearly 1800 years, to the revival process of classical antiquity during the Renaissance. The German astronomer Johannes Kepler, who formulated the laws of planetary motion, described his new astronomy in *Astronomia Nova* (see Kepler, 2015) on the original title page as "celestial physics" and strongly studied Aristotle's work. The most important instruments for his work was the geometry developed by Archimedes and other classical scientists like Euclid, Apollonios, Pappos and Proklos (Bialas, 2004, p. 50). His contemporary Galileo Galilei, the famous Italian astronomer, also studied speed, gravity and motion of physical bodies extensively, which brought him, amongst other things, the nickname "father of modern physics" (Whitehouse, 2009, p. 219). Galilei's experiments on falling bodies and his strict contradiction of the Aristotelian hypothesis of forced motion (Jung, 2011) was later incorporated into Newton's law of motion (Drake, 1964). This, and the works of the aforementioned Johannes Kepler, namely *Astronomia Nova*, *Harmonices Mundi* and *Epitome Astronomiae Copernicanae*, were the foundations of Newtonian (or classical) mechanics in the 17th century, as in 1687 Sir Isaac Newton published his groundbreaking work *Philosophiæ Naturalis Principia Mathematica* (or Mathematical Principles of Natural Philosophy, for an English version see Newton, 1846). Adam Smith, the father of economics and original proponent of laissez-faire capitalism (see Brown, 1997; Bassiry & Jones, 1993; Newbert 2016), was greatly influenced by Newton's work (Hetherington, 1983; Diemer & Guillemin, 2011). The American philosopher James R. Otteson (2002, Chapter 3) even argues that *The Theory of Moral Sentiments* (written in 1759) and *An*

*Inquiry into the Nature and Cause of the Wealth of Nations* (often just called *The Wealth of Nations*, written in 1776) are both Newtonian in their methodology. Especially the law of conservation of energy, stating that the total energy of an isolated system remains constant and energy can neither be created nor destroyed, only transformed, left a lasting mark on economics.[2] Through this law, systems could be characterized by their equilibrium state. Whereas equilibrium for Newton meant a harmony of the cosmos and the forces that keep the planets in order, in neoclassical economics it represents the natural state of the market and the harmony between supply and demand. And while the emergence of neoclassical economics can be dated to the first half of the nineteenth century (the French engineers Jules Dupuit and Charles Minard employed mathematical methods in order to solve economic issues related to various technical projects, see Ekelund and Hébert, 1999; 2002; Jakimowicz, 2020), one could argue, if economics was developed around a hundred years later, after Darwin published *On the Origin of Species* (see Darwin, 2019 for a new edition of one of the most important scientific works ever written) in 1859, that neoclassical economics would be much less rigid and unchangeable with its economic laws. A good indicator for this argument is, that in the early twentieth century economics was actually enriched by a Darwin-inspired approach. A major contributor to this new approach was Thorstein Veblen (see Hodgson, 2004, Chapter 3). Not only did he criticize the neoclassical utilitarian explanation of human behavior by saying "It is characteristic of the school that whatever an element of the cultural fabric, an institution, or any institutional phenomenon, is involved in the facts with which the theory is occupied, such institutional facts are taken for granted, denied, or explained away, (…) And yet these economists are lacking neither in intelligence nor in information." (Veblen, 1909, p. 621-622), he further stressed that we have to pay attention to human learning to understand economics by saying "the physical properties of the materials accessible to man are constants; it is the human agent that changes – his insight and his appreciation of what these things can be used for is what develops" (Veblen, 1898, p. 387), and he also developed the first definitions of evolutionary economics by concluding "an evolutionary economics must be the theory of a process of cultural growth as determined by the economic interest, a theory of a cumulative sequence of economic institutions stated in terms of the process itself" (p.393). He later connected human biology (in what he called instinct psychology) with institutional change (Veblen, 1914). Cordes (2005) actually shows that present-day cognitive sciences support aspects of Veblen's evolutionary theory of institutional change. Later, there were other important works in economics that use an evolutionary approach, for example, Hayek (1971) developed a (tacit) cultural learning theory, Henrich (2004) and Richerson and Boyd (2005) integrated natural selection operating at the level of the genes and cultural transmission mechanisms in their dual inheritance theory, and North (2005)

[2] The foundations of the law of conservation of energy originally were written down by Gottfried Wilhelm Leibniz in his *Vis Viva* (living force), and later tested and formulated by Émilie du Châtelet with the help of Newtonian mechanics (Arianrhod, 2012).

emphasizes the role of human cognition in theory of economic change (for a broader overview, see Witt, 2008).

Meanwhile, the core theory of mainstream economics, in the neoclassical model, still argues that the agents will always act with perfect rationality to maximize their utility based on complete information, so the market quickly reaches an equilibrium state, in which commodities find the price that perfectly balances supply and demand. Modern economists, of course, now recognize that real human agents do not always act in such a coldly rational way and generally have to manage with incomplete information. But although Nobel prizes in economics were awarded in 2001 (markets with asymmetric information, see e.g., Akerlof 1970,1976; Spence, 1973,1974; Rothschild and Stiglitz, 1976; Stiglitz and Weiss, 1981; and Shapiro and Stiglitz, 1984) and 2002 (foundations of behavioral and experimental economics, for a collection of these papers see Smith, 2000; and Kahneman and Tversky, 2000) for works that recognizes these limitations, the idea of equilibrium remains central to mainstream economics (Ball, 2006). Therefore, it shouldn't come as a surprise, that neoclassical economists researching sustainability topics (known today as environmental economics), still rely on equilibrium based methodology[3]. Hence, sustainability theories in environmental economics are basically an evolution of a physical concept.

The relationship between biology and physics should be obvious: there are numerous phenomena in biology based on physical processes, like blood circulation, breathing or heat transfer in our bodies (Feynman et al., 2011, Chapter 3). Every living being is influenced by physical forces like heat, pressure, or light, and zooming into our cells we arrive at some point on a chemical level which by closer inspection leads to a fundamental atomic and, therefore, physical level. This underlying physical origin and the conclusion that economic agents are humans and humans are per definition biological beings, makes it safe to assume that biology and economics should be compatible in some ways. This compatibility is researched, inter alia, by evolutionary (see Nelson & Winter, 1982; Witt, 1992; Hodgson, 2002; Cordes, 2006) and ecological economics (see Boulding, 1966; Georgescu-Roegen, 1986; Costanza and Daly, 1987; Ayres, 1998; Cordes and Schwesinger, 2014). In the second half of the 20$^{th}$ century mankind finally recognized its impact on the global ecology and the limitations of earth's resources. Modern environmental conservation had its start in the 1960s, inspired by books like "*Silent Spring*" in 1962 (see Carson, 2002). This new environmental movement also reached into economics, where Kenneth Boulding differentiated in his essay "*The Economics of the Coming Spaceship Earth*" (1966) between an open economic of the past and a closed economic of the future. In his work, the economy of the past is symbolized as a "cowboy economy", because of the violent and exploitative

[3] At least the traditional branch of environmental economics still relies on this methodology, for an introduction see Baumol & Oates (1988), Kneese & Sweeney (1985) and Siebert (1995). Perman et al. (1999) show a new and modern approach mixing traditional economics and ecological economics.

behavior towards the seemingly endless resources, while the economy of the future is described as “spaceman economics”, wherein the earth, as a whole, is our single spaceship with limited resources to keep it going. Later, Georgescu-Roegen (1986), based his theories on a different field of physics: thermodynamics, the study of heat and temperature in relation to energy, work, radiation and matter. While thermodynamics still accepts the laws of energy conservation it states that within a closed system the amount of usable energy always declines over time. There is no substitution for an energy rich resource that has already been used, and while the energy is not lost, it is transformed into an unusable state. Biological systems (or life), as well as our modern economy, are consuming a lot of usable energy, thereby transforming it into unusable energy and increasing entropy in the system. This path of using thermodynamics (instead of mechanics) and biological concepts became known as ecological economics. Nowadays, a lot of interdisciplinary scientific branches have evolved and established themselves successfully in the academic world. Therefore, it seems kind of unprogressive, that mainstream economics is very timid in accepting new interdisciplinary or heterodox ideas. In spite of the significant contribution of physics in the development of neoclassical economics, even mainstream economics and physics have started to grow apart from each other and key discoveries that have resulted from the application of methods of physics in topics like entropy, econophysics, complexity economics or quantum economics still remain outside of mainstream economics, since they undermine traditional economic knowledge (see e.g. Mandelbrot, 1963; Anderson, Arrow, and Pines, 1988). This has to change, because just like a single particle in thermodynamics is not able to produce temperature or pressure, a single isolated view on economics can only explain a small and idealized model of our real world. Therefore, the acceptance of behavioral economics in the last decade of the twentieth century, should be seen as a positive sign for the future of economics, especially in the light of global warming and other environmental crises looming in the future.

## 3. The Present - the Pervasive Danger of the Entropic Abyss

Nicholas Georgescu-Roegen (1986), the father of ecological economics, was the first economist to use the term entropy in economics in 1971. His critique of the neoliberal camp included parallels of biological and economical processes and used the second law of thermodynamics, which must be fulfilled in both disciplines. The more resources are used for production, the more the entropy in our thermodynamically closed system, defined as our planet earth, will rise. There is still a lot of discussion if our planet counts as an open or closed system. It is not helpful that in different scientific fields open and closed systems have different definitions. In terms of matter, the earth is a closed system, because gravity keeps all states of matter inside of the system. In terms of energy it is an open system, getting energy from the sun and radiating energy back into space. Economic processes that use matter will, therefore, lead to higher entropy in the system and transforming the matter to unusable states. More production will automatically lead to a faster exhaustion of our natural resources. This process is unavoidable and irreversible. The logical conclusion for Georgescu-Roegen was to stop economic growth and start a form of degrowth-economics to keep the system running for the longest possible time. His way of thinking, later coined entropy pessimism, states, that there is no way to have a sustainable economy and the downfall of humanity is unavoidable. The only thing mankind can do is to delay the inevitable. Our modern economy still is based on the idea of infinite economic growth. Aside from the fact that infinity is impossible to grasp for our human brain, it should be obvious that a mathematical infinity cannot be sustainable with non-infinite resources. Historically we have multiple examples of populations that went extinct, because of a continuous overuse of their resources. Jared Diamond (2005) describes how the indigenous people of Rapa Nui (Easter Island) overused their resources and a series of events unfolded that ultimately resulted in destructive societal changes. Whether they cut down all the palm trees on their island to move the big monolithic figures, called Mo'ai, or their demise was hastened by exploitation and diseases brought by European contact, is still debated today. At least it seems to be clear that people, not animals or the climate, were the reason for the deforestation and soil erosion on Rapa Nui and the following societal downfall (Mieth & Bork, 2010). Another example for culturally induced unsustainability are the Eastern and Western settlements of the Norse in Greenland (Diamond, 2005). These colonies must have been economically viable at some point, or they wouldn't have lasted for 450 years. The Norse however, treated the environment in Greenland equal to their ancestral homeland of Norway. They cleared the land to raise cattle and used wood and turf to build houses like in Scandinavia, but they didn't realize that the ecosystem of Greenland was far more fragile. The growing season in this climate was shorter and slowly trees, shrubs and grass were receding. This lead to the removal of the topsoil and further reduction of usable pastures. Instead of adopting the cultural practices of the Inuit (a group the Norse despised and just called "wretches"), who were living in this region for centuries, they insisted on their culturally evolved lifestyle and European agriculture system. This culturally evolved behavior even seem to have prevented the Norse to catch and eat fish, a food resource that was plentiful available (Buckland et al., 1996). In the end they ate their livestock, afterwards their pets, and ultimately they starved to death (Pringle, 1997). The insistence to hold on to their Scandinavian culture in a different ecological landscape eventually lead to the collapse of their society. These examples show, on a small scale, that culturally evolved behavior and beliefs can lead to unsustainable practices and eventually the downfall of populations. We have to acknowledge that this can also be happening on a large scale like our globalized world. The point is, that our culturally acquired belief that economic growth is necessary all the time, may very well also lead to a slow and sluggish response to the decline of our global resources. Some scholars even believe that the point of no return has already passed (Randers & Goluke, 2020; Bradshaw et al., 2021). While the population of humans stayed mostly constant over the last thousands of years, we made a giant leap during the Industrial Revolution and humanity's numbers soared during the last 200 years. Kremer (1993) notes that the total world population of homo sapiens for most of its existence was well under 1 million. It took nearly twelve thousand years of technological progress to reach 1 billion people in 1800, and since then it only needed 200 years to increase sevenfold. In that timeframe we also consumed resources millions of years in the making and made the biggest leap to become unsustainable. Whether or not the Second Industrial Revolution (new firms were far more capital-intensive and were able to exploit the potential of economies of scale and scope more efficiently through new technologies, for an overview see Chandler, 1992) was the tipping point for becoming unsustainable, it is clear that we are nowadays on the edge of the, poetically titled, entropic abyss. Rifkin (2009, page 452) argues that "to attain the level of economic security necessary to allow people to shift from survival values to materialist values and finally to quality of life values…" we have unfortunately to ride "atop the growing entropic stream that's turning much of the planet into a wasteland and further impoverishing a large proportion of the human race.". A typical response to this critique is the advancement of technology but we have to take into account that (1) technological growth is predicted to decelerate in the future (Grinin, Grinin, & Korotayev, 2020) and (2) the innovation of technology is already stagnating since the 1970s and mostly the result of incremental processes (see Cowen, 2011; Gordon, 2012). Most people assume that humanity is relatively save, in terms of extinction events, because of our species dominating nature through culture and technology (and technology can be seen as an extension of our human evolution, see Bejan, 2020). This assumption is daring, because in evolutionary biology, Van Valen (1973) proposed the "Red Queen Hypothesis"[4] to explain his law of extinction, which states that probability of extinction is always constant for every species over time. The age of the species does not matter, only the ecology does. Even if a species had millions of years to adapt to a certain environment, it won't help if the ecology shifts and the environment changes. Still, taken into account that humanity has now existed for around 200,000 years and we, hence, have a relatively constant but low risk of extinction (otherwise it would be unlikely that humanity would have survived as long as it has) through comet or asteroid impact, supervolcano eruption and a following volcanic winter, we should not forget that we do not have a track record for relatively recent anthropogenic risks of extinction. Therefore, it would be ill-advised to think, humanity shouldn't fear extinction (or at least a collapse of our known society), especially after we put so much effort into changing our global ecology through recklessly exploiting all resources and cumulating their waste products.

Even cognitive psychologist Steven Pinker (2011; 2018), who in his books always assures that the titanic ship of progress is unsinkable, life is better than ever, and will

[4] The name originates from Lewis Carrol's (2010) book *Through the Looking Glass*, where the Red Queen tells Alice "Now, here, you see, it takes all the running you can do, to keep in the same place.". Van Valen implies that species have to keep running (meaning evolving over time), otherwise they go extinct.

surely keep improving, had to admit: “*It’s incorrect to extrapolate that the fact that we’ve made progress is a prediction that we’re guaranteed to make progress*.” (King, 2019). A collapse of our society also doesn’t have to be abrupt and bitter. Jared Diamond (2005) accurately points out that an abrupt collapse indeed is a very rare historical phenomenon.[5] John Michael Greer (2008, p. 29) states: “*The same pattern repeats over and over again in history. Gradual disintegration, not sudden catastrophic collapse, is the way civilizations end*.” And while he estimates it would take around 250 years for civilizations to decline and fall, he sees no reason why modern civilization shouldn’t follow this “*usual timeline*”. Critics could argue that there is definitely a difference between our industrial civilization and historical civilizations in the past. But this only makes his argument stronger. Yes, like shown before, we differ radically from historical populations since the industrial revolution, but in aspects that only accelerates and intensify the (possible) collapse and worse, in aspects that also increase the difficulty of recovery. Our modern civilization is still totally based on a non-renewable energy source: fossil fuels. At the moment, regardless of energy alternatives, there is no realistic replacement that can deliver the net energy fossil fuel provides (Heinberg, 2011). Additionally, a collapse of a society has always happened on a regional scale, so the harm was temporary and geographically limited, but now we face a planet-wide crisis through the damage to earths living systems which will further impede a recovery.

## 4. The Future – on the Importance of Change and the Possibilities of a Bio-Economy

The realization that the economic system has to change, to avoid catastrophic consequences, exists for multiple decades now. After Meadows et al. (1972) postulated that we need a change, after their extrapolations for the Club of Rome, many ideas how that change should come sprouted from the ground. Many of them were either radically demanding a reverse of economic growth (Georgescu-Roegen, 1977), a stabilization of the economy at a fixed point (Daly, 1974), individual-based concepts that demand renunciation of consumerism (Paech, 2012) or usage of psychological biases to nudge populations into a desired outcome (Schubert, 2017). Unfortunately, it doesn’t seem likely that the majority of people would accept and adopt such a sustainable change. Psychologically humans tend to prefer to avoid losses, even if they would acquire equivalent gains (see loss-aversion as part of the prospect theory; Kahneman and Tversky, 1979) and humans tend to have an emotional bias (the status-quo bias, see Samuelson & Zeckhauser, 1988; Kahneman, Thaler, and Knetsch, 1991) to prefer the current state of affairs. A change, not at the point of output of production or consumption, but at the level of input into production should be far less problematic in terms of psychological resistance of the population. A biological cycle has the natural advantage

[5] For an endogenous explanation of collapsing institutions viewed from various paradigmatic and disciplinary perspectives, see Cordes et al., 2021.

that without too much interference the cycle will not deplete. If biomass or biotechnology is implemented into the production of goods, services and energy, it would reduce or in the best of cases replace our dependency on non-renewable resources. This concept is known under many different names in the literature: biobased economy, bioeconomy, biotechonomy, circular economy and biomass cascading. Often these terms are used interchangeably, but in reality they mean different things and it makes sense to distinguish between them. The term biobased economy, for example, is only meant for the production of non-food goods (see Lange et al. 2021), while a bioeconomy includes the biobased economy and also the production of food and feed through biomass (Schmidt, Padel, and Levidow, 2012). Biotechonomy just refers to the use of biotechnology in the specified areas of biotechnology firms. A circular economy is presented as an economy “where the value of products, materials, and resources is maintained in the economy for as long as possible and the generation of waste is minimized.” (European Commission, 2015). The use of biomass cascading was already done before the term circular economy was invented, and is mostly just a part of it, since the goal of both ideas is resource efficiency. While all these concepts are different in nature, they often overlap and have the same target: a more sustainable production that is resource efficient, an organic recycling pathway, that expands the economy, a lower reliance on fossil fuels, and a lower ecological footprint in general. While a shift of the economy from fossil fuels to biomass seems like a logical and good idea, it naturally doesn’t come without its own pitfalls. Not only would it need a significant shift in social, agricultural, economic and technological systems, there are also discussions about land-use (fuel vs. food), forest management, monocultures and genetic engineering that have to be settled. If biomass is grown for energy production, then that area of cultivable land cannot be used to grow food simultaneously and the typical biogas plants like maize are creating ever-growing fields of monocultures, which doesn’t really help biodiversity at all. The next generation of these so called “agrofuels” or “biofuels” is now trying to not compete with traditional food sources in using non-edible wood and grass biomass for fuel production, but in Germany we see that the forest management is already under pressure from wood-use for construction and heating, even without additional usage as biomass for energy production[6]. Gomez, San Juan, Bogdanski & Dubois (2019) also show that a bioeconomy is not automatically sustainable. Lastly, the multitude of ethical questions in the usage of genetic engineering and the (in Europe) really bad image of genetically modified organisms (GMOs) are additional problems that a bioeconomy has to solve. All this shows that the bioeconomy, as promising as it sounds, is practically still in its infancy. Nonetheless, we know that the fossil fuel era is practically over and that the bioeconomy is a valid strategy to tackle climate change in the future. Furthermore, the limitations of land-use for biomass production are already experimentally widened in

[6] Agrofuels are divided into three groups: (1) first generation agrofuels made from food crop, which already can be produced on a large scale, (2) second generation agrofuels based on non-food biomass, which are expected to be the staple for the coming decades and (3) third generation agrofuels, completely procured from algae, that are currently in the research and development phase.

e.g. aquatic biomass production and the idea of finding the best utilization of biological resources for the economy is nothing new. The initial idea of a bioeconomy would therefore be an economy where the basic building blocks for materials, chemicals and energy are derived from renewable biological resources, such as plants or animals (European Commision, 2012). For the European Commission the bioeconomy is the key component for smart and green growth, but it must be carefully designed and intelligently implemented. The European Commission states that the bioeconomy in Europe already has a market size of over 2 trillion Euros and around 9 percent of the total EU labor force (Ronzon & M'barek, 2018). This rapid progress is the result of the recent increase in knowledge and expertise in the field of biotechnology, the science of using living things to produce goods and services.

A color code was implemented to differentiate between the vast array of different areas of biotechnologies and methods that are used in the bioeconomy. Steiner (2020) distinguishes between white biotechnology (industrial use of enzymes and microorganisms to produce bio-based products in a diverse range of sectors), grey biotechnology (technological solutions to protect the environment), green biotechnology (improving agricultural processes with the use of life science knowledge), blue biotechnology (marine and aquatic applications), red biotechnology (health sector and pharmaceuticals), yellow biotechnology (mainly concerned with food production), brown biotechnology (research of drought resistant plants), violet biotechnology (concerned with ethical and moral issues), gold biotechnology (bioinformatics), orange biotechnology (concerned with what and how to teach in biotechnology), and outside of the color scheme, dark biotechnology (concerned with the abuse of biotechnological research) and modern biotechnology (genetic engineering and cell fusion). Biotechnology and the bioeconomy are nowadays inextricably linked, the OECD (2009, p. 8) for example states, that "Biotechnology offers technological solutions for many of the health and resource-based challenges facing the world." and "A bioeconomy can be thought of as a world where biotechnology contributes to a significant share of economic output."

Gottinger, Ladu and Quitzow (2020) identify for a sustainability transition, to be effective, policy interventions are necessary that should build on a systematic understanding of transition processes and their dynamics. They also argue that the transition into a bioeconomy poses particular challenges because multiple sectors have to be transformed simultaneously and new value chains have to be developed. Therefore, related entry-points for policy have to be identified and while the number of research papers into the matter is increasing, a holistic vision to cope with the complexity of reality is still missing (Sanz-Hernández, Esteban & Garrido, 2019). Bröring, Laibach and Wustmans (2020) classify four different types of innovations that are needed for a bioeconomy: (1) "Substitute Products", referring to the replacement of fossil based products through bio based products, (2) "New Processes", referring to more efficiency in the production of products, (3) "New Products", referring to entirely new bio based products with new functions and (4) "New Behavior", referring to changes at the consumer's side or new business models et cetera. Another barrier for a transition to a functioning bioeconomy is that "*industrial economies have become locked into fossil fuel-based technological systems through a path-dependent process driven by technological and institutional increasing returns to scale*" (Unruh, 2000). At the moment we are at the crossroads of two different approaches to the bioeconomy: (1) a technology-based transition approach, that is focused on innovation, biotechnology and resource efficiency and (2) a socio-ecological transition approach, that is focused on social innovation, participation of the society and reduced resource demand. However, those two approaches don't have to be necessarily incompatible (Priefer, Jörissen and Frör, 2017). To achieve an integration of both processes in the transition, governments may need to play a stronger role, on the one hand to compensate for competitive disadvantages in comparison to fossil-based products and on the other hand to ensure compliance with ecological and social sustainability targets (Hinderer, Brändle and Kuckertz, 2021).

## 5. Conclusion

Economic fields concerned with environment, ecology and sustainability are, in their framework, all based on natural sciences. Even if their underlying foundation comes from different fields of these natural sciences, like mechanics, ecology or thermodynamics, they are connected by laws of nature. These scientific laws implicitly reflect causal relationships fundamental to reality and, therefore, economics based on these principles must be compatible with all natural sciences. Biology and economics are compatible as soon as economics reaches into the sphere of natural sciences. This means that all economic theories, that somehow deal with human behavior, have to also deal with biological facts – for example, that preferences are fundamentally shaped by culture and are not stable, fixed or homogenous - even if this entails central challenges to traditional economic theories (see Chai, 2017, Cordes, 2019; Witt, 2001). The goal of this conjunction is not a "biologicalization" of economics, where all economic parts are sooner or later replaced by biological methods. It should be understood as an interconnection of different branches of science with different methods, ideas, questions and approaches, that can help to solve old problems or lead to new schools of thought. The rising problems of resource scarcity and environmental degradation are questions of unprecedented magnitude. While people have worried about their environment to sustain them, since time immemorial, we now know that the industrialization has pushed us to the edge of the entropic abyss. In the 20th century more and more people from different scientific fields have comprehended the necessity to tackle the problem of unsustainable behavior. Scientists have warned over and over again that we are at the tipping point of climate change and that already the next generation will be the long-suffering victims if we make the wrong decisions. The role of the bioeconomy, supported by the ongoing research and innovations in the field of biotechnology, will continue to be debated in the near future. More and more economists and politicians are recognizing the fact, that the actual economic status quo is not able to tackle the environmental problems with a laissez faire approach and continued expanded growth. Even big companies are realizing that a sustainable approach now comes cheaper than a stark cost explosion through resource scarcity in the future. The economic shift to a bioeconomy will therefore not be paradigm shift, but a slow and continuous implementation of biotechnologies in the already existing system. This will further lead to the mindset that unsustainable resources are outdated and makes the use of them obsolete. The section above illustrates that transformation of the prevailing economic system towards a bioeconomy is an extremely complex process. New emergences of industries will be accompanied by innovative adjustments in already existing industries, just as mature industries will disappear. Nonetheless, the bioeconomy is more or less the obvious choice for our economic system if we want to avoid the societal collapse in the future. Digitalization will allow us to replace many fossil fuel based products and energy intensive services by bits and bytes. Simultaneously, digitalization offers a wide range of opportunities by coordinating decentralized and very detailed bioeconomic technologies and processes such as energy production and distribution (Pyka and Prettner, 2018). A growth part based on bioeconomics is more than just the replacement of crude oil by renewable energies. It requires a reorganization of the entire economy, new production and consumption patterns, and transformation process in the fossil fuel based paradigm. A lot of questions still have to be answered, but we have possible solutions for these problems at hand. Now we just have to carefully design and intelligently implement them.

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**Editors**

Prof. Dr. Christian Cordes
Evolutionary Economics
Phone: +49 (0)421 218 66616, e-mail: c.cordes@uni-bremen.de

Prof. Dr. Dirk Fornahl
Regional and Innovation Economics
Phone: +49 (0)421 218 66530, e-mail: dfornahl@uni-bremen.de

Prof. Dr. Jutta Günther
Economics of Innovation and Structural Change
Phone: +49 (0)421 218 66630, e-mail: jutta.guenther@uni-bremen.de

Prof. Dr. André W. Heinemann
Federal and Regional Financial Relations
Phone: +49 (0)421 218 66830, e-mail: andre.heinemann@uni-bremen.de

Prof. Dr. Torben Klarl
Macroeconomics
Phone: +49 (0)421 218 66560, e-mail: tklarl@uni-bremen.de

Prof. Dr. Michael Rochlitz
Institutional Economics
Phone: +49 (0)421 218 66990, e-mail: michael.rochlitz@uni-bremen.de

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