Faculty of Business Studies and Economics
University of Bremen

Doctoral Thesis

Essays on the Macroeconomic interrelations of Human and Nature

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A thesis submitted to the Doctoral Commission Dr. rer. pol. of the University of Bremen in fulfilment of the requirements for the degree of Dr. rer. pol

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Date of submission: June 14, 2024
Date of colloquium: September 30, 2024

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Bremen, 2024

Content

Chapter 1

Introduction: On the challenges of Nature-Human interrelations, determining factors and potential solutions

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Abstract

This introduction provides a theoretical basis for the following empirical studies (chapters 2-4). It provides a holistic perspective on the interrelations between economy and nature. Section 2 introduces the core environmental concepts, to build an understanding of the ecological challenges and how central economic processes, like resource extraction, are connected to this. In section 3 current economic ideas and concepts to encounter those challenges are introduced and discussed. Section 4 provides an overview of the studies included into this dissertation and a summary of how these were conducted and their main findings and contributions. Section 5 concludes this introductory chapter (chapter 1) and the essence of an overall conclusion. To encounter the predicted challenges, relying on technological development alone will probably not be efficient and a decoupling of economic activities from environmental impacts will be possible only very limited.

Keywords: Decoupling, Green Growth, Decoupling, Planetary Boundaries, Resources, Sustainable Development

JEL Classification: O13, O33, O43, O44, Q10, Q24, Q57

Publication: This is the introductory chapter to this cumulative dissertation.

1.1 Introduction

"Nature is dying – and the world looks away"[1] (Schwägerl, 2018) – This was headlining a 2018 article of the German magazine *Spiegel Wissenschaft*, about the 14th world summit on nature conservation, which had just ended at that time. This "looking away" seems to be the mantra for too long – at least regarding taking effective action. *The Limits to Growth* (Meadows et al., 1972) report was published in 1972, initiating a debate about the risks of continuing economic growth. More than a decade later the report *Our common Future* (United Nations, 1987) was published, not only setting the famous definition of Sustainable Development, but also pointing to critical sustainability risks and issues (United Nations, 1987). The suggestions and warnings did and do exist, but it seems like appropriate actions are missing. Carbon emissions keep rising (IPCC, 2023), biodiversity and ecosystems keep declining (IPBES, 2019; WWF, 2020) and our economies keep growing (Krausmann et al., 2009). The problem is, however, that we as humans depend on nature and its provision of goods and services, like water, air, soil (Brown et al., 2007) and overall global ecological stability (Rockström et al., 2009). As the UN Secretary General António Guterres puts it in 2020 regarding the state of the planet: "Humanity is waging a war on nature. This is suicidal. […] Making peace with nature is the defining task of the 21st century. It must be the top, top priority for everyone, everywhere." (Guterres, 2020). The recently formed Taskforce on Nature-related Financial Disclosure (TNFD) summarizes the term Nature as the natural world, emphasising the diversity of living organisms, including people, and their interactions with each other and their environment; consisting of the four realms land, ocean, freshwater and atmosphere (TNFD, 2023). It is thus a holistic term for the environment, of which society[2] is integral, interacting with and across all four realms. In its 2023 Global Risk Report the World Economic Forum identifies six environmental risks among the of top-ten major risks that humanity faces in the upcoming decade (World Economic and Forum, 2023). *Failure to mitigate climate change* leads the list[3], followed by *Failure of climate change adaptation*[4], Natural disasters and extreme weather events[5], *Biodiversity loss and ecosystem collapse*[6], *Natural resource crisis*[7], and *Large-scale environmental damage incidents*[8]. With human and economic development, the utilization of natural resources has

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[1] Translation of the author.

[2] Corporations and economies are covered by the term society and are components of this.

[3] First position

[4] Second position

[5] Third position

[6] Fourth position

[7] Sixth position

[8] Tenth position

transformed and became large-scale (Haberl et al., 2011), leading to transgressed ecological and planetary boundaries, threatening the "safe operating space" for humanity (Richardson et al., 2023; Rockström et al., 2009). Natural resources are central inputs into economic activity (Kerner et al., 2023) and economic systems are closely interlinked with the environment (TNFD, 2023). To encounter those environmental developments and to allow economies and societies to adequately exist under those circumstances, different approaches are proposed. The most prominent and currently most represented in political agendas is the approach of *green growth*, with the idea of decoupling economic processes from environmental impacts at its core (Hickel and Kallis, 2020). Directed technical change, from environmentally damaging and "dirty" to environmentally friendly and "clean" technologies, is a central mechanism to allow for this. But this rather paradigm-incremental approach is not without critique. Alternative and more radical approaches have been developed in parallel, like the degrowth movement, putting physical and ecological reasoning and institutional changes at its core (Couix, 2019).

This thesis revolves around the empirical evaluation of urgent environmental issues, within the context of economic systems and factors. It comprises this introductory paper (chapter 1) and three scientific papers (chapter 2-4). The three papers contribute to the understanding of critical interrelations between issues regarding the realms of nature, like biodiversity loss and climate change, and economic system components like natural resource extraction, economic growth and technical change. All three papers address relevant components of the theory and discussion around decoupling in a broader sense. Technologies, institutions, and economic growth are the central factors in this concept. Chapter 2 globally investigates the role of institutional governance mechanisms on the relationship and impact of natural resource extraction and biodiversity loss. Institutions and governance mechanisms are a foundational aspect of environmentally sustainable natural resource management. Effective management institutions are described as a core solution to the natural resource crisis (Acheson, 2006). Those problems have to be matched with governance institutions, allowing for such an effective resource management (Acheson, 2006) and the implementation of new and potentially decoupling processes and stronger biodiversity conservation. In chapter 3 a global convergence analysis regarding meat consumption and assessment of the potential force of income growth on meat consumption is outlined. In this way, it links to the concept of the Environmental Kuznets-Curve (EKC) hypothesis[9], which assumes decreasing environmentally harmful behaviour in the course of increasing income. After increasing impacts in the first place, in a period where

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[9] See for example Cole and McCoskey (2013), analysing meat consumption within the context of the EKC.

income growth has the highest priority to raise living conditions, decoupling potentially happens, due to a higher valuation of an intact environment[10]. Chapter 4 analyses the potential effect of technological change, by evaluating the impact of Environmental Innovation on carbon dioxide emissions, within the European Union. Technology is one key element to achieve green growth. It is the central factor that enables the decoupling of future economic growth from environmental impacts. Carbon dioxide emissions are a prominent and important environmental measure in this context. This paper thus directly connects and contributes to the discussion on decoupling.

This introductory chapter will provide the basis for the subsequent chapters. It builds the theoretical understanding of the values contributed by chapter 2-4. It is fundamentally assumed that the earth system is only capable to compensate a certain amount of pressure and nature is only able to provide a certain amount of goods and services under exploitation. Section 1.2 therefore provides the basic environmental groundwork and different interrelations between ecological and economic factors, that are the basis for the empirical papers. Special attention is payed to the planetary boundaries as a holistic environmental evaluation model in section 1.2.1 and the prioritization of biodiversity loss and climate change, as the so-called twin crisis, in section 1.2.2. Section 1.2.3 then directly connects those environmental problem situations and the extractive practices of economic systems, and vice versa the dependence of the latter on natural resources. Section 1.3 introduces two different theoretical economic concepts of how those ecological challenges can be faced. The different conceptual solution approaches are delineated against each other and evaluated. Section 1.3.1 introduces the concept behind green growth and the idea of decoupling economic growth from environmental impact. One key concept of green growth, directed technical change, is described in more detail in section 1.3.2, leading to a presentation of two general theoretical schools of thought within the realm of environmental and economic issues in section 1.3.3 – Environmental and Resource Economics and Ecological Economics. Both represent different viewpoints regarding the ability to continue and pursue economic growth, what will be processed in section 1.3.4.

Section 1.4 provides an overview of the three empirical papers of this dissertation and presents how they are linked to the issues outlined in the previous sections, how they are interlinked with each other, and what is contributed to the respective literature. A short overview to each

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[10] See Section 1.3.1 for a more detailed description of the EKC hypothesis.

paper is outlined in the sub-sections 1.4.1-1.4.3. Section 1.5 draws a summary and conclusion of the introductory chapter of this dissertation.

1.2 The Earth´s biocapacity and natural resource consumption

Our Earth has the ability to regenerate itself from damage and to restock its regenerative resources (WWF, 2020). This so-called biocapacity is a relatively wholistic view of nature's ability to adapt to human-induced demands and stresses. The term has emerged from the prominent and established concept of the Ecological Footprint (Galli et al., 2014). The Ecological Footprint itself can be described as the demand side – the ecological assets like productive land and sea area[11], that a population or humanity requires to produce the renewable resources and ecological services it consumes[12]. Biocapacity in contrast builds the supply side, by tracking the ecological assets available and their capacity to produce those resources and services. Due to improvements in technology and land management practices, this biocapacity has increased by about 28% in the last 60 years (WWF, 2020). During the same period humanity´s ecological footprint, however, has increased by around 173 %, now exceeding the biocapacity by 56 %. Put another way, 1.5 Planets Earth would be necessary to sustain the current consumption of natural resources in the long run (Danish et al., 2019). It becomes more and more obvious and present that ecological limits also limit the potential for economic growth (Gabbi et al., 2021). The following sub-sections introduce the current state of science on the state of the global environment and potential priority topics. The connection between ecological problem situations and economic developments will be established before the latter will be investigated in more depth.

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[11] The Ecological Footprint differentiates between six footprint-categories, besides the biocapacity (WWF, 2020): Carbon, Built-up land, Fishing grounds, Forest product, Grazing land and cropland. The method allows to calculate separate footprints for all of them and the cumulative total Ecological Footprint.

[12] The Ecological Footprint as well as the biocapacity are described in the globally standardized and comparable unit of "global hectares", a hectare of biologically productive land (Galli et al., 2014).

1.2.1 Planetary Boundaries

The Planetary Boundaries framework identifies nine key processes that are critical in maintaining the stability and resilience of the Earth system (Richardson et al., 2023). Within this approach, those nine processes are quantified and attributed with critical threshold values of anthropogenic perturbation, that, if respected, allow to keep our Earth within a “Holocene-like” interglacial state, as we have experienced it approximately over the last 10,000 years[13]. By this, a state below those boundaries characterizes a “safe operating space” for humanity, since it allows to maintain the known environmental conditions, in which the society, as we know it, was able to evolve, without any radical disturbances, like e.g. ice ages (Richardson et al., 2023). Within those boundaries, long-term economic development was and will be possible, as well as agriculture that has emerged and was enabled by the Holocene (Rockström et al., 2009). A constant re-evaluation and update of those processes enabled a monitoring of the state of those. Initially developed and presented by Rockström et al. (2009), a comprehensive update in 2023 by Richardson et al. (2023) has shown that six of the nine boundaries have been transgressed, suggesting that the Earth system is now well outside a safe operating space for humanity. Especially alarming is that all biosphere-related boundary processes, which provide resilience to the Earth system, are at or close to a high-risk level of transgression (Richardson et al., 2023).

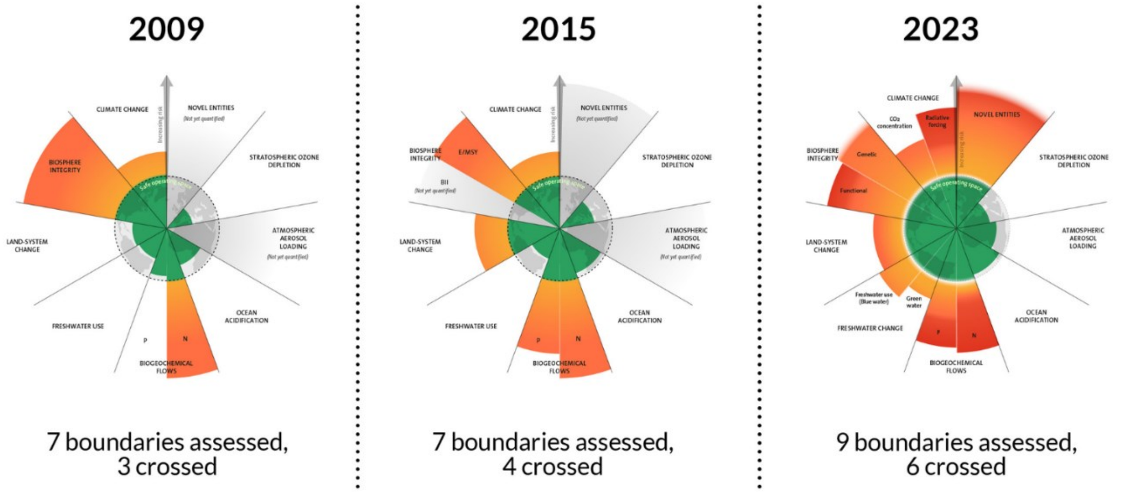

Figure 1: The evolution of the planetary boundaries framework

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[13] This period of Holocene as an interglacial state is characterized by a relatively stable environment and climatic conditions that is suggested as the precondition for complex societies (Rockström et al., 2009).

Source: Stockholm Resilience Centre (2024), based on Rockström et al. (2009), Steffen et al. (2015b), and Richardson et al. (2023)

While the concrete consequences of one or more boundaries transgressed cannot be named with certainty, there is severe warning that global environmental changes can no longer be excluded (Rockström et al., 2009). Transgression may even be catastrophic, with the risk that crossing thresholds triggers non-linear, abrupt environmental change within continental- to planetary-scale systems. The 2009 assessment identified three boundaries as transgressed: Climate change, rate of biodiversity loss and changes to the global nitrogen cycle (see Figure 1) (Rockström et al., 2009). Today, around fifteen years later, the boundaries transgressed has increased around 24%[14] compared to the number evaluated, and the intensity of transgression increased (Richardson et al., 2023). Based on these indications and evidence, it is inevitable to conclude that humanity has left its safe operating space and is risking such global environmental changes, if not immediate and severe action is taken.

The changes, causing transgressions, are mostly driven by social and economic systems run on unsustainable resource extraction and consumption (Rockström et al., 2023). Agriculture is a leading cause for the transgression of multiple planetary boundaries globally and regionally (Gerten et al., 2020). To guarantee future food security, as the world moves towards the mark of >9 billion people in 2050, the transformation of the agricultural system towards sustainable practices is indispensable if the Earth system resilience should be maintained. The planetary boundaries, if maintained and not transgressed, would only allow to produce food for 3.4 billion people under current agricultural practices (ceteris paribus). As much as ~ 49% of the current food production thus violates the planetary boundaries. The trade-off between the future food consumption of a rising and potentially wealthier population and the Earth´s biophysical carrying capacity, requires radical changes of the production and consumption patterns of our food. Among others, efficient international trade, food waste reductions and the shift towards less resource-demanding diets are crucial measures. It is shown, however, that those shifts would allow for a net increase of ~ 53% above the current level. Novel technologies, e.g. in agriculture, agroforestry, or desalination, entail important unexplored future potentials to further increase a sustainable food supply. However, agriculture and its accompanied processes are not the sole cause for planetary boundary transgression. It is rather the overarching socio-economic development of consumption and production that exerts multi-faceted pressures on the Earth system (Steffen et al., 2015a). As mentioned, the stable Earth state of the Holocene

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[14] Own calculation, based on the numbers of boundaries evaluated and transgressed.

enabled the development of the economy and society that is known today. With the industrial revolution and the invention of the steam engine, around the end of the 18th century, as it is argued, a new state was entered – the Anthropocene (Steffen et al., 2015a), in which humans constitute the driving force of changes of the Earth system (Rockström et al., 2009). The industrialization was and still is accompanied by socio-economic changes, like e.g. water use, fertilizer use, transportation, increasing GDP and population growth, towards ongoing increasing consumption of resources and fossil fuels, resulting in Earth system trends of increasing ecological pressures, like increases in GHG emissions, tropical forest loss and terrestrial biosphere degradation or ocean acidification (Steffen et al., 2015a). Those developments are summarized as "the great acceleration", referring to the strong growth in both socio-economic development and Earth system pressures. While the industrial revolution, with the enablement of large-scale utilization of resources and fossil fuels, is often set as the beginning, after World War II (WWII) there occurred a period of massive economic growth and resource use (Fischer-Kowalski et al., 2014; Steffen et al., 2015a). Therefore, the period after WWII is considered as the start of this transformation (Fischer-Kowalski et al., 2014). The combination of observed over-extraction of resources and potential interactions and feedbacks (Sureth et al., 2023) provide the need for monitoring. The planetary boundaries are a necessary and useful framework to assess the human-economic pressures on natural equilibria and manage the human use of natural resources (Sureth et al., 2023).

However, while all boundaries are essential to respect, they are not necessarily equally important in a sense of prioritization. Some of them form the basis for all others and provide for holistic, global stability. The biosphere and the atmosphere provide the basis and should take precedence as they allow for overall ecological stability.

1.2.2 Climate Change and Biodiversity Loss

Climate change and biodiversity loss currently are the most prominent ecological crisis. Both are manifestations of the imbalance between human extractive and polluting activities and the Earth´s regenerative capacity (Sureth et al., 2023). One representing the necessary stability of the climate humanity depend on to strive and develop in, the other representing the stability of the biosphere, providing humanity with vital ecosystem services, like food, fresh water and air, and resources. Both are strongly interlinked, which is why they are also called "The Twin Crisis" (Farber, 2015) or "The Double Crisis" (Sureth et al., 2023). The biosphere and atmosphere together build the core foundation of the functioning Earth system humanity and current civilization as well as the ability to achieve sustainability and any other UN Sustainable development Goals depend on (Folke et al., 2016).

The Industrial Revolution has unleashed human-induced ecological degradations of important ecosystems, like forests and grasslands, threatening the human-wellbeing and natural world (WWF, 2020). Around 75% of the ice-free Earth´s surface has been altered, leading to approximately 1 million species being threatened by extinction, over the coming decades to centuries. According to the Living Planet Index (LPI)[15], between 1970 and 2016 species populations have declined around 68 %. However, this global decline is highly region-specific. The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) splits the World into major geographical regions, with comparable conditions, to allow appropriate assessment[16](IPBES, 2019; WWF, 2020). While in all geographical regions the LPI has declined, this development differs in its dimension. The most drastic decline is recognized in Latin America and Caribbean with around 94% (WWF, 2020). This is followed by Africa, with 65%, Asia Pacific with 45%, North America with 33% and Europe and Central Asia with a decline of 24%.

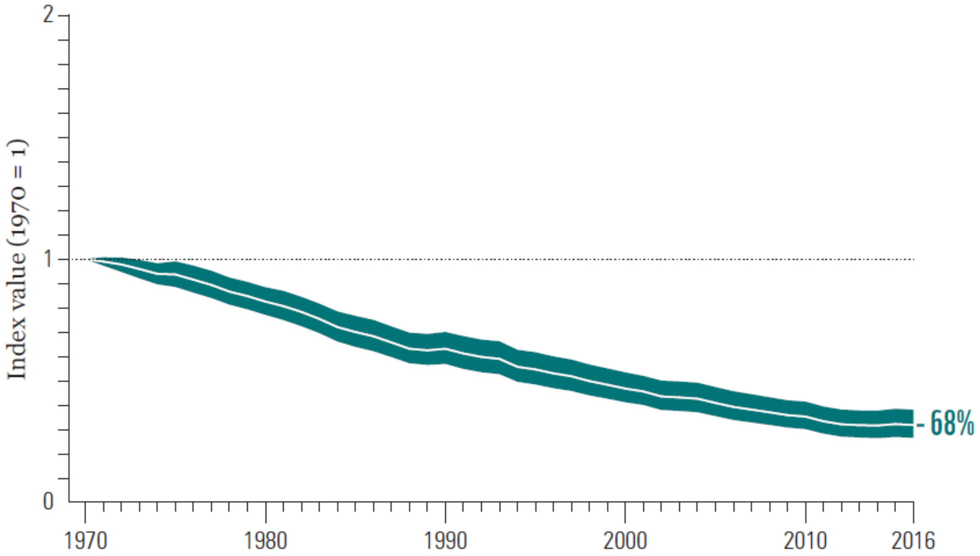

Figure 2: The global Living Planet Index: 1970 to 2016

Source: WWF (2020, p. 16)

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[15] The LPI is a tracking measure conducted by the Zoological Society London, to represent and monitor the abundance of certain species populations and measures the approximate changes in global biodiversity (WWF, 2020). The version of 2020 captures 20,811 populations of 4,392 different species. Those species cover different taxa like mammals, birds, fish, reptiles and amphibians.

[16] For further detail see the individual regional assessment reports by IPBES, https://www.ipbes.net/regional-assessments

The leading cause of this destruction is the expansion of agricultural land, and the accompanied conversion of natural ecosystems (Wilson, 2002; WWF, 2020), what is a vivid example for the character of the "twin crisis". This conversion of land to agricultural area is a major threat to wild land that stores large amounts of carbon and harbours biodiversity (Farber, 2015). The destruction of ecosystems, like rainforests, is not only a major driver of biodiversity loss, but simultaneously a major source of carbon emissions. Consequentially, carbon emissions are released to the atmosphere, carbon sinks are reduced or lost, biodiversity is reduced or lost, and both exert effects that destabilize the remaining ecosystems in the long term. Both developments and systems are thus mutually influencing and accelerating each other. While climate change globally has not been the most important driver of biodiversity loss yet, it is projected to become more important than the other drivers in the coming decades (WWF, 2020). Global warming is caused by such human activities, through the emission of greenhouse gases (GHG) (IPCC, 2023). The IPCC (2023) defines the contributions and causes for ongoing increasing GHG emissions "*arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and among individuals*" (IPCC, 2023, p. 4), further highlighting the interrelation between nature[17] and climate. The global surface temperature is reaching 1.1°C above 1850-1900 in 2011-2020, caused by GHG emissions from human activities over the period from 1750 onwards (IPCC, 2023). The cumulative and human-induced GHG emissions, from 1850 to 2019, are around 2,400 $GtCO_2$. Of these, 58 % occurred between 1850 and 1989 and 42% between 1990 and 2019, with the highest average GHG emissions ever recorded within a decade between 2010 and 2019 (IPCC, 2023), demonstrating that nearly the same amount of anthropogenic emissions has been cumulated during the last ~30 years, as it has been during the ~140 years before, with increasing growth. The changing climate has already manifested in an increasing number of weather events (Sureth et al., 2023) and has led to widespread adverse impacts and losses to nature and people (IPCC, 2023). Approximately 3.3 to 3.6 billion people live in contexts highly vulnerable to climate change, and substantial and partially irreversible damage has been caused to ecosystems of all types, like hundreds of local species lost to extreme heat, with mass mortality events recorded on land and sea.

The current addressing of anthropogenic perturbations of the global environment, like climate change, biodiversity loss or pollution, assumes that those can be separated from one another (Richardson et al., 2023). Thereby, however, the non-linear interactions between those

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[17] Here represented by "land use" and "land-use change", as well as the climate mitigation actions, mentioned in the following.

processes and the aggregate effect on the overall state of the Earth system are neglected. Human impacts on the individual processes must be thought in a systemic context, with specific focus on biosphere integrity and climate change boundaries. Technological innovations are an important part of the urgent measures that are necessary to implement (Mori, 2020), to combat this twin crisis. Nevertheless, while an industrial application can to some degree sequester carbon, it is impossible to fully substitute natural processes (Mori, 2020). This is why the loss of biodiversity can even entail the loss of opportunity for climate change mitigation and adaptation (Mori, 2020), when too much of ecological capacity to combat climate change is destroyed. The most powerful mean that humanity has in fighting climate change, is to respect the land system change boundary and to restore the global forests to the levels of the late 20th century (Richardson et al., 2023). In 2100 this could provide a substantial cumulative sink for atmospheric CO_2 (Richardson et al., 2023) and would contribute tremendously to halt biodiversity loss. But also in the shorter term this is estimated to be an effective measure: The IPCC (2023) estimates the reduction of conversion of natural ecosystems to be the most effective GHG mitigation option until 2030, only surpassed by the transformation to solar energy supply (IPCC, 2023). However, current notified levels of ambitions for climate actions[18] are inadequate to achieve the necessary goal of limiting global temperature rise. The 1.5°C threshold could already be reached by early to mid-2030s and the 2°C threshold by 2050-2070, further heading the pathway to 3-4°C temperature increase, entailing devastating effects on nature and thus humanity (WWF, 2020). An important driver for both climate change and biodiversity loss, that receives increasing attention from international bodies like the IPCC, UNFCCC, and IPBES, is the impact of livestock production and dietary choices (Mori, 2020).

It has thus been outlined that climate change and biodiversity loss are strongly interconnected and reinforce each other. The global commons are all linked with each other (Farber, 2015). However, one facet must be added in this linkage. While the earth system itself is interconnected, it is also linked to and by one sub-system of central importance, with respect to environmental pressures – the global economy (Farber, 2015).

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[18] Like e.g. the climate pledges of the Paris Agreement signatory parties.

1.2.3 Natural resources and economic growth

Over the last two million years, humans have colonized almost the entire biosphere on Earth (Haberl et al., 2011), amounting severe pressures on the ecological systems, as described above. This colonization process has created socio-ecological systems of which fundamental patterns and processes are co-regulated by socio-economic and ecological systems, and whose interaction with nature has developed and transformed over time (Haberl et al., 2011). Those interactions of the system can be described as “socio metabolic regimes”, describing the entire flow of materials and energy that is required to sustain all human economic activities. Three main regimes can be distinguished so far: hunter-gatherers, agrarian societies, and industrial societies. During the hunter-gatherer regime, humans were living rather like nomads, habited by nature and its ecosystems. With the agrarian society, the transformation of natural ecosystems into agriculturally cultivated land like arable land, grazing land or meadows started. Also, forestry practices started to be employed. The central innovation of that regime was the appearance of this new society-nature interaction, a land-use change also called “colonization of nature”, describing socially organized activities that alter natural systems to increase human benefits. The energy[19] employed in this regime was primarily derived from biomass (Fischer-Kowalski et al., 2014; Haberl et al., 2011), technical conversion of e.g. wind power and only to small extents based on the burning of charcoal (Haberl et al., 2011). This brought constraints on the potential to increase productivity, since output increases could only be attained by additional labour at declining marginal returns (Haberl et al., 2011). The next regime shift and socio-ecological revolution was and still is[20] from the agrarian society to an industrial one, in which fossil fuels are employed as the prime energy source. This transformation led to new patterns of material and energy use and triggered environmental changes on a global scale (Haberl et al., 2011). Due to the acceleration in economic growth after WWII and the increase in impact, the period afterwards is argued to be a new transformation and regime on its own, the “Great Acceleration” (Fischer-Kowalski et al., 2014). While the demarcation of regimes after the industrial revolution may not be entirely clear, a dividing line in the scale and dynamics of the human impacts upon Earth is set with the employment of fossil fuels. The term socio-metabolic regime can thus be described as the relationship and the way how human socio-

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[19] In this case energy is understood as the required food and energy to sustain their survival and their capacity to work (Haberl et al., 2011).

[20] Only one third of the world populations lives in developed and industrialized countries, with a big share of the rest still depending on agriculture and still rather living in agricultural societies (Haberl et al., 2011).

economic systems altered and employed the ecological system. This employment of nature has grown, accelerated and transformed over time.

The mentioned environmental challenges and their accelerations have a common cause: the continually growing use of natural resources to sustain the social metabolism (Haberl et al., 2011). Economic activity is inherently connected to the use of natural resources (Kerner et al., 2023) and they are an important source for national wealth around the world (Gylfason and Zoega, 2006). After WWII the input of resources has grown and has lately been growing faster than composite inputs of labor and capital[21] (Solow, 2016). On the aggregate level, the use of natural resources is strongly coupled with economic growth, while on a disaggregated level heterogeneity between countries exists (Kerner et al., 2023). This suggests that there is a difference of impact of GDP growth on resource use growth between countries. While natural resources are an important economic input, it is also experienced and discussed, that richness in those is not necessary for economic growth, since some of the World's richest countries like Japan, Luxembourg or Switzerland do not owe their wealth to nature (Gylfason and Zoega, 2006). As Mideksa (2013) reviews, there are two strands of literature on the economic impact of natural resources. One that argues them as economic blessings, as tradable goods in the construct of world economy, and one that argues them as an economic curse, that trap economies in lower wealth equilibriums relative to without them (Mideksa, 2013). Discussing the different argumentations behind those strands is beyond the scope of this work. With a perspective on the global economy and economic growth in general, it can be concluded that resources are an essential input factor, enabling economic activity overall and building the foundation for a global economy.

As a relationship it is indicated that economic growth leads to (further) industrialization, which expedites the extraction and consumption of natural resources (Ahmad et al., 2020). As pointed out in Solow (2016), it is not easy so far, to identify an approach of how much of the economic value growth is really due to natural resources (Solow, 2016). A recent report of the World Economic Forum, however, estimates that $44 trillion of economic value – more than half of the world´s total GDP – is moderately or highly dependent on nature and its provided resources and services (World Economic Forum, 2020). The world economy is dependent on resources as inputs and its continuing provision. The quantitative relation of the availability of natural resources and the rate of growth of real output mainly depends on the "importance" of such resources, the degree of substitutability between resources and the pace of technological

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[21] Both arguments are represented empirically for the U.S. economy in Solow (2016).

progress (Solow, 2016). The narrowing of a resource base or the increase in its prices will have a drastic effect on the level of growth and output if the resource cannot be easily substituted by an alternative or labor and if the progress of resource-saving technologies is too slow. In the following, those aspects will be discussed in more detail. At this point, it can be concluded that natural resources were and are a key factor for economic and human development and are the foundation of economies.

How natural resources and their economic processing and the resulting economic growth are interrelated is, however, interlinked with the domestic institutions (Gylfason and Zoega, 2006; Kerner et al., 2023). Gylfason and Zoega (2006) find that economic growth is directly related to the level of education, investment and civil liberties, but inversely related to natural resource dependency. They conclude that natural resources may affect growth directly through macroeconomic factors and indirectly through institutions (Gylfason and Zoega, 2006). How resources, technologies and economic growth are interlinked within an economy, is shaped and directed – at least to a certain degree – by institutional or governance factors. Kerner et al. (2023) e.g. suggest pronounced heterogeneity in the procyclicality of resource use between countries, i.e. the effect of economic on resource use growth, mediated by institutions. This heterogeneity in institutional effects, and that governance mechanisms are fractured into multiple jurisdictions at all scales, constitute it as one of the great challenges to learn how to deploy adequate governance systems in an increasingly linked world (Farber, 2015). The relationship of humans and the natural system habiting them is thus not only shaped by technological development, but also by institutions and governance mechanisms.

As Sureth et al. (2023) point out, it is surprising that the Planetary Boundary framework is not integrated stronger into economics, since it is fundamentally connected to the notion of "resources" and defines a global budget for natural capital flows that are utilized by humans (like carbon, water, nitrogen, etc.) (Sureth et al., 2023). Planetary boundaries like e.g. biodiversity and freshwater, are common pool resources, that are used by economic agents. Overarchingly, two potential ways exist by which transformational processes, reducing environmental pressure, can be induced: The actors that exert negative effects can be regulated – this could be described as supply side interventions – or the demand that drives these activities could be reduced – describing demand-side interventions (Farber, 2015). Referring to the notions of the "socio-metabolic regimes", two-third of the world population is currently in transition from an agrarian society to an industrial one (Haberl et al., 2011), such that the environmental burdens can be expected to increase accordingly. Already today the unsustainable extraction and consumption of natural resources has reached an all-time high in emerging economies (Ahmad et al., 2020), of which most belong to the noted two-third of the world population transforming from agrarian to industrial societies. To mitigate this development and avoid further damage, rapid development to a new regime is necessary – the sustainable regime (Haberl et al., 2011). The transitions between regimes changes the socio-ecological interaction fundamentally, while changes and variations within a regime are gradual (Haberl et al., 2011). Therefore, it is argued that the implementation of technical fixes and increasement of eco-efficiency alone is not sufficient and rather a variation within the existing regime than a transformation.

This sustainable regime differs from the industrial regime, similar to the difference between the industrial regime and the agrarian. The Earth carrying capacity cannot sustain the future projected human population under the energy standards of the current industrial regime (Fischer-Kowalski et al., 2014). What is needed, thus, is a re-orientation of society and the economy, what simultaneously entails the biggest challenge for sustainability.

The following sections will provide an overview of the overarching economic approaches and discussions on the necessity of such a holistic and global regime transformation and the anticipated effectiveness of technology in combating the global ecological pressures, to enable a future economy within the safe operating space for humanity.

1.3 Economic theory and the environment

At this point it can be summarized that natural resources are key input for the global economy, that the interaction between nature, the resources provided, and economic processes has changed over time and was shaped both by technological development and institutional conditions. The critical relationship between economic systems and the environment has gained increasing attention within the economic literature. Different conceptual frameworks have emerged from those discussions. While all of them recognize and evaluate the impact of economic processes on nature, the proposed counter actions and mechanisms employed within the concepts, to harmonize economic and ecological systems, differ strongly.

This section describes and differentiates the main conceptual frameworks, prevailing in theoretical economic discussions and political debates. Starting with the dominant concept of green growth as a framework of how to green the current economic paradigm, those traditional assumptions will be discussed and challenged in this section, with alternative framework propositions that gained more and more traction in recent years.

1.3.1 Green growth and the idea of decoupling

The attention from economists and politicians on climate change and its effects has generated valuable insights into the potential environmental harm due to economic growth. This favoured a shift from the sole pursuit of economic growth towards ecologically friendly economic growth (Danish et al., 2019). This concept is generally referred to and described as “green growth”. It seeks to encourage economic growth and development while balancing the concerns regarding environmental harm with the need for long-term economic growth (Popp, 2012). The United Nations Environmental Programme (UNEP) states that “*In a green economy, growth in income and employment should be driven by public and private investments that reduce carbon emissions and pollution, enhance energy and resource efficiency, and prevent the loss of biodiversity and ecosystem services*” (UNEP, 2011, p. 2). While there are definitions of “Green Growth” from a variety of official institutional bodies like the Organisation for Economic Co-operation and Development (OECD), World Bank or European Commission, there is also a lack of clear and simple indicators of whether economic growth at different scales (cities, nations, world) is “green enough” to enable economic evolvement within the Earths biophysical safe operating space, i.e. the planetary boundaries (Stoknes and Rockström, 2018). These definitions differ in their “degree of hardness” and can be categorized into “weak” and “strong” green growth (Smulders et al., 2014). The mentioned UNEP definition represents the strong version, as it focuses on the complementarities of maintaining natural capital and income growth. The weak view accepts that there are trade-offs between income growth and the environment and that those can be softened by appropriate policies (Smulders et al., 2014), like e.g. the one from The World Bank, that only seeks to “minimize” environmental impact of growth (Hickel and Kallis, 2020). This does not state anything about the degree of this minimization, and this definition or goal is still met and possible, despite overall increasing environmental impact.

Smulders et al. (2014) present a simple model, to illustrate the essence of green growth. A natural capital containing maximum output of an economy is given by

$$Y = F\ (K, R, N)$$

With the production function[22] F, containing the stock of man-made capital K, a stylized measure of natural capital[23] N, and a measure of resources extracted from the natural environment R. The premise is that nature as a stock provides direct benefits to consumers (Smulders et al., 2014). For example, a high-quality forest, a stock of whales or clean water have a positive value. N as well as R affect production. Once environmental pressures increase or ecosystem services decrease, total factor productivity will be negatively affected. The stocks of man-made capital and natural capital change over time when economic processes affect both. K increases with net investment, that is the output not consumed, nor used for extracting resources or used to replace worn-out capital.

$$\dot{K} = F(K, R, N) - C - \mu R - \delta K$$

C denotes the consumption, μR the costs of extracting resources, with μ being the unit extraction costs, and the depreciation rate of capital δ.

$$\dot{N} = E(N) - R$$

Nature has a regenerative capacity, E, and environmental quality improves if the resource use is less than the rate of this regeneration. This capacity, however, cannot grow infinitely large, why it is a function of the stock of natural capital. $E(N)$ approaches zero, if a stock of natural capital approaches its bio-physical maximum, is depleted beyond its point of recovery[24] or is non-renewable (Smulders et al., 2014). Put simply, green growth is possible and happening, if $E > 0$, that would be the case if production relies on renewable resources that recover faster than they are consumed. Such an economy could increase its GDP even without increasing its energy and resource input, by expanding the man-made capital. In this economy the intensity of resource use and the consumption of certain goods could be limited and ensured that $R = E(N)$ and $C < F(K, E(N), N) - \mu R - \delta K$, to keep environmental quality constant and net investments in man-made capital positive. The general idea is that reduced pressure on renewable resources can increase ecosystem services and ecosystem production, that ultimately

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[22] The production function is assumed with standard neoclassical properties: quasi-concavity, positive but decreasing marginal products of inputs, unbounded marginal product as the use of an input goes to zero; and the labour-force assumed constant to reduce complexity in expression (Smulders et al., 2014).

[23] This describes the stock of capacity that ‘nature’ possesses for providing diverse kinds of goods and services to the economic (and social) system, called ecosystem services (Smulders et al., 2014).

[24] The first both circumstances apply to regenerative natural capital rather than non-renewable, according to my interpretation. If a stock is not depleted and at its maximum, no recovery or renewal takes place. If it is depleted too far, renewing cannot take place anymore. And a non-renewable resource cannot recover anyway, causing E always equal to 0.

leads to increasing economic productivity within the sectors depending on those ecosystems (Smulders et al., 2014).

To ensure "genuine green" growth, that operates within those critical boundaries, science-based targets for stable Earth systems are required (Stoknes and Rockström, 2018). Since the current discussions and definitions are vague and lack concrete measurable indicators, the term is not without critique. The danger is seen, that it is a continuation of the conventional growth model, just under a new label – achieving only incremental efficiency and sustainability gains, but still disregarding ecological limits of ecosystems and the Earth. Green growth that, first, gets back into those limits, and, second, stays within them, could thus be defined as "an increase in economic output that lowers total environmental footprint" (Stoknes and Rockström, 2018, p. 42). This proposes absolute decoupling of economic output and growth from environmental damages and burdens (Stoknes and Rockström, 2018). An increase in GDP must thus result in a larger increase in resource productivity[25], i.e. in a larger decrease of environmental damage per unit of value added than growth in value added. This resource productivity must capture and be measured in a variety of different categories, like carbon, ecological footprint, and in the end any other realm of planetary boundary, to ensure a holistic and sustainable approach. Green growth in the category of climate, for example, would be given if the GDP of a country or the world increases by 2 %, while the carbon productivity increases by 4 %. In contrast to that, "grey growth" could be characterized as an "increase in economic output that also increases the total environmental footprint" (Stoknes and Rockström, 2018, p. 42), meaning that even if incremental improvements in efficiency are achieved, the total environmental damage does not decrease, due to absolute economic scale effects. (Stoknes and Rockström, 2018).

A mechanism that is considered for promoting and achieving green growth and the aspired decoupling is technological change – entailing both the widespread adoption of existing green technologies and the creation of new ones (Popp, 2012) (see section 1.3.2 for more detail). In neoclassical growth theory technological change is one of the primary growth drivers, besides the accumulation of capital (Smulders et al., 2014). Following up on the introduced model, this can be illustrated by two different energy classes as inputs into the economy: one that is fossil, non-renewable and environmentally damaging, and one that is renewable and environmentally protective (Smulders et al., 2014). The stock of fossil fuel is then denoted by S and the extracted

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[25] In literature the terms "efficiency" and "productivity" are not used consistently in this context. However, the same target is described by both, the reduction on environmental impacts (either via reduced resource inputs or reduced emissions). Here, the term "productivity" is adapted, although it should be noted at this point that the term "efficiency" is often used in the economic literature in this context.

fossil reserves by R, such that $\dot{S} = -R$. Now, both forms of energy input require a form of generation that is connected to economic costs. The unit mining costs for fossil fuels is given by the decreasing function $M(S)$ and as a substitute for fossils, the generation of renewable energy from wind or solar is introduced, given by B and the unit generating cost of β, at which B is supplied unlimited. At first, the costs for generating this alternative renewable energy are considered above the initial but below the last fossil extraction costs, $M(S_0) < \beta < M(0)$. The production now depends on two types of energy.

$$\dot{K} = F(K, R + B, N) - [M(S)R + \beta B] - C - \delta K$$

Environmental quality and the preserved fossil fuel stocks are positively related, since the less fossil fuel is extracted, the less CO_2 is emitted to the atmosphere, which has a direct effect on climate protection. This implies

$$N = S - S_0 + N_0$$

and

$$\dot{N} = -R$$

This formulation implies that $E(N) = 0$, describing that this economy rather depends on non-renewable than renewable resources and produces irreversible pollutions and climate change (Smulders et al., 2014). Without environmental policy, this economy uses fossil fuels, at least initially, until the extractions costs increase to a point at which the generation of renewable energy becomes economically attractive. The use of fossils would continue, and the economy would grow, under increasing extraction costs; that in the long-term would place a burden on growth. Political interventions, targeting green growth, could take different forms, but would always require cuts in fossil energy use. Such interventions could reduce growth in the first place, due to higher energy prices, but avoid the opposite force of increasing extraction costs later.

To bridge this growth gap and sustain growth, technological change is considered a dominating force. Non-renewable resource input is clearly restricted, since it is finite, and becomes increasingly expensive in extraction. But also the renewable resource use is constrained by the natural regeneration rate (Smulders et al., 2014). The economic resource intensity must fall over time, generating the same or more output, with non-increasing resource use. This requires resource substitution and input-augmenting technical change[26] A_i.

$$Y = F\ (K, A_R\ R + A_B B, A_L L, N)$$

This technical change now allows the effective resource inputs to grow, without growing “real” resource input (e.g. the effective energy input $A_R R$ grows with constant R).

The foundational concept, assumption and aim of green growth and technological change in terms of environmental economics, is that economic growth can be decoupled from resource use and carbon emissions[27], at a rate sufficient enough to prevent climate change and ecological breakdown in other areas (Hickel and Kallis, 2020). “Absolute” and “relative” decoupling can be distinguished (Smulders et al., 2014). The first requires that the ratio of a negative environmental externality, e.g. emissions, per unit of GDP falls at a rate (at least) equal to GDP growth, with the latter describing a decrease in the externality-GDP ratio at a slower pace than GDP growth[28]. However, to reduce environmental overshoot to a safe limit and to stay within the planetary boundaries, sufficient rates of transformations towards a green economy and decoupling are needed, and only “minimizing” the impacts, constrained by the pursuit of growth, is not enough (Hickel and Kallis, 2020) (in section 1.3.4 the empirical evidence and existence of decoupling, as well as its impact, is discussed in more detail). The theory suggests that with increasing political pressure, increasing decoupling can be expected (Smulders et al., 2014). Another argument besides and intertwined with government policy is that technological innovation will enable this (Hickel and Kallis, 2020). How effective those political interventions will be in reducing environmental pressure, will depend on the possibilities for technical change, substitution possibilities and rebound effects (Smulders et al., 2014). However, the correction of market inefficiencies in implementing adequate environmental market prices plays a central role in achieving efficient and sustained growth. Regarding

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[26] Labour and associated technical change are explicitly introduced here, to account for the necessary components to sustain growth, not least since this a critical component regarding the interaction between different types of technical change (Smulders et al., 2014).

[27] I.e. of environmental impacts in general; however, under the notion of “resource use” a lot of impacts can be assumed as captured.

[28] A popular concept spanning the discussion about economic growth and its decoupling from environmental degradation and impact is the Environmental Kuznets Curve (EKC). The EKC describes the development of the relationship between income per capita and indicators of environmental degradation, hypothesizing that in the early stages of economic growth ecological quality decreases, until a certain level of income per capita is reached, and the environmental quality starts to increase again with further income rises (Stern, 2017). Formally, this relationship is described by an inverted U-shape. The driver of this decoupling is the development in valuation of environmental quality. With low-income, environmental quality is relatively less valued, in comparison to prosperity, but gains in valuation, with increasing satisfaction regarding the level of prosperity. This decoupling in theory generally driven by structural and technological changes (see e.g. Dinda (2004) and Stern (2017) for introductions and reviews on the EKC).

resource consumption a reduction of ~20 billion tonnes[29] of global annual consumption is assumed to must be achieved – only to be compatible with our planet´s ecology (Hickel and Kallis, 2020). Regarding climate change, most models that project green growth within the projections of the Paris Agreement, rely strongly on negative emission technologies. Technological innovation plays an important role in promoting green growth, especially by reducing the costs of both types of environmental protection (Popp, 2012). Such technological solutions, reducing environmental harm, can be technical, e.g. "end-of-pipe" solutions that remove pollutants at the end of the waste stream before they enter the environment, but also behavioural changes that reduce the resource use in production and consumption (Popp, 2012).

Regardless of the concrete type of solution, they are necessary not in the long run but immediately and must be effective enough to tackle the severe ecological challenges we are facing. To create such a green economy that reduces carbon and protects biodiversity, solutions must be fostered and facilitated. No matter which innovation – if technical or social – a fertile framework must be given. As explained in the model, an economy will not change towards green technologies, on its own, if there are no economic necessities. To ensure that innovative activities and technological change develop as desired, the idea emerged to direct those activities by conscious economic incentives and signals. The concept of *directed technical change* puts such incentives into its centre, to affect the direction the economy as a whole while its technological state is developing.

1.3.2 Directed technical change and the environment

The economic idea of technological change can be traced back to Schumpeter (1942)[30], who defined three stages in this process: The *invention* of new technology, the *innovation* – that marks the commercialization of an invention – and the *diffusion* as the process of widespread adoption and application by the market (Jaffe et al., 2002). The "output" of this process can be innovations and technologies of incremental nature – being described by rather "normal" technical process – and radical innovation, leading to the emergence of completely new technological paradigms (Dosi, 1982), both will be outlined in more detail in the following. At

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[29] Own calculation, based on Hickel and Kallis (2020) deriving the maximum amount of material extraction/consumption of about 50 billion tons globally per year, to stay within the planets boundaries, and Wiedmann et al. (2015), estimating the global total material consumption of around 70 billion metric tonnes in 2008.

[30] As cited in Jaffe et al. (2002).

each of the three stages, incentives like e.g. from prices or regulations, affect the development and adoption of new technologies (Popp, 2012). Economic policies can be a powerful tool in influencing consumption patterns as well as rates and directions of cultural and such technological innovation (Daily and Ehrlich, 1996). Incorporating environmental policy measures, that “artificially” influence the prices for non-renewable and/or polluting resources (i.e. fossil fuels, in the case of the model from section 1.3.1), somewhat “direct” this technical change in a socially favoured direction, fostering green innovations, allowing for green growth (Smulders et al., 2014). The general assumption within the literature around the so-called *directed technical change* (DTC) is, that innovation can occur in pollution- or damage-creating (“dirty”), as well as in pollution- or damage-abating (“clean”) applications, and that by temporary environmental and technological political intervention, permanent changes towards clean technologies and sustainable growth can be achieved (Fischer and Heutel, 2013). Technical change is thus not a phenomenon solely evolving out of political actions – it is a natural part of the economic system. However, it is not always happening in the direction or in the pace socially favourable or optimal. The mechanism that underlies DTC is illustrated by studies analysing energy efficiency developments, around the energy crisis in the 1970s. As summarized by Haas and Kempa (2018), studies covering the period before the crisis (i.e. 1950-1970) find increasing or constant energy intensity within most developed and emerging economies. For the period afterwards, substantial reductions of energy intensity are suggested (Haas and Kempa, 2018). Increasing energy prices lead to lower energy intensities and temporal price shocks might even induce a persistent redirection of innovation activities. Technological change passively adjusts to the pressures and signals economic forces, mediated through the market and factor prices in particular (Rosenberg, 1969). Utilizing this economic response in favour of a socially attainable goal is the idea of DTC. And the environmental impacts of economic and social activities are greatly affected by the rate and direction of technological change (Jaffe et al., 2002), making targeted interventions appealing in combating ecological problems.

Overarchingly, two categories of innovation processes, fostered by DTC, and subsequent streams of literature and models can be distinguished (Hémous and Olsen, 2021). One focuses on innovations complementing existing technological classes and inputs, meaning that efficiencies within those inputs, like scarce resources and energy, are utilized by innovation. An example is the recent study by Hassler et al. (2021) that show that energy-saving technical change started around 1970, as a response to the price signals of the oil shocks (Hassler et al., 2021; Hémous and Olsen, 2021). Summarizing, with respect to environmental aspects, those are innovations that make existing technological classes more environmentally friendly, by reducing their impact, given unchanged inputs. There is a widely-held view that a more widespread diffusion of already existing and economically attractive technologies in this category entails the potential to reduce environmental impacts significantly, without innovating new ones (Jaffe et al., 2002). Another approach is that DTC fosters innovation that allows a substitution of inputs from “dirty” to “clean” ones (Hémous and Olsen, 2021), thus – more or less – utilizing a different technological class. A prominent example is the study from Acemoglu et al. (2012), that does not model energy-efficiency gains, but rather the complete change of inputs.

Independent of the technological class, the hypothesis is that firms R&D – as the engine for new technologies – are profit-motivated investment activities, causing that the rate and direction of innovation is likely to respond to changes in relative prices and is thus influenceable by policy interactions (Jaffe et al., 2002). As an example, the relative prices of inputs, for e.g. energy provision, are assumed to have an important effect on the types of technologies that are developed and adopted (Acemoglu et al., 2012), as illustrated earlier by the examples of Haas and Kempa (2018). The assumption is, that the firms within an economy are subject to a path-dependency, regarding their R&D and innovation activities (Aghion et al., 2012). Without any impulses, the direction of the technological development would not change, since firms within economies that have innovated majorly in e.g. carbon inefficient technologies, will find it more profitable, to continue innovating those, rather than switching to new ones. This is especially a relevant mechanism, when facing global problems like climate change or resource scarcity. The economy would probably head to an environmental disaster, without political interventions, that direct innovation and productivity towards “clean” inputs (Acemoglu et al., 2012). The market size effect and the initial productivity of “dirty” inputs would further direct innovation towards such sectors, instead of new and environmentally friendly ones. Those interventions, redirecting financial flows and technical change, could be only temporarily in force, until new and clean technologies are sufficiently advanced. If such “dirty” and “clean” inputs are sufficiently substitutable, those temporary policy interventions can achieve sustainable long-run growth, without long-run distortions. However, to achieve this, rapid and strong initial intervention is needed, to accelerate the transition and shorten the slow-growth phase. Once, this phase is bridged, and firms are nudged towards researching and innovating in clean technologies, they are again more likely to continue to innovate in this technological class (Aghion et al., 2012). Political interventions thus have the potential to induce innovations in clean technologies and create a path dependency and indirectly use this mechanism, that makes it probable that firms continue that path. This momentum then leads to overall cleaner and more sustainable technological applications and growth (Fischer and Heutel, 2013). One classical example of a political intervention is the carbon tax[31], that would thus trigger technical change like it would be triggered by merit price shocks, leading to more energy efficient technologies (Hassler et al., 2021). However, the political interventions can and should be multi-faceted to achieve optimal output. As argued in Acemoglu et al. (2012), the optimal policy implements research subsidies devoted to clean technologies, to complement a carbon tax and strengthen the structural development of clean innovation and technology (Acemoglu et al., 2012; Hémous and Olsen, 2021). Especially in sectors of naturally low R&D activities[32] the combination of policy instruments becomes necessary to adequately foster innovation (Grubb et al., 2021). In general, two different characterizations of (environmental) political interventions can be made (Jaffe et al., 2002). The mentioned ones[33], like taxes and subsidies, follow rather a market-based approach, encouraging firms to undertake pollution control efforts, by utilizing a market mechanism. Besides those, command-and-control instruments can be applied that set uniform standards, e.g. regarding performance and technology. The latter, however, could be counterproductive, since the costs of e.g. controlling emissions, may vary greatly among firms, causing a technology being cost-effective in one situation, but -ineffective in another.

Hémous and Olsen (2021) summarize the amounts of empirical evidence that the direction of technical change responds strongly to economic incentives in the environmental context and that the assumptions of the DTC hypothesis are backed-up and endogeneity matters for macroeconomic output. According to Grubb et al. (2021) the literature also evidently states that innovation is a complex and multi-faceted process, with numerous interdependencies and uncertainties, not only influenced by the mixture of instruments and incentives, used and set by policy, but also the extent to which a government is committed to a certain course, like e.g. decarbonization. Besides the development and adoption of green technologies within developed countries, the transfer of such to developing ones is and will be of great importance, to further allow for green growth (Popp, 2012) and enable a fast and global sustainable development. As it is indicated throughout the chapters 2-4, developing countries are critical players in achieving

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[31] Carbon tax is already a specific intervention. In general, the tax is a classical category of political instrument, applicable to all sorts of economically relevant inputs, connected to environmental degradation or pressure (Baiardi and Menegatti, 2011).

[32] Sectors differ according to their level of R&D activity: Sectors like IT and pharmaceuticals are recognized as highly innovative, spending around 10-15% of their turnover on R&D; the major energy-using sectors, like industry and transport, however, only devote around 3-5% of their turnover to R&D (Grubb et al., 2021). Thus, carbon pricing alone would not be sufficient to stimulate/generate adequate innovation in the latter sector.

[33] Further examples could be tradeable permits and information programmes (Jaffe et al., 2002).

global sustainable development. Many of them are only at the beginning of their transformation from agrarian to industrial societies (Haberl et al., 2011), making it critically important to enable them to leapfrog directly to cleaner technologies, when they go through a phase of rapid economic growth (Herman, 2023). The appealing feature of DTC is the wide applicability to diverse economic resources and processes impacting the environment, and the simultaneous facilitation of further economic growth. The following sections will challenge this technology-reliant view and discuss alternative concepts and ideas.

1.3.3 From Environmental and Resource Economics to Ecological Economics

In economic theory two distinguishing streams of theory and economic schools have developed, according to ecological-economic issues and questions. Mainly triggered by the Limits to Growth report in the early 1970´s (see Meadows et al. (1972)), that suggests ecological collapse under continued economic growth, the *neoclassical environmental and resource economics*[34] (ERE) and *ecological economics* (EE) developed as two diverging approaches (Couix, 2019). The first is characterized by the idea and assumption that resource productivity can be increased indefinitely, thanks to substitution of capital to resources or technical progress, as outlined in the previous section. This idea is incorporated in this rather model-based approach and its applications. With their works in the early to mid-1970´s Solow and Stiglitz[35] provided the analytical framework, around which a whole literature emerged (Couix, 2019). The second, ecological economics, proposes theoretical considerations leaned towards the Limits to Growth-idea (Couix, 2019) and emerged as a response to ERE (Van Den Bergh, 2001). Initiated by Nicholas Georgescu-Roegen (1971) this economic theory is centred around the idea of thermodynamics and clear physical boundaries to resource productivity (Couix, 2019). Later, Georgescu-Roegen´s concepts were institutionalized by Herman Daly, concretely manifested as EE. The basic idea is that energy as well as matter within an isolated system, increase to an entropic maximum, describing a qualitative degradation from low entropy to high entropy and is thus irrevocable. Rooted in the physical laws of thermodynamics, this assumption states that

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[34] There are different terms in use, which all describe the neoclassical approach of environmental and resource economics. Van den Bergh (2001) uses the term “traditional environmental and resource economics”, Smulders et al. (2014) refers to it as “neoclassical environmental economics” and Couix (2019) uses the term “neoclassical resource economics”. The term “neoclassical environmental and resource economics” is employed in this section, to capture different potential features of the terms described and to represent the overarching approach.

[35] See e.g. Solow (1974) and Stiglitz (1974).

not all energy can be employed in a transformation (e.g. from coal to movement) and that it cannot be recovered fully (e.g. in case to transform into other energy forms). In EE clear physical boundaries to substitution and technical change are assumed to exist and to limit its solution potential to ecological issues.

In ERE, the central assumptions like substitutability and technical change primarily appear as mathematical properties of production functions (Couix, 2019). The fundamental issue here is that the different forms of substitution[36] rely on underlying mechanisms that are not explicitly represented in the model, and that they cannot be clearly distinguished from technical change. Some mathematical representations, leading to results and interpretations favouring unbounded resource productivity, are not grounded in conceptual appreciations of the production process, but instead in modelling practices and mathematical concern. The mentioned notion of "weak green growth" is a well-established perspective in ERE (Smulders et al., 2014). It does not seem to take absolute physical limits to growth and the economic system seriously into account and regards the problem of a "maximum scale" as irrelevant (Van Den Bergh, 2001). It is assumed and somehow relied on the premise that certain solutions to ecological issues are found in the economic system. In contrast to this model-based approach of ERE, interdisciplinary consistency is of major importance in EE (Couix, 2019). The consistency of the assumptions and results of economic theory with other scientific disciplinaries (Couix, 2019), bringing in the core contributing disciplines of physics and ecology (Van Den Bergh, 2001). A far-reaching integration of economics with insights from ecology is proposed, adding criteria like resilience and productivity of ecosystems and biodiversity, often covered under the term "ecosystem health" (Van Den Bergh, 2001). EE attempts to step away from a pure reliance on the problem-solving capabilities of the economic system via substitution and technical progress, towards a more critical and holistic view, not based on mathematical requirements, but on rather qualitative evaluation and incorporation of interdisciplinary evidence (Couix, 2019). Of special importance to EE is the structure and institutional context in countries and especially developing ones (Van Den Bergh, 2001). Both disciplines have claimed the "right path" of economic theory for themselves. However, both are facing important conceptual issues and none is providing a definitive proof of its own (Couix, 2019).

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[36] Couix (2019) points out, that there are essentially three different forms of potential substitution, that cannot be clearly distinguished from technical change in all cases. There can occur substitution between resources, substitution in a change of output composition, from resource intensive to less resource intensive goods, and it can denote a transformation of the production process towards fuel-saving technologies (Couix, 2019).

It can be emphasized that there is a general and overarching debate about the “right” way to harmonize economy and ecology, based on the general dispute points between ERE and EE. Hickel and Kallis (2020) has summarized that while not backed by empirics, green growth and decoupling are theoretically possible – at least in the short to medium run (Hickel and Kallis, 2020), what is also the time horizon generally considered in ERE models (Couix, 2019). Then the central question is, why it doesn´t happen and if there is an underlying fundamental and reason for that (Hickel and Kallis, 2020). From basic economics it is known that technological development causes economic growth and consumption. The Jevons´ paradox states that the more efficiently an economy uses resources, the more it grows and the more resources it ends up consuming; not referring to small micro-level rebound effects, outgrowing efficiency gains, but a more fundamental macro-level mechanism, through which industrial economies grow by utilizing resources increasingly productive[37]. There is no clear evidence nor argumentation, why increasing efficiency and more productive resource use would not lead to an overall, macroeconomic growth of the economy.

Following the discussion on “weak” and “strong” green growth, this notion is also applied to sustainability in general. Weak sustainability considers economic capital and natural capital as substitutable, aiming to maintain the sum of the total capital, neglecting its composition (Van Den Bergh, 2001). Strong sustainability requires that every capital is maintained separately. ERE starts from weak sustainability and EE usually from some type of strong sustainability, operationalized through goals such as protection of critical ecosystems or maintenance of biodiversity (Van Den Bergh, 2001). Barbier and Burgess (2017) interpret that respecting the planetary boundaries represents a “strong” sustainability perspective, since its processes and systems, the natural capital, are non-substitutable with reproducible or human capital (Barbier and Burgess, 2017). Adequately strong measures must be implemented, to bring the system back below those boundaries. All that is below those boundaries, the depletable stocks, however, can be managed under the principles of “weak” sustainability with standard tools of natural resource management and various conditions for optimal use, price paths and technological innovation (Barbier and Burgess, 2017). Since also optimal exploitation/use paths

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[37] The Jevon´s paradox overarchingly describes the correlation between increased natural resource consumption under simultaneously increased efficiency (Polimeni and Polimeni, 2006). The paradox states that technological improvement and efficiency gains will not lead to overall reduced consumption, but rather the contrary, namely even increasing demand and use. Like the steam engine, generating massive efficiency gains, that led to an overall increase in scale of production and in the demand for coal, efficiency gains of new emerging technologies will lead to more consumption in the end. The Jevons´ paradox is also known as the *rebound effect* and can be differentiated by the *rebound mechanisms*, describing the changes in consumption, and the rebound effect, describing the size of this mechanism (Lange et al., 2021). It can be related to all economic levels (micro, meso, macro and global) and short- as well as long-run time frames.

end up eventually depleting a safe operating space, innovation that reduces the dependence and demand of an economy on and for natural resources is of importance to extend the lifespan of the safe operating space, possibly even indefinitely. It is thus of importance for policy to foster innovation, especially those that reduce GHG emissions or improve agricultural yields and sustainable land management practices to reduce the pressure for crop land expansion and the need to convert natural forests. Regardless of the argumentation, however, it is unchallenged that all technological innovations possible are needed and that governmental policy must drive those innovations (Hickel and Kallis, 2020). Challenged is the assumption, that this alone will be enough. The difference between the targets and the anticipated effect of current actions regarding climate change mitigation could serve as an example. As stated earlier, in section 1.3.1, most models that project green growth within the targets of the Paris Agreement, rely strongly on negative emission technologies (Hickel and Kallis, 2020). Those, however, are unproven (or potentially even dangerous) at scale. There is no existing evidence that green growth in a sense of continuously increasing growth rates and sufficient decoupling is possible (see section 1.3.4 for more detail). The only combination enabling to economize within the carbon budget, are growth rates approaching zero and the most aggressive possible and immediate mitigation policies – and this only allows to stay within the 2 °C budget. Reaching emission reductions necessary for the 1.5 °C budget are empirically not feasible, except in a de-growth scenario.

From the discussion between ERE and EE the following can be distilled: technological change and innovation towards the relieve of the Earth system is necessary and favoured. Nevertheless, potential physical limits should not and cannot be ignored. Furthermore, while technological solutions are necessary, they cannot solve all ecological issues on its own, and should not be propagated as the only viable and necessary solution. An alternative approach that has emerged to first, bringing the global economic system back into the safe operating space, and second, staying within it, is the concept of degrowth. This more radical idea seems to have gained traction recently, as a counterpart to techno-centred green growth. The following section will discuss the concept of degrowth in more detail, before the dissertation papers are summarized and set into context.

1.3.4 The Growth Debate and the concept of degrowth

Apart from discussions around different terminologies of sustainability, like “weak” and “strong”, or different theoretical approaches, a more general and overarching discussion has emerged. This often so-called “Growth Debate” is essentially characterized by three main questions: is economic growth desirable? Is it feasible? And, is it controllable (Van Den Bergh, 2001)? ERE and EE have different answers to those questions (Van Den Bergh, 2001). ERE is in general more optimistic, that the current economic system with its mechanisms can solve ecological problems, under or even with continuing economic growth, e.g. by decoupling through technological solutions. EE is rather precautionary and refers to the different dynamics and feedbacks between growth and ecological systems. While this debate has emerged out of the dispute between ERE and EE, the suggestion of growth rates not only approaching zero but even negative ones, has born a concept of its own – the idea of degrowth. This alternative concept states that economic growth and ecological sustainability are incompatible and a downscaling of consumption and production is required for a sustainable society (D’Alessandro et al., 2020) and further economic growth should not be aspired. Hickel (2021) defines degrowth as “[…] a planned reduction of energy and resource use designed to bring the economy back into balance with the living world in a way that reduces inequality and improves human well-being”[38] (Hickel, 2021, p. 1105).

As outlined (see section 1.3.1), the policy proposal of green growth is the main response to sustainability challenges (D’Alessandro et al., 2020). However, despite its prominent position, it is increasingly questioned, due to certain drawbacks. The ability of market mechanisms to reduce or solve environmental damage, to meet the planetary boundaries and its capacity to create jobs, under decreasing correlation between growth and employment due to new technologies, are unclear. The green growth concept still represents the traditional economic assumption that perpetual economic growth is necessary, and tries to find ways to harmonize this growth with environmental constraints, primarily by the idea of decoupling (Hickel, 2021).

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[38] A further important aspect of degrowth is the increase in global income equality and just distribution of wealth and well-being (Hickel, 2021). Since it focuses on the reduction of excess resource and energy use, it does not apply to economies not practicing such excesses. The “global North”, describing the global high-income and developed countries, is responsible for most of the ecological breakdown, while the “global South” (the low-income and developing countries) suffers the most from the consequences. Degrowth tries to provide solution approaches to enable the global South to build economies and social systems, absent of environmental and social damages. This has consequences for the access of the North on cheap natural resources and the accumulation of wealth. While this discussion is an important and integral part of the idea of degrowth, it is beyond the scope of this work to go into this topic in depth at this point.

While current empirical evidence suggests rather relative than absolute decoupling, the latter is still not suggested unfeasible in theory (Smulders et al., 2014). However, the ability to effectively decouple is currently not represented sufficiently to perceive it as a resilient solution that can be fully relied on. Parrique et al. (2019) extensively review the empirical literature on the existing decoupling of different resource uses and impacts. They describe their findings as "overwhelmingly clear and sobering" and conclude that there is not only no empirical evidence supporting the existence of decoupling anywhere near the scale needed, but also that such decoupling is unlikely to happen in the future[39] (Parrique et al., 2019). Hickel and Kallis (2020) also summarize that historical trends show relative but no absolute decoupling, and the recent trend of the 21st century displays a worsen of efficiency and rather a re- than a decoupling, with respect to resource use[40]. A sufficient decoupling of growth from carbon emissions is also not found (Hickel and Kallis, 2020). At a global level the CO2-emissions have increased steadily, falling only during recessions. And overall, the rate of global carbon productivity[41] improvements has been stagnating since approximately 2014. Business-as-usual is set to lead to 4.2 °C of global warming by 2100, making it dramatically insufficient to reach the targets of the Paris Agreement, of 1.5-2 °C (Hickel and Kallis, 2020). Empirical data suggests that absolute decoupling of emissions from GDP is possible and already happening in some regions. Nevertheless, it is assumed unlikely that this decoupling happens fast enough to stay within the carbon budget necessary to respect the 1.5- or 2-degree mark. Despite the little grounding and missing historical evidence of absolute decoupling (Hickel, 2021; Hickel and Kallis, 2020), policy holds on to this. If the decoupling from carbon emissions is assumed as possible in general, despite the discussions of its rate is sufficient to reach climate goals, this concept assumes and requires a decoupling from all environmental impacts, like also deforestation, biodiversity loss, and soil depletion, etc. (Albert, 2020). This requires total resource consumption and land use to shrink or remain stable, even as the total output of the global economy increases, like the assumed tripling by 2060. The concrete magnitude of the decoupling challenge remains unclear. Although technological change can also make a difference here, it can be assumed that the necessary decoupling will be more difficult, and it is unclear whether this can be achieved at all (Albert, 2020; Parrique et al., 2019)

Degrowth, or often also coined as "post-growth", breaks with this, and entails a new paradigm rather oriented towards cultural and value-based changes. Besides traditional environmental

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[39] For an overview of reviewed studies and results, see Appendix of Parrique et al. (2019)

[40] This statement is based on the use of resources (see Hickel and Kallis (2020)).

[41] A measure of CO_2 emitted per unit of GDP produced.

policy measures, it incorporates measures that focus on reducing the “unnecessary” (at least from an environmental standpoint) and call for a holistic sustainable shift of the society. Suggested measures are for example working time reduction, coupled with governmental job guarantee programmes and the creation and an engagement of and in an “amateur economy” that provides goods and services that substitute “professionally” and energy-intensively produced goods, employing the saved working time available (Sekulova et al., 2013). While the reversal of economic growth is central to this concept, it is not about reducing GDP per se, but rather about reducing the material throughput of the economic system, what is the important aspect from an ecological viewpoint (Hickel, 2021). Of course, such a reduction can potentially result in reduced GDP, why this outcome must be considered and managed in a planned, just, and safe manner. While sometimes criticized for mimicking a recession with all its negative effects, degrowth is not the same. It is argued to be a planned and coherent policy, to harmonize the economic system with the boundaries of the Earth system, by scaling down those economic activities that are ecologically destructive and socially less necessary, like e.g. the production of SUV´s, beef or planned obsolescence.

In a macrosimulation, D’Alessandro et al. (2020) investigate the long term effects of three different economic scenarios on France for the period 2014-2050, regarding a set of different economic and sustainability measures (D’Alessandro et al., 2020). One of them is a green growth scenario, based on technological developments and environmental policy, to foster incentives for innovations, the adoption of renewable energy, and implementation of mechanisms like a carbon tax and carbon border adjustments[42]. And one is a degrowth scenario, covering the attributes of the green growth scenario, but adds more radical policies, like incentives for labour-saving technologies, a job guarantee program, working time reduction, a reduction in consumption and imports and a wealth tax. The first achieves a significant reduction in GHG emissions at the costs of increasing income inequality and unemployment. The degrowth scenario achieves the highest reductions in GHG emissions and income inequality of all scenarios, but is accompanied by the highest public deficit, despite the introduction of a wealth tax (D’Alessandro et al., 2020). Independent of the social benefits and drawback of public deficit, the degrowth scenario is the only one in the study able to achieve emission reductions high enough, to fulfil the set reduction goals.

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[42] Similar to a carbon tax on imported goods, according to their incorporated carbon emissions (D’Alessandro et al., 2020).

Van den Bergh (2011) argues that degrowth is still not a fully stringent concept and rather inconclusive, involving different strategies that are not clearly differentiated (Van Den Bergh, 2011). Further, most interpretations of degrowth do not represent strategies which guarantee a reduction of environmental pressure nor a systemic sustainable transition and are rather idealistic discussions than evidently working and effective solutions. Degrowth also neglects relevant aspects. First, it underestimates the role of technological change. While it becomes increasingly evident, that technology is not the sole solution one should rely on, it is a critical component of a sustainable transformation and economy. Second, it tendentially focuses on bottom-up movements and rejects top down environmental policy, what is suggested as the fundamental basis and effective measure to reduce pressure and induce change. Third, in emphasising bottom-up developments, degrowth concepts often lack in considering modern insights from psychology and behavioural economics. Human characteristics like bounded rationality, myopia, a large degree of self-interest and the propensity to seek comparison and status, are critical to consider when aspiring transformation (Van Den Bergh, 2011). Cultural and institutional aspects must be taken into account as central ones, when paradigm changes like degrowth are aspired. D’Alisa and Kallis (2020) argue that besides grassroot actions also institutional changes are essential. While most degrowth economists may differ in the details of their diagnosis, they basically agree on the solutions called for: carbon and green taxes, resource caps, green bonds, maximum and minimum income or working hour reduction, etc. (D’Alisa and Kallis, 2020). How to create those radical “green institutions” and where they come from remains discussed relatively less detailed. The state plays a major role in fostering and interacting with those institutions. At the level of political strategy, as a first step the groundwork at the realm of civil society is proposed. Institutions that allow for an acceptance of potential degrowth measures, absent of the idea of continuing growth and unlimited wealth, should be strived towards. Since the state is not independent of the civil society, both must change in symbiosis, on what science could have a supportive function. As already mentioned in section 1.3.3 in the context of Jevon´s paradox, there may be rather overarching forces, hindering the environmental utilization of gained efficiencies. Richters and Siemoneit (2019), for example, point out that possibly a systemic “growth imperative” exists that makes growth policies inescapable. Those are defined as exterior conditions that make it necessary for economic agents[43] to increase their economic effort and to grow, to avoid existential consequences (Richters and Siemoneit, 2019). For firms such an imperative is technological development itself, requiring steady increases in efficiency, to remain profitable and able to

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[43] Those economic agents can be individuals, firms or even states (Richters and Siemoneit, 2019).

survive. The aspired growth could thus rather be a matter of a lack of systemic possibility than a lack of willingness. This strengthens the need for appropriate institutions that limit resource consumption and prevent or redistribute resource and land rents (Richters and Siemoneit, 2019).

While the discussions on the role of the state and potential degrowth pathways are still at a conceptual and rather ideological level, Van den Bergh (2011) stresses that demonising GDP (and also growth) in every context would be misleading, since its information is the basis for macroeconomic decisions, also to decide if to aspire further growth or degrowth. It is proposed to rather become indifferent about GDP-growth, suggesting the term "GDP a-growth".

Independent of the terms coined, also from the modelling example of D'Alessando et al. (2020), it becomes evident that more than some taxes and subsidies are needed, to engage technological development. This is a critical component, but not the sole solution. To achieve a lasting safe operating space and the politically set goals, actions towards green technologies and green institutions are needed, not shying away from incorporating more radical ideas and movements, if necessary to ensure the health of planet Earth in a just way.

1.4 Overview of the Dissertation Papers

This section gives an outlook on the following chapters of this thesis. The papers investigate the role and developments with respect to all mentioned core aspects of the sustainability transformation, namely: the role of governance and institutions, the role of consumption, and technological change. The papers employ, geared to the specific question at hand, different indicators capturing different environmental dimensions and central aspects of decoupling including resource indicators, as input indicators (like raw materials, land and energy), as well as impact indicators (like biodiversity loss and carbon dioxide emissions)[44]. By taking a global perspective, understanding is gained on the current role of these critical aspects in fostering developments towards sustainability within the current regime. All of them operate on the aggregated country level, elaborating both general and overarching trends and distinctions and specificities of and between the countries analysed. The studies altogether provide a good overview and new insights into critical sustainability questions, that concern the world of economics and politics.

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[44] For a more detailed distinction between resource and impact decoupling indicators see Parrique et al. (2019).

Table 1: Overview of the dissertation papers

Chapter	**Title**	**Geographical scope**	**No. of Countries**	**Time span**	**Dependent Variable**	**Main econometric method**
2	On the tension between natural resource extraction and biodiversity – do governance characteristics matter?	Global	156	1996-2012	Domestic Raw Material Extraction	Fixed Effects Regression
3	Global convergence of meat consumption – is income growth an insurmountable force?	Global	121	1984-2013	Per capita Meat Consumption	Convergence Clubbing Algorithm & Ordered Logit Regression
4	The Impact of Environmental Innovation on Carbon Dioxide Emissions	European Union	27	1992-2014	CO_2-Emissions	Difference Generalized Method of Moments Regression

All the papers address concrete anthropogenically and economically driven environmental pressures. The first study (Chapter 2) contributes to the literature on economic material consumption and its implications on biodiversity, specifically incorporating governance characteristics. Economic processes and growth depend on natural resources, exposing increasing pressure on natural capital. To gain a detailed understanding of the impacts of different material classes becomes increasingly important, especially in the light of changing resource demands, like e.g. due to global digitalization or agricultural demands. To understand, how certain governance mechanisms mediate or influence this impact is of critical importance, especially, to evaluate and design political measures. The second study (Chapter 3) addresses the increasing concerns regarding global meat consumption, potential convergence towards high "western" levels with increasing income, and its impacts on ecosystems and climate. Meat consumption is assumed to increase with increasing income, entailing severe risks for nature and climate, if developing countries would start to aspire similar consumption, as they experience economic growth. A better understanding of the income-consumption relationship and potential inhibitors are of central importance, to first, anticipate developments and second, design appropriate counter measures. The third study (Chapter 4) addresses the question of reducing impacts of environmental innovation (EI) on carbon dioxide emissions, an environmental indicator of high ecological and political importance. By this, the prevailing paradigm of green technical change and innovation for a decoupling between growth and emissions and a resulting green growth is investigated in more detail.

All studies are thematically linked to each other in one or more ways and aspects, which reflects the systemic nature of the overarching topic. In analysing the impact of resource extraction on biodiversity, the frame is set to look at developments of one big driver of this resource consumption: meat consumption. Livestock production has immense impacts not only on ecosystems, but also on carbon dioxide emissions and climate change, linking to the question of the potential solution power and material effects of EI, emerging out of directed technological change, with respect to a broader scope of the economy.

1.4.1 On the tension between natural resource extraction and biodiversity – do governance characteristics matter?

This paper studies the relationship of natural resource extraction and biodiversity, and the influencing effect of certain governance characteristics. It is motivated by the urgent and crucial question of the destructive impacts of natural resource extraction for economic processes on the vitally important global biological diversity, and the ability and influence of governmental characteristics on mitigating those. To gain a better understanding of the impacts of resource extraction on the macro-level, especially quantitative analysis is valuable to both literature and practical-political decision information. This paper contributes to the literature on the relationship of environmental pressures and governance characteristics, as well as resource and environment interrelation.

For empirical studies it is challenging to proxy biodiversity since it is such a multi-faceted measure, and globally available indicators are still scarce. This study employs forest area data from the FAO, since those represent biodiversity accordingly as a reasonable proxy for important habitat and bring along some advantages regarding scientific studies, compared to alternatives. For robustness, also protected area is incorporated. Four distinct classes of material flows are incorporated at an aggregated level, representing the direct, gross physical domestic extraction of such materials within a country. Those are Biomass, Fossil Fuels, Metal Ores, and

Non-metallic Minerals. As governance characteristics of interest, Control of Corruption, Political stability, and Rule of Law are incorporated. The study constructs a data set for 156 countries and a time span of 1996 to 2012. In the analysis, different descriptive evaluations and cross-sectional regressions are performed.

The study reveals the following insights. Resource extraction in general is found to exert a negative impact on biodiversity. As most impactful biomass extraction is identified. Furthermore, fossil fuels and metal ores extractions are also found to significantly affect biodiversity in a negative way. Only Non-Metallic Mineral extraction is not found to impact the proxy of forest area, but the indicator of protected areas. The results suggest that governance characteristics matter. In countries with a low institutional level, the amount of resource extraction has doubled, and forest area decreased, contrasting that in countries with higher institutional levels, the amount of extraction stayed constant with increasing forest area. While there is not found an interacting effect of institutions on the relationship between resource extraction in general and biodiversity loss, especially Rule of Law is suggested to have a positive effect, indicating that increasing levels of Rule of Law (ROL) could be accompanied by forest area growth, and i.e. better forest area and biodiversity conservation. This could indicate towards the importance of contractual and property rights in mitigating deforestation and habitat loss, since those are central components of ROL, highlighted by the literature. When focussing on biomass, however, all governance characteristics seem to have significantly positive interacting effects. This suggests that increasing institutional quality has the potential to diminish or cushion the generally negative effect of biomass extraction on biodiversity.

This study makes two main contributions. First, it contributes to the literature on the relationship between institutions and biodiversity, with a special focus on resource extractions. It delivers important insights into the potential power of governance mechanisms to mediate or interact with the destructive impacts of resource extraction. Second, it contributes to the literature on extractivism, by quantifying the impacts of different resource categories on biodiversity. This is of special importance and value, since most existing studies look at agriculture, however, not at other resources that also potentially harm biodiversity. Especially the quantification is of value since it provides a concrete baseline for a prioritization of further investigations. Biomass seems not only to exert the most severe impact on biodiversity, but also seems to be most receptive for governance mechanisms.

1.4.2 Global convergence of meat consumption – is income growth an insurmountable force?

This study analyses the global convergence behaviour and influencing factors of meat consumption, with special attention paid to income as a prime driver. It is motivated by the severe pressures that increasing meat consumption and accompanied livestock production exert on the environment and public health, and the enormous potential increase in consumption, if developing countries grow economically. In my first outlined paper (see section 1.4.1 and the whole article in chapter 2) it became evident that biomass extraction is impactful on biodiversity. One substantial part of this extracted biomass is grazed biomass and fodder crops[45], utilized to feed animals. Driver of increasing habitat loss and other environmental pressures is the accompanied land-use change and agricultural practices of meat production. As a driving force of meat consumption, however, economic growth and increasing income and affluence are regularly associated, based on observations from developed and "western" or "westernized" countries. This study is dedicated to the question if there is a global convergence of meat consumption, and if income is indeed the only or dominant determining force.

As the dependent variable, this analysis employs data from the FAO on meat consumption per capita and year. The main analysis processes those in a clubbing algorithm, as outlined by Phillips and Sul (2007). This procedure investigates if there is overall convergence within a sample towards one shared equilibrium, or if there are rather "clubs", i.e. sub-groups, that converge to club-specific equilibria. In addition, besides descriptive statistics, an ordered logit model is estimated, incorporating a variety of socio-cultural factors, like e.g. religion, demographics, and education, assumed to potentially influence and shape the convergence trajectories of meat consumption under increasing income. Two estimations are performed, one with the individual control variables and another with the control variables and GDP per capita, testing for the potential dominant effect of income. A strongly balanced data set is needed for the main analysis. Due to data availability some countries must be excluded. The final data set, employed by this study, covers 121 countries over the time period of 1984-2013.

Overall, this analysis allows deeper insights into convergence dynamics and the potential power of influencing factors and suggests a variety of interesting results. During the observed time period, the difference in the amount of meat consumption between the countries decreased,

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[45] See Technical Annex for Global Material Flows Database.

suggesting convergence. Furthermore, by conducting a convergence regression, it is shown that the initial level of consumption is a significant determinant of future consumption growth rates. The lower the initial level of consumption, the higher the average future growth rates in consumption. This indicates that countries consuming relatively less meat, “catch-up” in the future. The clubbing algorithm rejects overall convergence and suggests the existence of two clubs, converging to different equilibria. One club tends to consist of developed countries and the other of developing ones, pointing out that there are differences. Most of the control variables become insignificant when GDP per capita is added in the ordered logit regression, indicating that income captures the effects of those determinants. However, religious backgrounds, with a persistent consumption decreasing effect of Islam, is found significant and education seems to significantly increase the probability of higher meat consumption levels, which is at odds with many considerations of higher education fostering more sustainable consumption patterns. My results strengthen the assumption of GDP per capita, i.e. income, as the major driving force of meat consumption increase.

This study contributes twofold to the literature on meat consumption convergence: First, it provides a global analysis of club convergence, providing new context regarding different sub-groups of countries. Second, it gives quantitative context to the discussion, which factors potentially influence meat consumption and are potentially mitigating consumption growth, despite increasing income.

1.4.3 The Impact of Environmental Innovation on Carbon Dioxide Emissions

As outlined above, besides the loss of biological diversity, climate change is one of the biggest current and future challenges. The two previous papers analysed resource extraction, the accompanied deforestation, and livestock production, i.e. meat consumption, which both are recognized as central drivers of greenhouse gas emissions and thus accelerators of climate change (see sections 1.2.2, and chapters 2 and 3). This study is motivated by the relevance of carbon dioxide emissions and its contribution to climate change, and Environmental Innovation (EI) as a solution approach. In this paper we analyse the impact of EI on carbon emissions, at the national level, and provide relevant value and evidence to the literature, if it is politically desirable to pursue EI.

This paper is interested in analysing the impact of EI on CO_2 at the national level. To construct a comprehensive indicator for EI, patent data are employed. Yearly patent counts of EI patents are utilized, classified based on official search strategies from the World Intellectual Property Organization (WIPO) and OECD. The data set constructed captures 27 EU countries for the period of 1992 to 2014. In our analysis we focus on the effect of domestic green innovation on territorial carbon emissions. With this study we aim to identify the impact of EI on carbon emissions. Technological development and change are a central solution approach to combat climate change and decouple economic growth from environmental pressure. It is of great interest therefore, to quantify the concrete potential effect of current green innovative activities, and to discover, if this effect is indeed unique to EI. Furthermore, we want to deliver insights into the country heterogeneity regarding those impacts.

In the study, a dynamic panel analysis is employed. The results contribute in different ways. In addition to the analysis of the concrete quantitative impact of EI on carbon emissions, the importance of country-specificities in this relationship are highlighted. First, our main finding is that EI has a significantly reducing effect on carbon dioxide emissions. And this effect is distinct from general innovation, that are not found to have a significant effect. Second, the amount of energy consumed and its composition play an important role in reducing CO_2 emissions. Energy consumption and the share of renewable energy in the energy mix are found significant with large effects. Third, the effect of EI is found to be weaker in less developed economies Eastern European than in developed Western ones. When countries are excluded based on their domestic fossil industry, this effect becomes even stronger, suggesting that the effect of EI may be weaker specifically in countries with a strong domestic fossil industry. This indicates that national institutional aspects seem to be important with respect to technological mechanisms and effects. The mixed results regarding the effects of EI in Eastern European countries indicate that the level of heterogeneity concerning technology effects is higher in less developed economies.

The paper contributes to the literature on the environmental effects of EI. It is the first cross-country study on CO2 focussing on the national instead of sectoral level. Furthermore, with the findings on the heterogeneous effects of EI, this study contributes to institution and development economics argumentations. The institutional and governmental conditions, such that green technological innovation emerges and is applied matters.

1.5 Conclusion

This introductory chapter provides a scientific basis and context for the following chapters and empirical papers of this dissertation. Core concepts and environmental challenges, like the planetary boundaries, climate change and biodiversity loss are introduced and explained. This thesis contributes to different important aspects, all central to the concept of decoupling, which is the core mechanism of current environmental policy aspirations. With the basic idea of decoupling environmental harms from economic activities, continuous growth without (or with only minimized) negative effects should be enabled. Core element of this process is the application of environmentally friendly technologies and green innovations. This should be fostered by concrete political interventions, directing the development of the technological state. While such decoupling could be possible with greenhouse gas emissions that accelerate climate change, it would also be necessary with other and more complex indicators like resource and land use, central aspects in stopping biodiversity and ecosystem service loss. Targeting those with technological decoupling is assumed more complicated and unlikely, if possible at all (see e.g. Parrique et al. (2019)). A critical evaluation on this was conducted and in it alternative concepts like degrowth interwoven. Chapter 2 addresses the question of the concrete quantitative impact of resource extraction on biodiversity and its interrelation with relevant governance mechanisms. It is indicated that resource extraction exerts a negative effect on biodiversity. The findings suggest that especially the extraction of biomass has major negative impacts, compared to other material classes like fossil fuels or metal ores. However, it is also indicated that institutional governance traits potentially influence those impacts. All analysed traits positively mediate the impact of resource extraction and cushion it if institutional quality is higher. Chapter 3 addresses the question, if meat consumption inevitably increases with increasing income and if globally a convergence towards high "western" levels is expected. This is of importance since the accompanied effects of livestock production can have severe impacts on nature. It is found that the difference between countries, in the amount of meat consumed, has decreased, suggesting convergence. Such an overall convergence is rejected by the main analysis, however. The employed clubbing algorithm suggests two different groups. A distinguishing feature of the group´s country-assembly is the development state. A further analysis supports the assumption that income growth is the major factor driving consumption growth. This effect seems to trump certain socio-cultural and geographical factors that were assumed to influence meat consumption under rising income, with few exceptions. Given those results, it can be concluded that cultural or other factors do not curb increasing consumption effectively if income grows. Chapter 4 analysis the impact of EI on carbon dioxide emissions and contributes to the literature and discussion of directed technical change and resulting decoupling. EI is found to have a distinct reducing effect on emissions, while innovation in general is not found significant. The amount and composition of energy consumed play a central role, with a high share of renewable energy having large effects. The effect of EI is found to be weaker in developing countries, however. This is even reinforced when countries with a strong national fossil industry are excluded. This indicates that technological effects are determined to a certain degree by national institutional characteristics.

All three papers indicate that cultural and institutional factors can play an important role in mediating how economic factors affect environmental ones. Chapter 4 in specific shows that the effect of technological development, via EI and renewable energy, and thus potentially directed technical change exists. By this, especially the assumption of possible decoupling from greenhouse gases is supported. However, the magnitude of the effect, is still low, compared to increases in economic growth and energy consumption, questioning its capability to compensate future growth. Chapter 2 and 3 indirectly emphasize the critical point in the mentioned argument, that a decoupling also from e.g. biodiversity loss and land use must be possible. Resource extraction exerts destructive impacts on nature. Like mentioned above, this paper finds increases in extraction over time, as well as chapter 3 finds an increase in environmentally negative consumption patterns, when enabled by increasing income. While those effects can also be targeted with technological solutions, such possibilities seem to be limited in its application and certain effect[46]. These dimensions more strongly depend on systemic changes, possible through institutional and cultural factors. Those can support the effect and application of certain technologies but provide the foundation for impactful changes.

The majority of the Earth´s planetary boundaries is overstepped, and we are in danger of pushing the whole system out of the safe operating space for humanity (Richardson et al., 2023). The destruction of the biosphere, causing rates of species extinction 100 to 1,000 times higher than naturally occurring in pre-human times (Pimm et al., 1995), and a global warming of already 1.1 degree above pre-industrial levels (IPCC, 2023), are major problems at a global scale. They reinforce each other and danger the provision of ecosystem services like water purification, pollination of plants, food provisioning or clean air (Brown et al., 2007) – all

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[46] For examples of such, thematising potential solutions, see e.g. Pikaar et al. (2018), discussing microbial protein as an alternative feed for livestock, with the potential to replace 10-19% of conventional crop feed and thereby decreasing cropland area by 6% on average globally, in 2050. Or Czech (2008), discussing technological solutions against biodiversity loss overarchingly, referring to potential effects of end-use innovations.

essential for us humans to exist. The extractive practices of the global economic system have set essential resources and its providing ecosystems under pressure (WWF, 2020). The focus on economic growth and the expansion of consumption possibilities has neglected the given ecological boundaries (Daly and Farley, 2004; WWF, 2020) and supported a situation of increasing global wealth inequalities and concentrations (Zucman, 2019). Our behaviour and interrelation with and impact on nature is risking unknown ecological dynamics and consequences. Also unknown, however, is humanities capability to handle and manage those consequences. How to deal with and operate within an "unsafe space"? The current political answer to this question seems to be "green growth". Decoupling economic growth processes from its environmental impact. Environmental policies, activating market and price mechanisms, fostering targeted environmental innovation and green technologies, planning to allow for continuing growth and consumption, expanding the planetary capacity. Not breaking with the prevailing paradigm of growth, but rather making incremental improvements in comparison. This green growth strategy is increasingly questioned in its effectiveness in reality[47]. Currently, there is no empirical evidence that this strategy alone will be enough. Rather the contrary is the case, suggesting that more is needed. While the concept of degrowth or post-growth proposes a radical paradigm change towards new social institutions, values, and economic systems, it is still rather described as an ideologic concept than an actionable policy strategy. It neglects central human psychological mechanisms and would need to focus on the creation of green institutions and acceptance.

The global poverty has fallen dramatically over the last decades (Wietzke, 2020). However, since there are still countries that live under poor conditions, rapid and sustained economic growth will persist as the suggested mean of choice to encounter poverty (see e.g. Milanovic (2013) or Škare and Pržiklas Družeta (2016)). Overall, the perception of economic welfare should be re-evaluated and set into perspective. Our global economy must operate and persist into strict ecological limits. The production side as well as the consumption side must change and must take actions to respect those limits. Economic growth, measured by GDP, was for a long time and mostly still is the equivalent of economic welfare and the index of choice for policymakers – the more a country´s economy grows, the wealthier it becomes and (assumed) the happier the people become, since their demands are increasingly supplied[48] (Daly and

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[47] See e.g. Parrique et al. (2019) and Hickel and Kallis (2020).

[48] Total welfare is the sum of economic welfare and noneconomic welfare. The assumption was and often still is, that total welfare moves in the same direction as economic welfare. However, increases in economic welfare can induce a more than offsetting decline in noneconomic welfare, that lead to decreased total welfare (Daly and Farley, 2004).

Farley, 2004). However, this perspective is increasingly questioned, especially in the light of sustainability issues. One consideration is that GDP as the (sole) measure of national wealth should be complemented by further aspects. There are many approaches and ideas to change the indicators by which prosperity and economic development could be measured, instead of measuring sole growth. Those are ranging from e.g. Environmentally Adjusted Multi-factor productivity (EAMFP) measures, still rather considering economic growth as the basis but providing an aggregate and more holistic picture of the economy, like the Biocapacity Adjusted Indicator (Gabbi et al., 2021), to indicators considering completely different paradigms and values. One example of the latter category is the Happy Planet Index that divides a country´s "happy life years" (life expectancy adjusted by subjective well-being) by its ecological footprint, as a measure of ecologic-economic efficiency (Daly and Farley, 2004). Independent of the concrete measure, there is the general argument that existing measures of economic performance, should be adjusted or complemented by measures of ecosystem services and biodiversity (Vačkář, 2012), to monitor that economic activity stays within the planetary boundaries. And ecological measures are not the only aspects missing within the current indicators of welfare. As above indicated by the word "happy", indicators should also consider modern and context specific adjustments of well-being. As Van den Bergh (2011) argues out of the degrowth discussion that GDP (growth) is not a robust, reliable indicator of social welfare (i.e. progress) (Van Den Bergh, 2011). While unconditional growth is not a wise aim, GDP growth can be good for some countries in certain times and is not bad in every context. The correlations between GDP and welfare or environmental impact are not fixed over time. GDP growth is neither necessary for sufficient progress nor for sustainability (Van Den Bergh, 2011), but it can help the least developed economies to achieve a certain level of welfare as a basis to approach alternative measures. However, those measures must find acceptance and application, to be tested, developed, and adjusted in practice, even if only supplementing the traditional GDP-/growth-focus, to inform about alternatives and set growth into perspective.

Multifaceted policies that foster both simultaneously, natural resource restoration and technological innovation, are needed to tackle the global ecological challenges ahead and reduce the human ecological footprint (Ahmad et al., 2020). Parallel, institutional changes must be facilitated, considering human psychology (Van Den Bergh, 2011), to enable the broad acceptance of necessary restrictions in consumption and the transformation of not only production and consumption patterns, but also social values. Needed is the combination of all available solution approaches, that are customized and managed context specific (Van Den Bergh, 2011). Top-down measures like effective environmental policies, as e.g. the taxation of status goods with serious environmental impact, regulation of commercial advertisement of those, facilitating technical and technological development; and bottom-up developments like e.g. reduced working hours or certain sufficiency movements, are effective in combating the multifaceted ecological crisis we are facing. Existing policy measures and strategies, focusing of increasing efficiency, must be accompanied and complemented by the pursuit of sufficiency – downscaling the production in relevant sectors, parallel to a reduction in consumption (Parrique et al., 2019). This together has the potential to enable a good life within the planet´s ecological boundaries.

As D'Alisa and Kallis puts it: "It is not enough for us as scholars to come up with good ideas. If we want to see change, we need to act as action researchers to see these changes happen. And there is no better place to start than our own home or workplace" (D'Alisa and Kallis, 2020, p. 8). We cannot afford to lose ourselves in endless ideological discussions about current strategies and wishful states, without effective outcomes. But we also cannot afford to blindly pursue continuing growth, despite all catastrophic consequences, and rely on one measure like technological innovation to solve all problems. Therefore, we must allow those ideologic discussion, to evaluate if the existing or aspiring paradigm is right and necessary to pursue. But those discussions must be effectively streamlined to concrete actions, protecting nature and the planet. We are increasingly confronted with ecological threats and anticipated risk scenarios that require us to no longer just do what we find comfortable, but to do what is necessary to secure our basis of life and the future of generations to come.

Chapter 2

On the tension between natural resource extraction and biodiversity – do governance characteristics matter?

Authors: Daniel Töbelmann

Abstract

Natural resource extraction is one major reason and accelerator of one of today’s most severe problems: the loss of the Earth´s biological diversity. As a critical part of the solution in mitigating and controlling this harm, institutional governance frameworks are assumed. Quantifications of the concrete effects and relationships would be valuable but remain scarce. This paper studies the macro-level relationship between biodiversity, resource extraction and different governance traits. Thereby, the focus lies on the influence the quality of institutional governance has on the impact of resource extraction on biodiversity. In concrete, corruption control, political stability and rule of law are employed as institutional variables, and biomass, fossil fuels, metal ores and non-metallic minerals as resource extraction variables. Using a global data set on 156 countries for the period between 1996 to 2012, this paper empirically investigates the relationships and estimates the effects with panel data methods. It is found that resource extraction exerts negative effects, led in magnitude and persistency by biomass. Especially high levels of rule of law positively affect biodiversity conservation, but all used governance traits positively affect the interaction between extraction and biodiversity.

Keywords: Biodiversity, Resource Extraction, Governance, Institutions, Deforestation

JEL classification: Q57, Q23, E02, O13, Q38

Publication: This is an unpublished manuscript.

2.1 Introduction

A global gross domestic product (GDP) increased by a factor of 27 within one century (Krausmann et al., 2017), enabled by an exponentially grown global resource extraction (Krausmann et al., 2009) and accompanied by a loss of biological diversity of approximately 68% (WWF, 2020), paint the picture of a fading nature. Economic growth and biodiversity loss are linked through increasing resource use (Otero et al., 2020). Expanding economies increase the use of resources, which in turn degrades biodiversity through various processes, like land-use and climate change. While the concrete number of species and extinct species is unknown, there is clear evidence that modern extinction rates are exceptionally high, increasing in speed and suggesting the beginning of the sixth mass extinction within the 4.5 billion year history of the Earth (Ceballos et al., 2015).

While agricultural expansion and the accompanied conversion of natural ecosystems—especially forests—is the most dominant driver of biodiversity loss (Dudley and Alexander, 2017), changes in the composition of resource demands make an evaluation of other resource categories besides biomass[49] highly relevant. Growth enabling infrastructure development, for example, is primarily accompanied by an increasing demand for non-metallic minerals and metals (Krausmann et al., 2017). Projections suggest that the demand for many metals will grow, and thus, mining operations will shift towards more dispersed and biodiverse areas (Sonter et al., 2018). Large-scale metal mining activities may so far not belong to the top driver of biodiversity loss, but exerts and intensifies pressure on biodiversity, by directly and indirectly changing habitats on a local and regional scale (Murguía et al., 2016). This increasing pressure is likely to expand to intermediate and high biodiversity areas, but also within mega-diverse zones. Various studies suggest that extractive industries augment forest area loss and constitute threats to biodiversity conservation (Kinda and Thiombiano, 2021). Mining is a significant driver of deforestation (Siqueira-Gay et al., 2020) and poses a serious threat to biodiversity (Sonter et al., 2018). With technological development and changing technologies, those impacts become even more relevant. While technologies are also expected to entail conservational effects, technological advances permit the exploration of previously uneconomical resources, which significantly extends mined areas. A similar argument holds true for fossil fuel extraction. It exerts a direct effect by habitat loss and pollution and an indirect one by climate change and increased accessibility (Harfoot et al., 2018). A difference to mineral and metal extraction is

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[49] The biomass considered here, which enters the economic process, consists largely of agricultural products.

that the current areas under fossil fuel extraction are high in species richness and endemism, but it might be possible to move to less biodiverse areas in the future. However, the expansion process of extraction areas alone could endanger sites of high local biodiversity. And even local or limited biodiversity loss can initiate large cascade effects on ecosystem functions and productivity (Butt et al., 2013). Unlike the impact of agriculture, as the primary driver of forest and biodiversity loss, the impacts of other resource extractions, like oil, gas, or mining, have received less explicit attention (Kinda and Thiombiano, 2021).

Much of the world´s biodiversity is habited in countries with high rates of corruption, low private property right protection, and persistent political instability (Abman, 2018). Thus, for a holistic investigation of the impact of resource extraction on biodiversity, institutional governance frameworks within countries need to be included in the analysis[50]. They shape and direct the structure of an economy and its change, by creating order, reducing uncertainty, and providing its incentive structure (North, 1991). Through such determination of choices and provision of incentives, institutions affect the sustainable use of natural resources and improve the environmental quality (Culas, 2007). For example, the relationship between factors like, on the one hand, population growth, commercial logging, or shifting cultivation, and on the other hand, deforestation is filtered and shaped by institutional governance (Bhattarai and Hammig, 2001). This raises the question, of their ability to conserve biodiversity and habitat under different forms of economic resource extraction, and their potential power to guide this relationship in biodiversity-friendly ways. Previous literature focused especially on the relationship between deforestation and the institutional governance traits of political stability, corruption control, and rule of law. The argument is, that political stability and corruption control determine a country´s ability to preserve its natural resources and higher levels of environmental quality, by affecting its ability to govern (Galinato and Galinato, 2013). It is assumed that a reduction in corruption leads to an increase in the stringency of environmental regulations (Buitenzorgy and Mol, 2011) and the enforcement of environmental policies, resulting in higher environmental quality (Sui et al., 2021). This is intuitively comprehensible, since, for example, illegal logging activities would be easier in countries with high levels of corruption, as one could pay bribes to avoid prosecution (Abman, 2018). Political instability and frequent regime changes create uncertainty regarding future landownership of private or government-owned forest land, potentially leading to increased timber harvest (Abman, 2018) and a reduction in resource stocks (Galinato and Galinato, 2012). Political unrest is shown to

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[50] The terms “governance” and “institutions” are used interchangeably here, since in the literature both are common term for the same context.

delay environmental improvements, suggesting the importance for governments to aim for and maintain political stability to foster environmental quality (Mrabet et al., 2021). Political stability includes stable contracts and property rights as well as the accompanying enforcements, which create an institutional environment of high quality. Such rather aggregated high-level factors, however, only provide a limited concrete description of other important aspects in protecting natural resources, like especially property and contractual rights itself (Culas, 2007). The rule of law can be interpreted as a proxy for the security of property and contractual rights, since it tends to establish rather peaceful mechanisms for adjudicating disputes (Knack and Keefer, 1995).

In their empirical analysis, Bhattarai and Hammig (2001) employ a composite indicator for political institutions also capturing e.g. rule of law and the level of corruption in governments. They find that political institutions reduce the rate of deforestation in Africa and South America, but increase it in Asia. Barbier et al. (2005) identify a mitigating effect of corruption control on agricultural expansion, in tropical low- and middle-income countries. Furthermore, they find an amplifying effect of increasing corruption control in the interaction with terms of trade, on its negative effect on agricultural expansion. Culas (2007) results suggests a reducing effect of contract enforceability of governments on deforestation, however, only for Latin America but no effect for Africa and Asia. In addition, the incorporation of the institutional variable technically vanishes the negative effect of agricultural production. Nguyen Van and Azomahou (2007) identify an increasing effect of political institutions on deforestation. Buitenzorgy and Mol (2011) investigate the differences between political regimes in sustaining environmental health, i.e. avoiding environmental degradation, measured by deforestation rates. The results suggest that strengthening democratic institutions, especially in transition and semi-democratic countries, favours forest protection and reforestation. They also include control of corruption as a control variable but cannot find a significant effect. In both their studies, Galinato and Galinato (2013, 2012) estimate that control of corruption reduces and political stability increases forest cover. Combes et al. (2018), analysing the effect of capital access on deforestation, find no significant effect of government stability on deforestation. Abman (2018) estimated the influence of control of corruption, political stability, and rule of law on deforestation rates within protected areas. The results show that the protection status avoids more deforestation in countries with higher control of corruption, more protection of property rights, and more democratic institutions. A combined institutional variable of corruption control and rule of law significantly decreases such kind of deforestation. For political stability no effect is found. Kinda and Thiombiano (2021) find non-homogeneous effects of resource rents on forest loss, for 52 developing countries. Employing a System-Generalized Method of Moments approach, specifically mineral and gas rents contribute to an accelerating forest loss, while oil rents and resource taxes contribute to a reduction of forest loss. Furthermore, they identify partially significantly positive effects of increasing political institution on forest area loss. The overarching assumption, based on the literature, is that governance institutions of high quality entail the potential to favour biodiversity protection. However, the role institutions play in the control of resource extraction still requires deeper analysis that contributes to a better understanding of the impact on biodiversity. Furthermore, there is a need for quantification of the direct effects of resource extractions, since for example regarding fossil fuels in contrast to the indirect effects, the quantification of the direct effects has been relatively neglected so far (Harfoot et al., 2018). This study aims to provide such a contribution. I analyse the relationship between biodiversity, resource extraction, and institutions on a global basis, employing panel data estimations over the time period of 1996 – 2012. To do so, biodiversity is proxied with data of forest area, and material flow data on biomass, fossil fuels, metal ores, and non-metallic minerals are used as resource extraction variables. The institutional variables are *corruption control*, *political stability*, and *rule of law*. Significantly negative effects of biomass, fossil fuel and metal ores extraction on biodiversity are found, led in magnitude by biomass extraction. For the institutional traits only for *rule of law* a consistent direct effect is identified, that tends to be significantly positive. *Corruption control* is not found to be significant and *political stability* is in some cases identified significantly negative. However, for all institutional traits, a significantly positive interacting effect with biomass extraction on biodiversity is found.

This paper contributes twofold. First, it contributes to the literature on the relationship between institutions and biodiversity, with a special focus on resource extractions. And second, it contributes to the literature on extractivism, by quantifying the impacts of different resource categories on biodiversity. To the best of my knowledge, this paper is the first, evaluating these effects empirically on a global basis. The paper is structured as follow. Section two provides the methodological strategy employed, before section three and four shed lights on the results and my discussion and conclusion of those.

2.2 Data and methodology

2.2.1 Data

Macroeconomic studies on biodiversity face one obstacle: the choice of an appropriate indicator. A variety of different indicators exist, each with certain advantages and disadvantages (Jones et al., 2011; Rydén et al., 2020). In general, most indicators show a tendency to cover terrestrial biodiversity (Jones et al., 2011). The major indicators defined by the *Convention on Biological Diversity* (CBD) to monitor and evaluate developments in biodiversity are the extent of forest area[51], the protected-area coverage[52], the Living Planet Index[53] and the Red List Index[54](Jones et al., 2011). Those differ according to their characteristics and, thus, their applicability in scientific studies. There will never be a perfect global indicator, and the existing ones perform well with respect to some desirable characteristics but not as well regarding others. Therefore, the selection of an appropriate indicator depends on the scope and interest of the study conducted. In this study, forest area is employed as the main proxy of choice for biodiversity, serving as a reasonable proxy for habitat (Abman, 2018). This choice is based on a variety of aspects: First, forests and especially tropical rain forests, contain high levels of biodiversity (Schmitt et al., 2009), often higher than any other terrestrial ecosystem (Mori, 2017), and does thus provide information on different elements of biodiversity (Jones et al., 2011). By approximately hosting 80 % of all amphibian species, 75 % of all bird species, and 68 % of all mammal species known worldwide, forest ecosystems harbour most of the global terrestrial biodiversity (FAO, 2020). Second, in comparison to more direct alternative proxies, the data are available on a global scale for all countries, and the time series are sufficiently long, which allows for a large-scale analysis (Rydén et al., 2020). Third, it is assumed that this indicator responds relatively quickly and reliably to political measures, like for example, financial conservation incentives (Jones et al., 2011) or regulatory changes, resulting in a reduction of forest loss. And finally, by performing different regionally and globally relevant ecosystem services like carbon sequestration, water purification, erosion control, or microclimate regulation (Mori, 2017), forests proxy long-term developments essential to species diversity. Forest area as an indicator for biodiversity also has drawbacks in

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[51] Derived from the Food and Agricultural Organization (FAO).

[52] Calculated by the UN Environment Program-World Conservation Monitoring Centre from data in the World Database of Protected Areas.

[53] Calculated by the World Wildlife Fund (WWF) and the Zoological Society of London (ZSL).

[54] Developed by BirdLife International, the ZSL and the IUCN.

representation accuracy. One is that the link to biodiversity is rather indirect[55] (Rydén et al., 2020). Further, small-scale degradation, like biodiversity losses due to poaching or the selective logging of valuable tree species not involving clear cutting are hardly represented (Abman, 2018). Despite those drawbacks, a useful biodiversity indicator does not necessarily have to represent all elements of biodiversity equally well (Jones et al., 2011) but has to be ecologically founded and meaningful, which is in my opinion given with forest area.

A global unbalanced panel data set for 156 countries is constructed, spanning the years 1996 to 2012[56]. The data for forest area are provided by the Food and Agriculture Organization of the United Nations (FAO). It is defined as: "*Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use*" (FAO, 2015, p. 3). The measure excludes, for example, oil palm and fruit tree plantations (FAO, 2015), primarily representing natural or, at least, natural-like forests. Forest area is given in 1,000 ha. The data on resource extractions are obtained from the Global Material Flows Database, provided by the United Nations Environment Programme (UNEP). To measure the effect of resource extraction, the data are employed on an aggregated MF[57]-4 level, representing the direct, gross physical domestic extraction (DE) of materials from the environment within a national territory[58] and, thus, the extractive pressure on natural resources within a country (UNEP, 2016). Resource extractions are only incorporated into the DE measure if they enter economic processes afterwards and are commodified. Therefore, I assume those measures to be appropriate indicators of economically originated resource pressure on

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[55] An alternative could be the extrapolation of a more direct proxy, like e.g., the species-area relationship (SAR) (see e.g., Dietz and Adger, 2003; Marques et al., 2019; Mills and Waite, 2009). It describes biodiversity, or species richness, in relation to the amount of a specific area, e.g., protected or forest area. Implicit assumption is that larger areas contain more species than smaller ones. Thus, the species richness is causally related to the size of habitat area: $S = CA^z$. In this general form S is the number of species, A is the area, and C and z are constants. C is reflecting the density of species per unit (Dietz and Adger, 2003) and varies in a poorly understood manner, among different taxa and ecosystems, and is in range not predicted by biogeography theory. In contrast, the z-value differs according to the type of area (Lomolino, 2000). While previous studies commonly used a value of 0.25, which is based on island biogeography and suitable for archipelagic SAR´s, terrestrial forest areas would rather be categorized as province. The suggested value range for interprovincial SAR is 0.6 – 1.0, with forests showing a tendency towards unity (Rosenzweig, 2003). Therefore, even in extrapolated measures, species richness technically nearly equals the habitat area. Furthermore, incorporating additional but uncertain factors could raise the risk of misspecification, which wants to be avoided here.

[56] While primarily all time-series were available exceeding 2012, this time frame was chosen to make all variables compatible to the Material Flow data. Those are also available for years after 2012, that according to the Technical Annex, however, should not be used for statistical purpose. The same holds for years before 1996, that are limited by the availability of the institutional variables.

[57] Material Flow

[58] See Technical Annex for Global Material Flows Database.

biodiversity and ecosystems. The MF-4 level aggregates the overall 62[59] defined material categories, used for initial system compilation, into the four major categories: Biomass, Fossil Fuels, Metal Ores and Non-metallic Minerals. DE data is also available on a less aggregated MF-13 level, clustering the classes into 13 more refined categories; however, the superordinate resource categories are of prime interest for this initial study. All four material categories are measured in tonnes. Data on the institutional variables are obtained from the Worldwide Governance Indicators (WGI) project, produced by Kaufmann et al. (2010). The WGI consist of six composite institutional indicators, covering over 200 countries from 1996 on (Kaufmann et al., 2010). Overall, these indicators are based on several hundred variables, obtained from 31 data sources including surveys of firms and households, subjective assessments of a variety of commercial business information providers, non-governmental organizations, and multiple multilateral organizations and public-sector bodies. The resulting indicators range from approximately -2.5 to 2.5, representing increasing perceived governmental quality with increasing values[60]. The resulting estimates are standardized to a zero mean and a standard deviation of one. Missing values for the years 1997, 1999, and 2001 are linearly interpolated here. As institutional indicators of interest for this study Control of Corruption, Political Stability and Rule of Law are selected[61], to represent a system of different institutional mechanisms potentially affecting the relationship between natural resource extraction and biodiversity. Data on GDP per capita in 2015 US$ is obtained from the World Bank. Data on terrestrial protected area is taken from the OECD (OECD, 2021). The protected area data are given for 63 countries and the time span 1950 to 2021, in percent of total land area. The data are transformed to percentage shares. All variables, except the index variables and percentage shares, are logarithmically transformed for linearization.

2.2.2 Methodology

To estimate the impact of resource extraction on biodiversity within a given institutional framework, a standard two-way fixed effects (FE) estimator is used as the primary estimation method. The baseline model is as follows:

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[59] See Technical Annex for Global Material Flows Database.

[60] The institutional variables values are not transformed in range in this study, since as argued in Buitenzorgy and Mol (2011) the data variance remains unchanged, leading to unchanged regression results.

[61] For a description of each institutional variable, see Table A1.

$$(1)\quad y_{it} = \beta X'_{it} + \varepsilon_{it}\ , \qquad with\, i = 1, \ldots, N\ \ t = 1, \ldots, T$$

$$and\ \varepsilon_{it} = \Phi_{it} + \lambda_i + \mu_t\ , \qquad with\ \Phi_{it} \sim I.I.D\ (0, \sigma_\Phi^2)$$

X' represents a $1xk$ vector of regressors, β a $kx1$ vector of corresponding coefficients, ε the error term in which Φ is the common stochastic disturbance, λ the country fixed effects, μ the time fixed effects, and the subscripts i and t denotes the cross-sectional unit (country) and the time, respectively.

The baseline model is given by

$$\begin{aligned}(2)\quad & Biodiversity_{it} \\ & \quad = \zeta Biomass_{it} + \lambda Fossil\ Fuels_{it} + \gamma Metal\ Ores_{it} \\ & \quad + \theta Non - Metallic\ Minerals_{it} + \Gamma Corruption\ Control_{it} \\ & \quad + \text{И} Political\ Stability_{it} + \text{Ш} Rule\ of\ Law_{it} + \varepsilon_{it}\end{aligned}$$

With Biodiversity as the dependent variable, Biomass, Fossil Fuels, Metal Ores and Non − Metallic Minerals as the independent resource extraction variables, and Corruption Control, Political Stability and Rule of Law as the independent institutional variables. Since correcting models when estimating global effects on deforestation, or in this case forest area, for serial correlation is a critical issue to generate reliable inference (Scrieciu, 2007), Driscoll and Kraay (DK) standard errors[62] are used that are robust towards serial correlation, heteroscedasticity, and cross-sectional dependence (Hoechle, 2007).

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[62] See Driscoll and Kraay (1998) for derivation and details

2.3 Empirical Results

This section presents all empirical results. First, the data are evaluated descriptively, before the results of the econometric estimations are presented.

2.3.1 Descriptive Statistics

Figure 1 illustrates the trend development of forest area and resource extraction over the period of 1996 to 2012. Both variables are separated by the level of institutional quality of the representative countries. Clear differences between the development of both variables in countries of rather high or low institutional quality can be identified. The sample of countries with an average institutional index > 0 show relatively constant levels of resource extraction and a slightly increasing forest area. On the contrary, the sample of countries with an average institutional index < 0 show the opposite—resource extraction levels approximately doubled in quantity and levels of forest area decreased constantly.

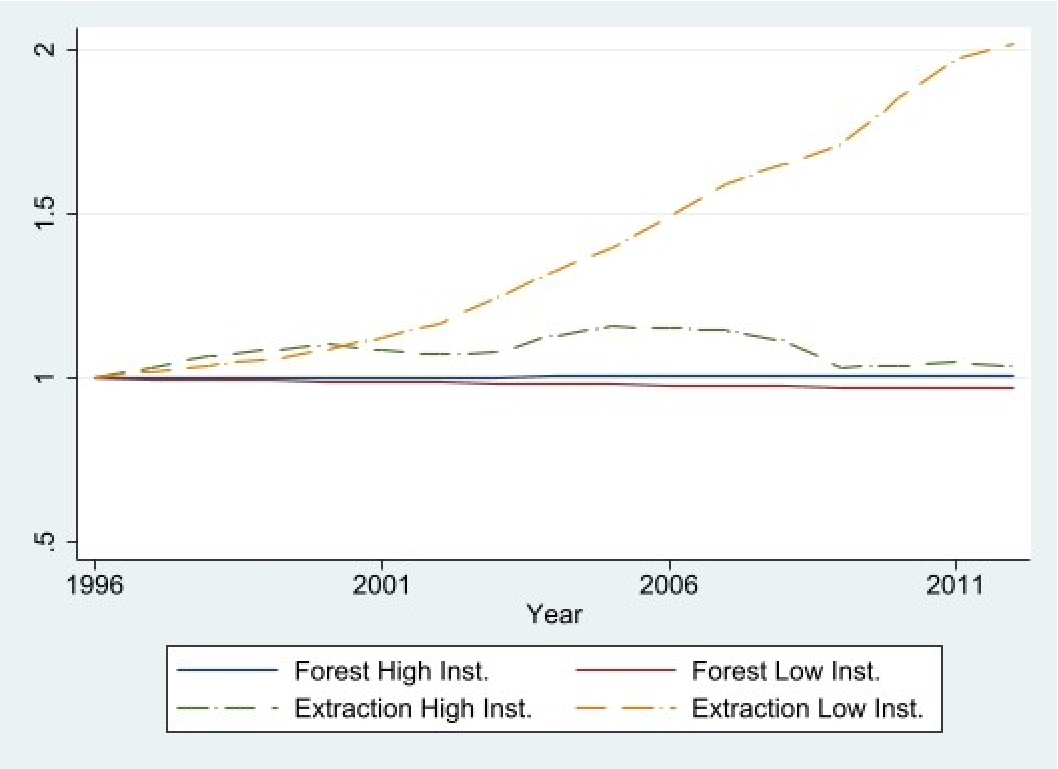

Figure 1: Development of forest area and resource extraction from index year 1996 on, separated according to institutional level

Note: “High Inst.” refer to an average institutional level over time > 0, and “Low Inst.” refer to an average institutional level over time < 0. The average institutional level over time is constructed as a composite variable of all three institutional indicators. The variables represent the total level values of each variable over time. Source: Own elaboration, based on data from FAO and Global Material Flow Data Base

In Figure 2 the relation between the yearly average growth rate in forest area and resource extraction is plotted, again separated according to the respective institutional level of countries. In tendency, countries with rather high institutional levels show rather low to even negative extraction growth rates. Furthermore, the majority has forest area growth rates fluctuating around 0%, with a slight tendency towards positive growth rates. A slightly negative correlation between resource extraction growth and forest area growth is illustrated for those countries. In contrast, countries with rather low institutional quality tend to have rather high resource extraction growth rates and a decline in forest area. For those, a clear negative correlation between resource extraction growth and forest area growth is indicated.

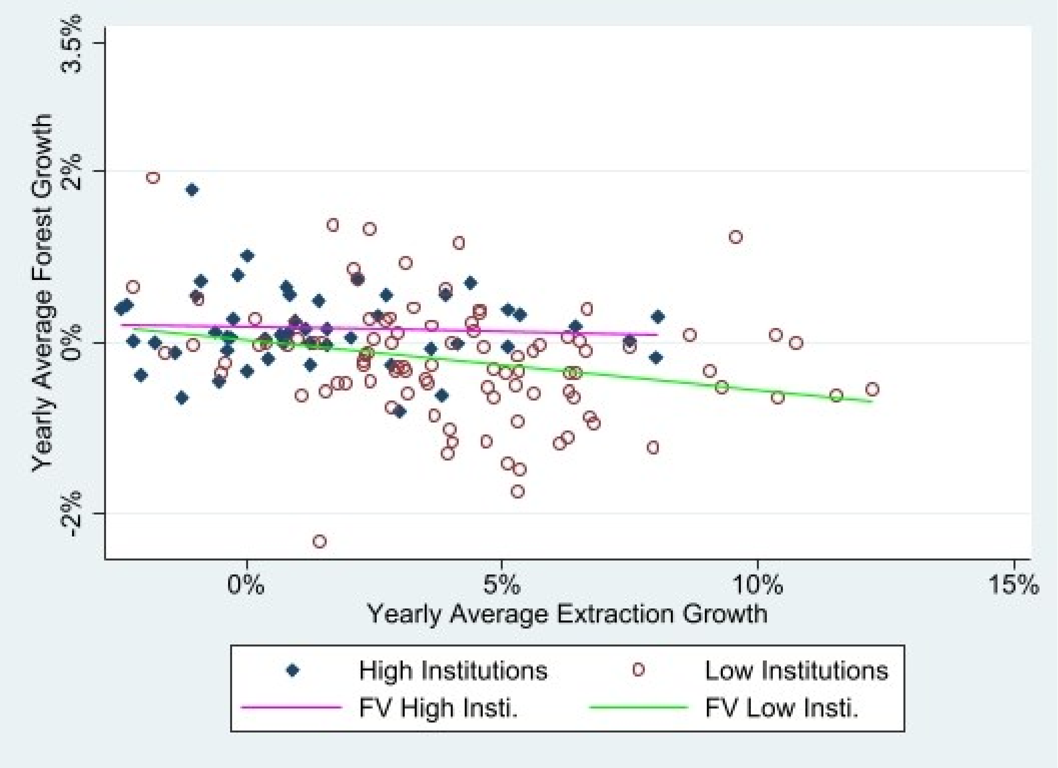

Figure 2: Scatter Plot of yearly average forest area and resource extraction growth rate, separated by institutional levels of countries, for the period 1996–2012

Note: “High Institutions” refer to an average institutional level over time > 0 and “Low Institutions” refer to an average institutional level over time < 0. The average institutional level over time is constructed as a composite variable of all three institutional indicators. Some countries were excluded from the sample, for illustration and general interpretation purposes, due to outlying. These are Azerbaijan with a forest growth rate (FGR) of ~ 0.49 % and an extraction growth rate (EGR) of ~ 18.84 %, Bosnia and Herzegovina with a FGR of ~ -0.07 % and an EGR of ~ 18.14 %, Equatorial Guinea with a FGR of ~ -0.30 % and an EGR of ~ 49.23 %, Iceland with a FGR of ~ 5.08 % and an EGR of ~ -0.89 %, Laos with a FGR of ~ -0.24 % and an EGR of ~ 29.14 %, Uruguay with a FGR of ~ 3.44 % and an EGR of ~ 7.55 %, and Vietnam with a FGR of ~ 1.54 % and an EGR of ~ 21.15 %. FV abbreviates "Fitted Values".

Source: Own elaboration, based on data from FAO and Global Material Flow Data Base

In Figure 3 the average level changes over time are illustrated. In countries with higher institutional quality the absolute changes in resource extraction are negatively correlated with changes in forest area which can be intuitively understood. More resource extraction is associated with more forest area loss. Surprisingly, in countries with lower institutional quality the opposite is indicated in trend. Higher levels of changes in resource extraction are related to forest area gain. However, it can be recognized that the majority of countries with negative changes in forest area are primarily the ones with low institutions, especially the bigger the forest area loss becomes. On the other hand, most countries with positive forest growth rates or at least constant forest areas show rather high institutional quality. A similar but inverted relation can be seen for changes in resource extractions.

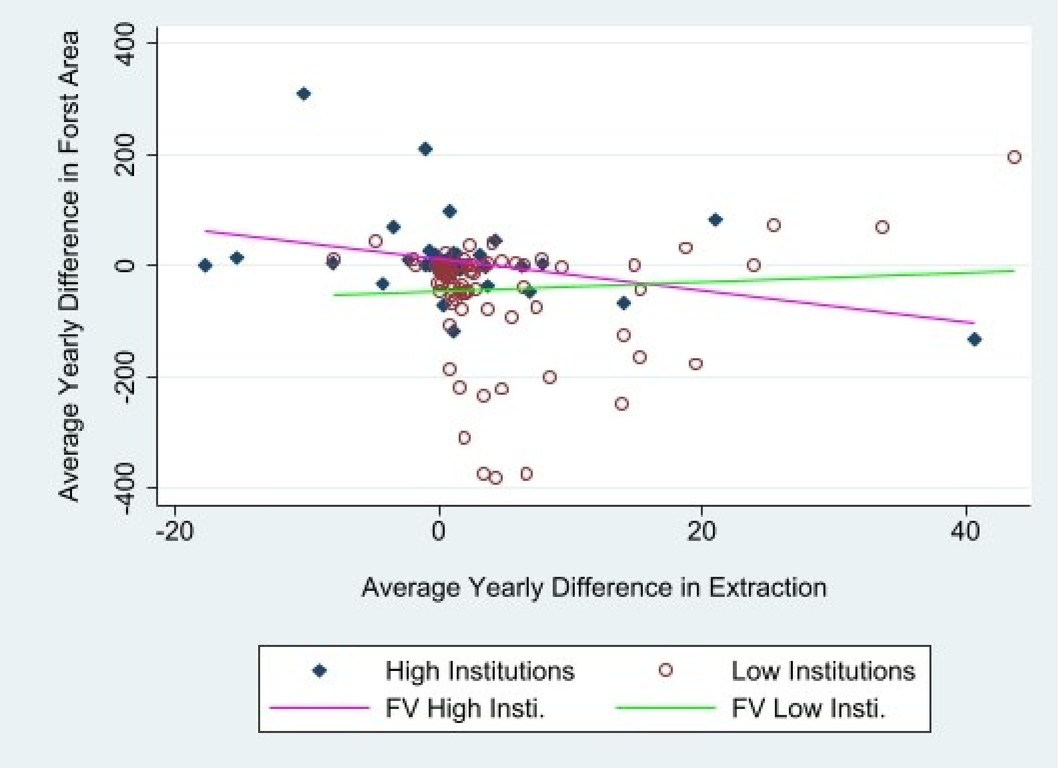

Figure 3: Scatter Plot of yearly average forest area and resource extraction change, separated by institutional levels of countries, for the period 1996–2012

Note: “High Institutions” refer to an average institutional level over time > 0 and “Low Institutions” refer to an average institutional level over time < 0. The average institutional level over time is constructed as a composite variable of all three institutional indicators. The resource extraction values are given in million tons, the values of forest area in 1,000 ha. Some countries were excluded from the sample, for illustration and general interpretation purposes, due to outlying. These are Brazil with an average yearly change in forest (FD) of ~ -3,654.35 and an average yearly change in resource extraction (ED) of ~93.82, China with a FD of ~ 2,151.97 and an ED of ~976.34, Democratic Republic of the Congo with an FD of ~-711.94 and an ED of ~1.66, India with a FD of ~276.86 and an ED of ~150.92, Indonesia with a FD of ~-942.65 and an ED of ~78.06, and the Russian Federation with a FD of ~302.00 and an ED of ~127.44. FV abbreviates “Fitted Values”.

Source: Own elaboration, based on data from FAO and Global Material Flow Data Base

2.3.2 Estimation Results

In this section all estimation results are presented. Before the main estimation results for the baseline model are shown, and several extended estimations and robustness checks are introduced in the following, a first cross-sectional regression is conducted to evaluate if overarching relationships can be assumed between forest area, resource extraction, and institutional quality.

Table 1: Cross-sectional regression

VARIABLES	(OLS) Forest Growth	(OLS) Forest Growth
Extraction Growth	-0.00736	-0.0374
	(0.0650)	(0.175)
Institutional Level	0.333***	0.347***
	(0.101)	(0.128)
EGrowthxILevel		-0.0457
		(0.193)
Constant	0.00321	0.00320
	(0.0768)	(0.0770)
Observations	155	155
R-squared	0.111	0.112

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note: In this estimation all variables are standardized to a mean of zero and a standard deviation of one.

Table 1 presents the results of the cross-sectional regression. The dependent variable is the yearly average growth rate of forest area by country. The independent variables are the yearly average growth rate of aggregated resource extraction and the average institutional level by country. In the estimation in the second column, the interaction term of both is added as a further independent variable. An OLS regression with robust standard errors is conducted. These results indicate a significantly positive effect of the institutional level of countries on forest area growth, but no significant one of resource extraction growth nor its interaction with the institutional level. A higher level of institutional quality is thus indicated to exert a positive effect on forest area growth. If there is a one standard deviation increase in institutional level of a country, forest area growth increases by 0.33 standard deviations.

Table 2 contains the estimation results for the baseline model over a global panel, estimated with a two-way fixed effects (FE) estimator (with and without Driscoll and Kraay standard errors (DK)).

Table 2: Estimation Results of the Baseline Model with Fixed Country and Time Effects

VARIABLES	(FE) Forest Area	(FE DK) Forest Area
Biomass	-0.0639***	-0.0639***
	(0.00548)	(0.0111)
Fossil Fuels	-0.00370***	-0.00370***
	(0.000553)	(0.000644)
Metal Ores	-0.00124***	-0.00124***
	(0.000389)	(0.000372)
N-m Minerals	-0.000120	-0.000120
	(0.000990)	(0.000686)
Corruption Control	-0.0106**	-0.0106
	(0.00515)	(0.00975)
Political Stability	-0.00496*	-0.00496**
	(0.00261)	(0.00197)
Rule of Law	0.0311***	0.0311***
	(0.00570)	(0.00763)
Observations	2,597	2,597
Time Effects	Yes	Yes
Number of Groups	156	156

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note: GDP per capita was intentionally not added to the baseline estimation, due to a high variance inflation factor, suggesting strong correlation between this variable and one or more of the others. This is intuitive, since only material flows that enter the economic process are captured, which makes them an integral monetary part of GDP. Table A3 in the Appendix provides the baseline estimation with GDP per capita for comparison.

Table 2 presents evident significant negative effects on the extent of forest area of three of the four resource extraction variables. The FE estimations indicate Biomass, Fossil Fuels, and Metal Ores to be significant. This is in line with prior assumptions and statements of other studies, qualitatively suggesting impacts of resource extractions. The highest impact is found for Biomass with an elasticity of -0.0639. If Biomass extraction increases 1 %, ceteris paribus, Forest Area decreases ~ 0.064 %. Fossil Fuels follow Biomass in the exerted effect with a significant coefficient of -0.00370, suggesting a 0.037 % decrease in forest area following a 1 % increase in fossil fuel extraction, given all else remains constant. For Metal Ores the impact is estimated with a significant coefficient of -0,00124. For N-m Minerals no significant effect is found. For the governance traits, it can be seen that Corruption Control is significantly negative in the FE estimation but turns insignificant when Driscoll and Kraay standard errors are added. Political Stability is significantly negative, suggesting that increasing political stability reduces Forest Area, with a coefficient of -0.00496. If the extraction level of all resources as well as Corruption Control and Rule of Law remain constant, an increase in Political Stability would lead to a decrease in Forest Area. Rule of Law is significantly positive over all estimations. This suggests a robust positive effect of increasing rule of law on Forest Area growth. If the levels of resource extraction, Corruption Control and Political Stability remain constant, an increase in Rule of Law leads to an increase of Forest Area. So far, the results suggest a relatively clear negative effect of resource extraction on forest area within countries, but a rather inconclusive or at least differing effect of institutional traits. The inclusion of institutional variables, however, reduces the negative impacts of Biomass and Fossil Fuels extraction, roughly suggesting a regulating effect of increasing institutional quality[63].

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[63] Compare Table A2 in Appendix.

Table 3: Estimation Results Baseline Model with Interaction Terms

VARIABLES	(FE DK) Forest Area	(FE DK) Forest Area	(FE DK) Forest Area	(FE DK) Forest Area
Biomass	-0.0710***	-0.0736***	-0.0699***	-0.335***
	(0.01000)	(0.0102)	(0.00974)	(0.0228)
GDP pc	0.0535***	0.0536***	0.0499***	-0.393***
	(0.00403)	(0.00353)	(0.00330)	(0.0292)
Corruption Control	-0.000119			
	(0.00981)			
BMxCC	0.0310***			
	(0.00581)			
Political Stability		-0.00504		
		(0.00375)		
BMxPS		0.0224***		
		(0.00495)		
Rule of Law			0.0107*	
			(0.00524)	
BMxROL			0.0403***	
			(0.00572)	
BMxGDP pc				0.0283***
				(0.00212)
Observations	2,599	2,599	2,599	3,411
Time Effects	Yes	Yes	Yes	Yes
Number of groups	154	154	154	154

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note: BMxCC, BMxPS, BMxROL, and BMxGDP pc describe the respective interaction variables between Biomass and Corruption Control, Political Stability, Rule of Law, and GDP per capita. The interaction terms are generated with the time-average of each institutional variable per country, the institutional variables itself are included as the regular time-varying variables. GDP per capita instead of GDP is incorporated for comparison reasons regarding other studies. GDP per capita is the primary measure for economic growth, emerging from our literature research. For robustness purposes, the estimations were also conducted with the level variable of GDP, that had no significant effect on the results. In the estimation of column 2 and 3 GDP turns insignificant, all other significance levels remain unchanged.

The evident dominant impact of Biomass on Forest Area prompts to conduct an in-depth analysis of its interaction with the different institutional variables. GDP per capita is included to indirectly capture the effects of the other resource variables[64]. Table 3 presents the estimation

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[64] Increasing GDP per capita is predicted to potentially stimulate increasing demand for agricultural and forest derived products, causing deforestation (Culas, 2007). There is a potential hypothesized positive effect of GDP growth on forest ecosystems if conservation instead of depletion is demanded. There is however evidence of a negative relation between GDP per capita and forest areas. Since the relationship between economic growth and natural assets like forest area is extensively investigated in the nexus of the Environmental Kusnez Curve, that does not provide conclusive results, less attention is attributed to GDP itself. Furthermore, it can be assumed that the major effects entailed by economic activities on forest ecosystems in the end go back to resource extractions,

results, and the two-way fixed effects estimator is used. The main effect of Biomass is again significantly negative in all estimations. GDP per capita is significantly positive in all estimations, except in column 4, where the BMxGDP pc interaction variable is added, it turns significantly negative. Corruption Control is not found to be significant. The BMxCC interaction term, however, is significantly positive. This indicates that increasing biomass extraction is mitigated in its negative effect, if the level of corruption control is high, given ceteris paribus. Reversely, an increase in Corruption Control exerts a rather positive effect on Forest Area if extraction levels are high and remain unchanged. A similar interaction effect is found for Political Stability. While Political Stability itself is insignificant, the interaction term BMxPS is significantly positive. Rule of Law is found to be significantly positive, as well as its interaction term with Biomass. Again, this indicates, that given constant GDP per capita and Rule of Law, the negative effect of increasing Biomass extraction is mitigated by high levels of Rule of Law. Vice versa increasing levels of Rule of Law exert a rather positive effect on Forest Area, if the level of extraction is high. In column 4, only GDP per capita and its interaction term with Biomass are incorporated. GDP per capita turns significantly negative and the interaction term is found to be significantly positive. This result indicates that increasing biomass extraction decreases its impact on the extent of the forest area if the level of GDP per capital is high, ceteris paribus. If the extraction level remains unchanged on a high level, the negative effect of increasing GDP per capita on the forest area diminishes, as well as the effect of the constant extraction level.

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leading to forest and habitat loss. Therefore, I see a major part of economic growth captured within the resource data.

Table 4: Robustness check by estimating baseline model with Protected Area as dependent variable, between effects and full extrapolation of institutional variables

VARIABLES	(FE DK)[a] Protected Area	(RE GLS)[b] Forest Area	(FE DK)[c] Forest Area
Biomass	-0.0294***	-0.0688***	-0.0826***
	(0.00700)	(0.00661)	(0.00830)
Fossil Fuels	-0.000552	-0.00404***	-0.00395***
	(0.000883)	(0.000665)	(0.000807)
Metal Ores	-0.00154*	-0.000395	-0.000407
	(0.000778)	(0.000492)	(0.000574)
N-m Minerals	-0.0122**	0.000392	0.000798
	(0.00520)	(0.00117)	(0.000853)
Corruption Control	-0.00825	0.0763	0.0271***
	(0.0115)	(0.431)	(0.00850)
Political Stability	-0.00461	-0.492**	0.00196
	(0.00481)	(0.209)	(0.00253)
Rule of Law	0.00933*	0.0420	0.0119**
	(0.00448)	(0.452)	(0.00564)
Observations	807	3,479	3,479
Time Effects	Yes	Yes	Yes
Number of groups	63	156	156

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note: [a]This estimation is the baseline model specification with interpolated institutional variables; [b]To estimate and check the between effects, the country-based time-average of the institutional variable was used. In this estimation all institutional variables enter as this average, why a random effects estimation is employed; [c]In this estimation the institutional variables enter as fully linearly extrapolated values for the years 1990–2012.

Table 4 presents additional robustness checks for the consolidation of results. Besides forest area, protected area is a further suggested indicator for biodiversity. Therefore, column 1 presents the estimation results of the baseline model for protected area as the dependent variable. The indicated results are in line with the previous findings. Biomass, Metal Ores, and Non-metal Minerals are found to be significantly negative; Fossil Fuels is negative but insignificant. Of the institutional variables, only Rule of Law has a significantly positive effect on the extent of protected area. These results strengthen the interpretation of the overall effects on biodiversity. To check for the between effects of the institutional variables, column 2 represents an appropriate estimation with country-based time-averaged variables. Only Political Stability is found significant with a negative coefficient. Due to the time period constraints, the baseline model outlined in Table 5 column 2 is extended with linear extrapolation for the years 1990–1995 in column 3. Here, Corruption Control and Rule of Law are both significantly positive. Biomass and Fossil Fuels remain significantly negative, while all other variables are insignificant. It must be mentioned that extrapolation is not a valid approach to identify resilient results, however, as an additional check it could suggest insights on relationships and effects if there are no outliers but a steady development in institutional frames.

2.4 Discussion & Conclusion

In this study the impacts of major resource extraction categories and three institutional governance traits – namely biomass, fossil fuels, metal ores, non-metallic minerals, and corruption control, political stability, and rule of law – on biodiversity are quantified on a global basis. Resource extraction is found to exert a negative impact on biodiversity, led in magnitude and persistency by biomass extraction. Fossil fuel extraction, like coal, oil, and gas, is also indicated to have a negative effect on forest area but not so on protected areas. Metal ore extraction is found to be significantly negative for biodiversity. All three extraction activities does thus result in forest area loss. Finally, non-metallic mineral extractions are not found significant on a global basis for forest area as the biodiversity proxy, but they affect protected areas significantly. Differences are suggested between countries of high and low institutional levels regarding the tension between resource extraction and biodiversity. It is important to understand the role institutions can play in avoiding further habitat conversion and species loss, as well as in promoting conservation. It is shown that in countries with rather low institutional levels, resource extraction has approximately doubled in amount in the observed time period from 1996 to 2012, accompanied by a decrease in forest area. In countries with higher institutional levels, resource extraction remained relatively constant with a slight increase in forest area. For both country groups a negative relationship between resource extraction growth and forest area growth is suggested, with a much stricter one for countries with lower institutional levels. The expansion of forest loss, on the one hand, and resource extraction, on the other, tends to be higher in countries with low institutional quality. The contrary seems to be true for countries of higher institutional levels. This indicated positive effect of institutional quality is backed up by the conducted estimations. Institutions are found to exert a significantly positive effect in the cross-section, even though they are not found to have an interacting effect on the relationship between extraction growth and forest area. Investigation of the three governance traits on the country level show that especially the rule of law has a persistently positive effect on biodiversity. Political stability is indicated to have a negative effect, and for corruption control no direct effect is found. When focussing on biomass extraction, however, for all three institutional traits a positive interacting effect on the relationship between biomass extraction and forest area is found, suggesting that increasing institutional quality has the potential to positively mediate the general negative effect of biomass extraction on biodiversity. These quantitative results fit well with the existing literature and the qualitative assumptions made. Transferring these findings into practical terms, resource extraction and, at the moment, especially biomass extraction causes biodiversity loss. Particularly in the face of increasing and shifting resource needs, the extent to which biodiversity is harmed by different resource categories needs careful investigation and monitoring. The institutional level of countries seems to be an essential part of the ability to manage nature and biodiversity loss under extractivism. Particularly, a strengthening of the quality, and thereby, the confidence in contract enforcement and property rights, seem to be an effective governing approach for the conservation of biodiversity and to mitigate the further encroachment of resource extraction into natural habitats. When there is increasing confidence in the enforcement of societal rules, contracts, and property rights, especially illegal and unauthorized logging activities could be curbed, and landowners could have more leverage, security, and confidence in fighting deforestation on their land, which could lead to a further strengthening of land protection. However, fostering a governance and institutional framework which enables a stricter biodiversity conservation under continuing resource extraction depends on more than strengthening just one trait. A holistic approach, increasing the overall governance quality, must be aspired. As shown here, all chosen governance traits are exerting a positive interacting effect on the extraction-biodiversity relationship concerning biomass. The relationships considered here, are highly complex, involving a variety of different factors and dynamics. And the assumed positive effect of institutional quality on the preservation of forests is unclear and still seems to be debatable (Kinda and Thiombiano, 2021). The negative direct effect of political stability, for example, is counter-intuitive at the first glance. An explanation could lie in unleashed growth effects introduced, for example, by productive investments or new technologies, encroaching forests (Kinda and Thiombiano, 2021) or complementing instead of substituting natural area consumption (Galinato and Galinato, 2013). Political instability discourages investments, also from foreign agents, limiting the number of parties with access to natural areas. When political stability increases, more investments and agents are attracted and economically access those natural habitats. Nevertheless, it must be assumed that strong and stable politics, governance, and other institutions are an essential cornerstone for a successful long-term biodiversity conservation. This represents demand for future research. Without effective governance mechanisms and political stability, conservation rather becomes a product of chance than an organized and calculated process. Under prevailing economic growth, extractivism, and nature exploitation, strengthening the quality of a state’s governance has the potential to shape these processes more biodiversity-friendly and is assumed as an integral and essential part of a holistic solution towards a sustainable and nature-positive world. The research and results reported in this study are not free of shortcomings. Data constraints are a limitation here. The estimation with extrapolated institutional variables shows different results, implicating that richer time-series could give refined insights. A further point worth improving in future research is the directness of the used biodiversity indicator. Forest area is assumed as an appropriate indicator, however, a more direct indicator, representing concrete developments of different species, could improve analysis. Especially with respect to resource extractions like non-metallic minerals, that clearly exert negative impacts on biodiversity and nature, but obviously not primarily within forest areas. This important field leaves a lot of potential for future research.

2.5 Appendix

Table A1: Definitions of the institutional governance variables

Variable	Definition
Corruption Control	Reflects perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests.
Political Stability	Political Stability and Absence of Violence/Terrorism measures perceptions of the likelihood of political instability and/or politically-motivated violence, including terrorism.
Rule of Law	Reflects perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence.

Note: The definitions are cited from the WGI.

Table A2: Estimation results of the base line model, without institutional variables

VARIABLES	(FEDK) Forest Area
Biomass	-0.0767***
	(0.00804)
Fossil Fuels	-0.00413***
	(0.000738)
Metal ores	-0.000456
	(0.000528)
Non metallic minerals	0.000383
	(0.000788)
Observations	3,479
Number of groups	156

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table A3: Baseline Estimation with GDP per capita as additional independent variable

VARIABLES	(FEDK) Forest Area
GDP pc	0.0623***
	(0.00567)
Biomass	-0.0675***
	(0.00988)

Fossil Fuels	-0.00448***
	(0.000791)
Metal ores	-0.00146***
	(0.000422)
Non metallic minerals	-0.00332***
	(0.00108)
Corruption Control	-0.00747
	(0.00935)
Political Stability	-0.00718***
	(0.00239)
Rule of Law	0.0183***
	(0.00471)
Observations	2,549
Number of groups	154

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Chapter 3

Global convergence of meat consumption – Is income growth an insurmountable force?

Author: Daniel Töbelmann

Abstract

Globally, the negative environmental and health effects of increasing meat consumption are high. While the level of meat consumption in developed countries is already considered high and slowly stagnating in growth, literature suggests that developing countries might catch up with increasing economic development. To gain better understanding of global convergence patterns of developed and developing countries I analyze 121 countries in the period of 1984-2013, within a convergence analysis and clubbing algorithm framework. Overall convergence is rejected, and two distinct clubs are identified. One consists of rather developed and the other of rather developing countries. This suggests that each club strives towards a group-specific but not a global equilibrium. The generally suggested major driving force of such an increase in consumption is rising income. As households get more affluent, dietary patterns seem to change towards more meat intensive ones. To investigate the role of income growth and other potentially influencing factors, like cultural, historical and geographical, an ordered logit regression analysis is conducted. By this, the relevance of income as a determining and consumption increasing factor is strengthened, while certain religious traits are found to have a mitigating effect. Together, the analyses contribute a quantitative and detailed basis for understanding convergence dynamics and its determining factors.

Keywords Meat consumption, convergence, income, clubbing algorithm

JEL Classification D12, L66, O47, Q01, Q24, Q54

Publication

This paper is an unpublished manuscript.

3.1 Introduction

On a global scale, meat consumption is increasing. This entails environmental and social consequences, since livestock production is a dominant driver of ecosystem destruction (Machovina et al., 2015; Recanati et al., 2015), greenhouse gas emissions (Machovina et al., 2015; Xu et al., 2021) and increasingly catalysator for diseases, both zoonotic and civilisation ones (Espinosa et al., 2020; Godfray et al., 2018; Kearney, 2010). Increasing consumption per capita is assumed to accompany increasing income (Kearney, 2010; Nam et al., 2010; Recanati et al., 2015; Sengul and Sengul, 2006). While the consumption levels in developed countries are already high, it is uncertain, how it will develop in developing countries, with currently still lower levels (Alexandratos and Bruinsma, 2012). The concern is that those countries catch up to “western” levels, when their income increases, simultaneously increasing all negative pressures and impacts of livestock production. However, there are also other factors influencing dietary behaviours, like cultural and societal ones, that potentially shape how and if increasing income is transferred to meat consumption. Two central questions are addressed in this study. First, if a global convergence of meat consumption levels can be identified quantitatively, i.e. if there is a common level global consumption is developing to. Second, if there is an effect of such other factors than income, that could potentially mitigate meat consumption, despite increasing income, or if income is indeed trumping all other aspects.

To investigate this, different analyses are conducted. A data set of 121 countries for the period 1984-2013 is constructed. For the main analysis, the Philips and Sul clubbing algorithm is performed, to investigate potential patterns of global convergence. To gain a deeper understanding of the different determinants of meat consumption, an ordered logit regression is employed, incorporating income and other potentially relevant factors. One of the key purposes of this study is to empirically investigate which of those potential factors influence meat consumption and convergence, with a special focus on income. To the best of my knowledge, this is the first study analysing the convergence behaviour of meat consumption in a quantitative and comprehensive clubbing-algorithm framework, on a global basis. Additionally employing the ordered logit regression to these data is a novelty added this stream of literature. The results show that the difference in meat consumption levels between countries decreases, indicating convergence. A global convergence, however, is rejected by the clubbing algorithm. Instead, two groups are defined, indicating that consumption does not move towards one common but two different equilibria. Those two groups highlight that there is a difference between developed and developing countries. One group contains primarily developed economies, with rather high consumption levels, while the other composes of developing economies, with lower levels. The ordered logit regression results suggest that certain cultural factors persistently influence the probability of higher meat consumption levels, like for example certain religious traits and education. Nevertheless, income growth seems to be one if not the driving force.

The paper is structured as follows. Section two structures the relevant literature. This literature review is parted in two, one summarizing on the environmental implications of meat consumption, and the other reviewing the existing empirical literature on convergence. Section three provides an overview of the methods and data used. Section four presents the empirical results and the discussion of those, before in section five a conclusion is drawn.

3.2 Literature review

This section provides a literature review. It consists of two separated parts. The first part, section 3.2.1, summarizes the environmental and health effects of meat consumption, i.e. livestock production, and gives an overview of the global developments and arguments for convergence patterns. The second part, section 3.2.2, summarizes the empirical literature and findings and builds the reasoning and context for the following analyses and variables.

3.2.1 Development of meat consumption and the environment

The human consumption of animal-based foods is described as the most powerful negative force, affecting the conservation of terrestrial ecosystems and biological diversity (Machovina et al., 2015). Meat consumption is expected to become one of the most relevant sectors in terms of environmental impacts globally (Recanati et al., 2015) and livestock production is the single largest driver of habitat loss (Machovina et al., 2015). Over the last 300 years[65] nearly the half of all natural grassland and one third of all forests were converted to cropland (Goldewijk, 2001). While food systems in general are responsible for around 60% of the global terrestrial biodiversity loss (Delabre et al., 2021), approximately 30% of the total human-induced biodiversity losses are related to livestock production (Westhoek et al., 2011). Future projections show, that if the current trends continue ~ 1 billion additional ha of land would be cleared globally until 2050 (Tilman et al., 2011). The by then projected human population of

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[65] Period ends in 1990.

9.8 billion would require a 100 – 110% increase in crop production, compared to 2005, what inevitably needs agricultural productivity or land to increase (Delabre et al., 2021). The gap between latest productivity increases and demands has widened, suggesting that the expansion of agricultural land and thereby increasing pressures on natural ecosystems is probably unavoidable. The agricultural output to produce meat and other animal-based products is way greater than in plant-based diets, requiring more agricultural land (Fukase and Martin, 2020), causing increased transformation of natural ecosystems like tropical rainforests[66] (Recanati et al., 2015). Furthermore, livestock production is also a leading cause of climate change, soil loss, water and nutrient pollution (Machovina et al., 2015). Agriculture in general, of all human activities, is the most dominant consumer of freshwater, of which nearly a third solely goes into livestock production (Godfray et al., 2018). The livestock sector is a key driver of several planetary boundary transgressions (Bowles et al., 2019) and agriculture and the associated land use is a major source for greenhouse gas (GHG) emissions (Xu et al., 2021). ~34% of the total global GHG emissions[67] come from food-systems (Crippa et al., 2021). Of those, ~57% correspond to the production of animal-based foods[68] (Xu et al., 2021). Particularly impactful is the production of ruminants, like e.g. beef (Bowles et al., 2019; Selinske et al., 2020), since it has the highest emission intensity of all types of meat (Godfray et al., 2018). 25% of the animal-based emissions stems from beef production alone (Xu et al., 2021).

Besides all ecological issues, meat consumption has been in concrete focus recently, due to its potential indirect causation of the COVID-19 virus and followed pandemic (Espinosa et al., 2020). Approximately 75% of all emerging infectious diseases are zoonotic ones[69]. Intensive animal farming creates conditions in which epidemics are facilitated, by often raising animals indoors, in high density, that are often in frail health (Coker et al., 2011; Espinosa et al., 2020). By the accompanied deforestation, farming indirectly contributes to the spreading of pathogens from wild animals (Espinosa et al., 2020). This so called dilution effect posits that more diverse ecological communities limit disease spread, consequently indicating that anthropogenic biodiversity loss increases human and wildlife diseases (Civitello et al., 2015). Livestock production is an incubator for antimicrobial resistances, caused by the amounts of antibiotics used for farmed animals[70](O´Neill, 2015). Parallel to those issues, dietary transitions towards

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[66] In the Brazilian Amazon approximately 65% of all deforestation is linked to cattle ranching (Recanati et al., 2015).

[67] This calculation is based on the year 2015, provided by Crippa et al. (2021).

[68] Including livestock feed (Xu et al., 2021).

[69] Meaning that they are transmissible between animals and humans (Espinosa et al., 2020).

[70] That is often times not therapeutic but prophylactically also given to healthy animals, to stop infections within herds or to simply accelerate animal weight gain (O´Neill, 2015).

more animal-based foods are also increasingly expected to negatively affect the public health (Godfray et al., 2018) by fostering civilisation diseases, like rising rates of obesity and chronic diseases as diabetes, cardiovascular disease and cancer (Kearney, 2010).

The environmental effects of livestock production are problematic from a sustainability point of view (Bowles et al., 2019) and the global average per capita meat consumption is continuously growing (Godfray et al., 2018). Meat contributes relatively little to the global food security, compared to the impacts it entails (Bowles et al., 2019). Resource consumptions are converging worldwide, with the tendency of less affluent countries aspiring higher levels (Pretty, 2013). The affluent ones have set desirable benchmarks that attract others. However, it is indicated, that this increasing consumption cannot be met by our finite planet. While the continuing growth in animal products consumption is in line with globally increasing affluence and urbanization trends, consumption patterns are non-linear across different world regions (Bowles et al., 2019). A plateauing or even decrease in some developed countries is suggested, but an increase in other ones, including those with large populations (Godfray et al., 2018). Such trends will drive the environmental impacts of the sector, if not mitigated (Bowles et al., 2019), and make an understanding of the development of consumption patterns in the light of its drivers across world regions highly valuable. Developing countries, and especially the tropical ones with high species-richness, play a major role in conserving biodiversity, since increasing affluence in those regions is risking to drive large area losses to agriculture, if not met by countermeasures (Henry et al., 2019).

It is argued that income increase is one major driver of meat consumption increases (see section 3.2.2). Then, the central question is, how currently developing countries will change their dietary patterns, when their economic growth continues. Due to potentially intensifying impacts, it is thus critical to evaluate how such increasing income is transferred to meat consumption. Two overarching dietary evolution scenarios potentially initiated by income growth emerge from the literature (Brunelle et al., 2014). The first scenario is a global convergence towards a livestock-based “western-style” diet[71],. The second scenario is still a convergence towards rather western-style meat consumption levels, however, significantly constrained and steered by regional specificities (Alexandratos and Bruinsma, 2012). While the meat and in general livestock consumptions in developed countries probably remain

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[71] A nutritional transition referred to as “westernization” – the predominant dietary pattern in developed countries (Brunelle et al., 2014) . This transition is primarily characterized by dietary changes towards increased animal-products and protein consumption and decrease of fibre, grains, and starchy staples (Fukase and Martin, 2020; Mathijs, 2015).

significantly high, not all developing countries necessarily transition fast towards those levels with increasing income. For some the reason could be only slow increases in income and persistent poverty, while for others cultural and religious factors could preserve current food habits and brake meat consumption growth (Alexandratos and Bruinsma, 2012). While there are commonalities in belief systems regarding meat consumption between countries, socio-cultural and institutional differences, like religion, seem to shape how those commonalities are perceived (Khara et al., 2021).

One example for the first scenario is the development of Chinese meat consumption behaviour. This raises concerns regarding potential developments of other developing and high-population countries. Historically, grains and vegetables significantly contributed to the Asian diet and only a relatively small amount of meat was consumed (Nam et al., 2010). Asia has experienced and still experiences a phase of rapid economic growth. Per capita income has increased 670% in the period 1956 to 2006. Parallel to this, the animal product consumption has increased 270%, and is expected to continue to grow (Nam et al., 2010). For India and Africa, however, those significant increases are not expected for the coming decades (Kearney, 2010). Much more, India could be a potential example for the second scenario, since it has maintained relatively low levels of meat consumption, despite increasing income and affluence (Pretty, 2013). The role of increasing income for a dietary change towards more meat heavy ones is of importance to investigate empirically in more detail. Convergence analysis and an understanding of the different dynamics behind food and meat consumption, can inform long-term planning by governments and non-governments on infrastructure developments and marketing strategies (Sengul and Sengul, 2006; Wan, 2005) to influence the dietary habits of populations towards more sustainable ones (Tschanz et al., 2022).

3.2.2 Empirical evidence of meat consumption convergence

Empirically, different studies analyse the convergence of meat or animal-based product consumption in different contexts. Regmi and Unnevehr (2005) analyse sigma convergence in food expenditure in 18 high-income countries for the period 1990-2004. Employing the coefficient of variation (CV) and regression analysis, they find significant convergence, resulting from expenditures in cereals and meat. Both categories account for about 40 % of total expenditure. Furthermore, they find per capita income rather insignificant in most cases, indicating that convergence is partly independent of income in high-income countries. Wan

(2005) analyse panel data on food consumption from 28 regions of China, for the period of 1982-1998. They employ data on different meat types that are meat, red meat, poultry meat, and animal fat. The findings of a CV analysis suggest convergence[72] for poultry meat but divergence for meat, red meat, and animal fats. Using panel OLS they find beta convergence for poultry meat. For meat no significance of convergence is found, and even divergence for red meat and animal fat. Sengul and Sengul (2006) look at Turkey and 15 European Union Countries, for the period 1970-2000 to investigate the relationship between food consumption and economic development. There are differences in dietary patterns between Turkey and EU countries, and between EU countries. They find increasing animal-based calorie consumption with increasing economic development in almost all EU countries, with an income elasticity for animal-based products higher than those of general food consumption. Beta convergence regarding the diet structure within the EU has been found, also with Turkey joining the EU. For animal-based calories specifically this is found significant for the EU, not however, if Turkey joins. Kearney (2010) finds that between 1963 and 2003 especially in developing countries the consumption of calories from meat, sugar and vegetable oils increased significantly, while in developing countries from those three only the consumption of vegetable oils increased. Pretty (2013) analyses the development and convergence of meat consumption and GDP per capita latitudinally over 189 countries and in more depth longitudinally over 60 years for Japan, UK and USA. By descriptive data analysis he finds partial divergence, or rather inconsistent convergence, in meat consumption patterns, with increasing GDP per capita, which is expected to be shaped by cultural and religious factors. A distinct example is India, that has maintained a low level of meat consumption, despite increasing affluence. On the contrast, however, Brazil, China, UK and USA are recording increasing consumptions with increasing GDP per capita. Allievi et al. (2015) investigate the development of meat and animal product consumption regarding efficiency, sufficiency and consistency for 140 countries and the period 1962-2009. They also incorporate a convergence analysis, focussing on beta, sigma and gamma convergence, for the three meat related variables of total meat supply per capita, number of animals slaughtered per capita and land requirement for animal product per capita. Employing regression analysis their results regarding beta convergence suggest absolute convergence in all cases. Sigma convergence is measured by the standard deviation of the variables. Regarding land requirements, they find decreasing standard deviation, suggesting convergence. For the

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[72] Wan (2005) identify a reduction in the CV, what they call gamma convergence. Based on Barro and Sala-i-Martin (1992) that define sigma convergence as a reduction in the cross-sectional standard deviation of income, i.e. consumption, over time, Wan (2005) argue that the reduction in the CV is defined with a different notion (Wan, 2005).

other indicators, the results are not that straight forward. There, rather divergence is found, with slight tendency of convergence only in the last few years. Lastly, gamma convergence, measured by the coefficient of variation, is found significant for meat supply and the number of animals slaughtered. They conclude that industrialized and developing countries are moving to similar patterns of animal product consumption and that thus convergence is given. Sans and Combris (2015) suggest economic development and urbanization as the main driver for increasing animal-based protein consumption worldwide, but also identify a significant variation in the composition of animal-based protein and the position of meat between countries of similar degrees of economic development. This suggests that historical, geographical, cultural and religious factors may play a role. Furthermore, in their analysis the initial level of per capita meat protein intake reveals as a poor predictor for future intake levels. Bell et al. (2021) find that dietary inequalities between countries in general has declined, with different intensities for different dietary components. With a Lorenz-curve and Gini-coefficient analysis they find for animal-sourced foods very unequal consumption levels in 1971 with convergence to a more similar level in 2010.

Major dietary changes are generally attributed to economic growth and the influence of globalization (Brunelle et al., 2014). In Literature the assumption that increasing income leads to increasing consumption of meat is highlighted[73] (Brunelle et al., 2014; Fukase and Martin, 2020; Nam et al., 2010; Regmi and Unnevehr, 2005; Tilman et al., 2011). However, it is also assumed that certain factors potentially influence and even partially prevent a global convergence in meat consumption – despite rising income. The following summarizes results and evidence from the literature, regarding those factors. These build the foundation for the employed variables in section 3.3.3. Beside increases in income, urbanization is found as a dominant determining factor for increasing meat consumption (East et al., 2005; Milford et al., 2019; Sans and Combris, 2015). It can have a profound impact on food consumption patterns, especially via the offering of greater food choices in cities, often towards more fast-food items, leading to a dietary shift towards more animal protein from meat (Kearney, 2010). Especially in developing countries urbanization will be impacting within the next decades (Mendez and Popkin, 2004). Religious backgrounds are found to influence and limit the consumptions of meat, in different regions of the world (Mensah et al., 2022; Nam et al., 2010). Due to potential religious and cultural factors, members of religious groups are potentially less likely to consume meat (Filippini and Srinivasan, 2019). One example is India, where a large share of the

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[73] And other animal-based products.

population is or were vegetarian, due to belonging to Hinduism. And most other religions have partial restrictions, like e.g. the ban of pork in Judaism and Islam (Vranken et al., 2014). Another potentially important aspect to consider is the demographic shift in populations, towards older adults. While there is not one major dietary pattern or trend of older adults regarding meat consumption clearly identified (Grasso et al., 2021; Tschanz et al., 2022)[74], this is important to analyse. According to the UN the share of the global population aged 65 Years or over will nearly double in 2050 (to approximately 17 %[75]), compared to 2019 (approximately 9 %[76]) (United Nations, 2019). For e.g. the Chinese population a significantly negative effect of age on consumption is suggested (Min et al., 2015). If this indication is found on a global basis, this has important implications in the face of socio-demographic changes. The educational level within countries is also a factor considered relevant. Higher levels of education were found generally associated with rather lower likelihoods of consuming meat[77](Guenther et al., 2005; Tschanz et al., 2022). However, the results are described as rather inconclusive. Especially for western countries, the relationship between education and meat consumption is unclear (Mata et al., 2023). While some studies identify effects, others find none. The general and intuitive argumentation, why higher education is associated with lower meat consumption is that better knowledge exists regarding the health and environmental benefits (Mata et al., 2023). Studies suggest that geographic location also determines dietary patterns (Mayén et al., 2014). For example, coastal regions diets are assumed to be relatively strongly based on fish and seafoods, provided by the near sea, like e.g. in the case of the traditional mediterranean diet (Del Mar Bibiloni et al., 2012; Maugeri et al., 2019). There are indications for regional differences in consumption, due to differences in availability of fresh seafoods (Myrland et al., 2000)[78], and for coastal fishing people a preference for fresh fish, against meat[79] is found (East et al., 2005). A tendency towards higher meat consumption in countries further away from sea might thus be expected. Meat production requires a high amount of land (Gerbens-Leenes and Nonhebel, 2002; Goldewijk, 2001; Machovina et al., 2015). The switch from a vegetarian diet to one that contains meat is estimated to enfold an

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[74] This could be due to the differences in scientific setup (Min et al., 2015) and the measures of meat consumption. Considering also consumption that takes part away from home, increases the amount of meat by approximately 30% (at least for China).

[75] In 2050 1 out of 6 people globally will be aged 65 years or over (United Nations, 2019).

[76] In 2019 1 out of 11 people globally were aged 65 years of over (United Nations, 2019).

[77] At least regarding beef and pork and processed pork products. On poultry consumption the effect of higher education is rather increasing on the likelihood (Guenther et al., 2005).

[78] This study solely looks at Norway and the regional differences appeared rather between urbanized and non-urbanized regions. The rational, however, could also indicate differences between costal and more central countries in general, since better logistics are suggested to increase the provision of seafood in central regions.

[79] In this study the consumption of bushmeat was analysed.

increase of land requirement of factor three or more (Gerbens-Leenes and Nonhebel, 2002). Not only is the required land area driven by population growth in general, but even more by those changes in dietary patterns.

The question of convergence in meat consumption is analysed in different studies, with mixed results. Those results are accompanied by the assumption of influencing factors like culture, religion, geography or demography potentially limiting or shaping the development of convergence (Allievi et al., 2015; Kearney, 2010; Sans and Combris, 2015). Especially the income level is described as a dominant driving determinant (Kearney, 2010), while also for recent developments like in Asia, those other factors like religion and geography are expected to limit further consumption growth in the future (Nam et al., 2010). To gain a better understanding, the following analyses contributes to this literature, by providing a first more sophisticated and quantitative framework for evaluating potential conversion dynamics.

3.2 Methods and Data

3.2.1 Econometric Method

The econometrics follows the method outlined by Phillips and Sul (2007). This approach has two main advantages for this analysis. First, by allowing for heterogeneity in convergence behaviour across countries and time, it captures the variety of different countries. The prevailing assumption is that β-convergence analysis of homogeneity of transition parameters can be misleading, if the actual parameters are heterogenous (Phillips and Sul, 2009). Second, it allows to identify converging sub-sets (club convergence), even if overall convergence for the full sample is rejected.

Phillips and Sul (2007) begin with a decomposition of the variable of interest.

$$(1)\ \ X_{it} = \delta_{it}\mu_t$$

X_{it} is the variable of meat consumption, δ_{it} measures the share of the common trend μ_t and thus captures a country´s transition path. The prescripts i and t describe the country and time. If those δ_{it} asymptotically converge to δ for all countries, growth convergence is indicated. If the convergence rate is fast enough, level convergence could be given as well. Phillips and Sul (2007) have developed a regression test, the so called "log t" test, utilizing the cross-country dispersion $H_t = \frac{1}{N}\sum_{i=1}^{N}(h_{it} - 1)^2$ of a relative transition parameter h_{it}, given by

$$(2)\ \ h_{it} = \frac{\log X_{it}}{N^{-1}\sum_{i=1}^{N}\log X_{it}} = \frac{\delta_{it}}{N^{-1}\sum_{i=1}^{N}\delta_{it}}.$$

This relative transition parameter h_{it} converges to unity and H_t to zero if convergence is given. The latter is used to test against the alternative hypothesis of divergence or club convergence, given by the equation

$$(3)\ \ log\frac{H_1}{H_t} - 2\log(\log t) = a + \gamma\log t + \varepsilon_t.$$

ε_t is a time-specific error term and $2\log(\log t)$ is a penalty function. This one-sided t-test of inequality for $\hat{\gamma}$ allows to test for the null hypothesis of convergence. With a t-statistic less than -1.65 the null hypothesis of convergence is rejected at the 5% level of significance. The speed of convergence is measured by the magnitude of the coefficient, with convergence in levels given by $\gamma \geq 2$ and growth convergence by $2 > \gamma \geq 0$ (Kerner and Wendler, 2022). Rejecting the null hypothesis for the full sample rejects overall convergence, however, the alternative hypothesis entails not only divergence, but also club convergence, describing groups of certain countries that converge to shared equilibria. The proposed algorithm by Phillips and Sul (2009, 2007) allows to identify the number of such convergence clubs and its members, as well as divergent countries. Five overarching construction steps[80] are involved in implementing the procedure: (1) last observation cross-sectional ordering, (2) core group formation, (3) sieve individuals for club membership, (4) recursion and stopping rule, and (5) club merging.

For the log t regression, a fraction of the time series data must be discarded. The initial observation in the regression is $T_0 = [rT]$, for some $r > 0$ (Phillips and Sul, 2009). For this fraction a value of $r = 0.3$ is used, as suggested by Phillips and Sul (2007) for small to moderate sample sizes[81]. For the sieving process a critical value c must be chosen as a sieving criterion for the algorithm (Phillips and Sul, 2007). Following Phillips and Sul (2009, 2007), $c = 0$, that is again suggested for small to moderate sized samples. Since the long-run development and dynamics of meat consumption are of interest, the procedure follows Phillips and Sul (2007) and removes the business cycle component from the data, to extract the long-run or trend

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[80] Only the stylized steps are reported here. For detailed descriptions of the procedure and steps, see Phillips and Sul (2009, 2007) and Du (2017).

[81] Small to moderate sample sizes are suggested around $T \leq 50$ for example, by Phillips and Sul (2007), which is appropriate for the present sample of this study.

component. Therefore, a Hodrick-Prescott (HP) filter is employed (Hodrick and Prescott, 1997), setting the smoothing parameter to 6.25, as suggested by Ravn and Uhlig (2002).

The methodological process in this paper closely resembles the empirical strategy by Kerner and Wendler (2022), which conduct a convergence analysis with clubbing algorithm on resource productivity.

3.2.2 Data

Data for the main variable of meat consumption is gathered from the Food Balance Sheets (FBS) from the FAO. This is a widely used source for food consumption data (Allievi et al., 2015; Azzam, 2021; Mathijs, 2015) allowing a wider spectrum of countries and years than potential alternative sources (Mathijs, 2015). The data represent essentially global meat consumption per capita and year in kilogram of different types of meat. The FAO provides data on the meat types “Bovine”, “Poultry”, “Pig”, “Mutton and Goat”, and “Others”. The employed dependent variable of meat consumption is an aggregate variable of all these types. An interesting feature is thus that an overarching, but also specific analysis of developments becomes possible with these data and differences between types of meat can be identified and evaluated. Especially in terms of evaluating certain environmental implications, this could be valuable. It must be mentioned that the FAO dataset is not actual and precise consumption data, but rather an estimation of the respective inland meat availability (Hawkesworth et al., 2010). It is calculated as the inland production corrected for imports, exports, and changes in national stocks[82], which is the divided by the national population to obtain per capita measures (Hallström and Börjesson, 2013). What is not covered, however, is the food waste after the retail stage. The measure does thus reflect what is available to people, not what is consumed. Despite this drawback, this dataset is an appropriate indicator of at least potential consumption and allows for a global comparison and analysis. Further potential datasets used in studies are e.g. the number of animals slaughtered, the land requirement of animal products, see e.g. Allievi et al. (2015), or nationally constructed data sets, potentially allowing for higher precision (Hallström and Börjesson, 2013). For the purpose of this study, the FAO FBS seems to be most

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[82] Available meat supply within a country is calculated as (national production + imports + opening stocks) – (exports + usage inputs for food + feed + non-food usage + wastage + closing stocks) (Hallström and Börjesson, 2013).

appropriate dataset, since it represents potential consumption and is available globally in a time series format.

The data on the control variables GDP per capita, Demographics, Educational Mean, Urbanization, Land Area and Agricultural Area are sourced from the World Bank. Data on Religion is sourced from the World Religion Database and the variable Distance to Sea from the Harvard Geography Dataset. Data on Demographics, Educational Mean, Urbanization and Agricultural Area were given in percent. GDP per capita is given in constant 2015 U.S. dollars. Demographics represent the population share aging 65 years and above and Urbanization the population share living in cities and urbanized areas. Distance to Sea is measured as the distance from the centroid of a country to nearest coast or sea-navigable river in km. Data on Religion are given in percent for each country and religion. The employed data are based on the year 2000. The control variable Religious belonging is generated by subtracting the share of Atheists within a country from the overall belonging. The data on Education represent the literacy rate of a respective country. Due to data constraints, the Educational Mean is generated by the mean of the literacy rate at the country level, to inform about the mean over all given years. The meat consumption data were initially given for the period 1960-2013. The employed methods require a strongly balanced panel. Therefore, the period spanned by the data[83] is customized to the available years, incorporating all included data. The data span the period from 1984 to 2013 for overall 121 countries.

3.3 Results and Discussion

3.3.1 Descriptive statistics

Figure 1 shows the global development of per capita meat consumption over time. A continuous increase in meat consumption becomes visible and confirms the general assumption of consumption growth. During the 30 years from 1984 to 2013 the global average per capita meat consumption has grown about 36%, from initial 36.75 kg to 50.04 kg. The lowest level sample is found for Bangladesh, with 3.38 kg per capita, followed by India, Sri Lanka, and Rwanda, with 4.12 kg, 5.14 kg and 5.29 kg. The highest for Hong Kong with 120.10 kg per capita, followed by the US, Australia, and New Zealand, with 118.10 kg, 112.37 kg and 105.21 kg.

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[83] For an overview of variables, their original data units, and sources, see Table A.1 in Appendix.

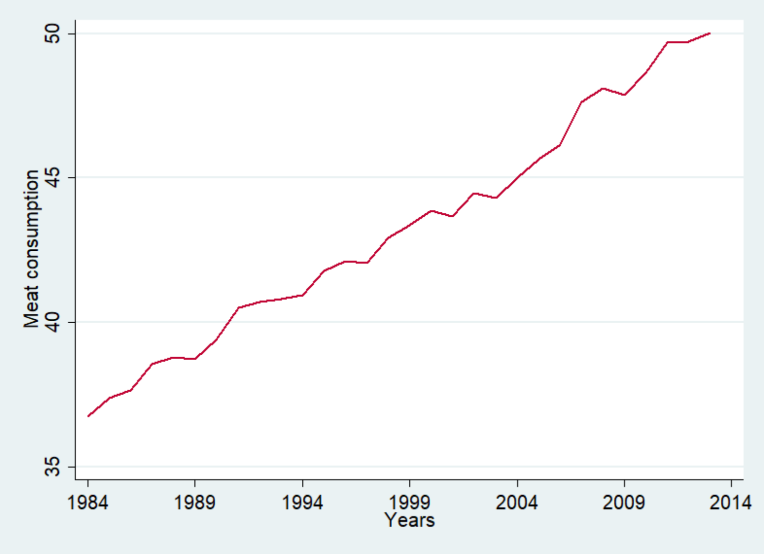

Figure 1: Development of global meat consumption per capita, in kilogram, for the years 1984-2013.

This cumulative consumption can be differentiated into different types of meat. Figure 2 shows the development of the meat categories bovine, poultry, pig, mutton and goat, and other meats separately. From all categories, poultry meat consumption has increased the strongest. With yearly per capita consumptions of 8.81 kg in 1984 and 21.31 kg in 2013, it has grown about 142%. This is followed by pig meat consumption that has grown around 30%. Bovine meat consumption has decreased by about 13%, with 12.98 kg and 11.27 kg in 1984 and 2013 respectively. Also, the consumption of mutton and goat as well as other meat has decreased, by 14% and 2%. First, these results suggest that not all meat type consumptions have contributed to the global average increase equally. The consumption growth is attributed to poultry and pig meat consumption, while all other consumptions have decreased. Second, this could indicate towards potential substitution effects. Eventually, the consumptions reductions of bovine, mutton and goat, and other meats were substituted and obviously overcompensated by poultry and pig meat.

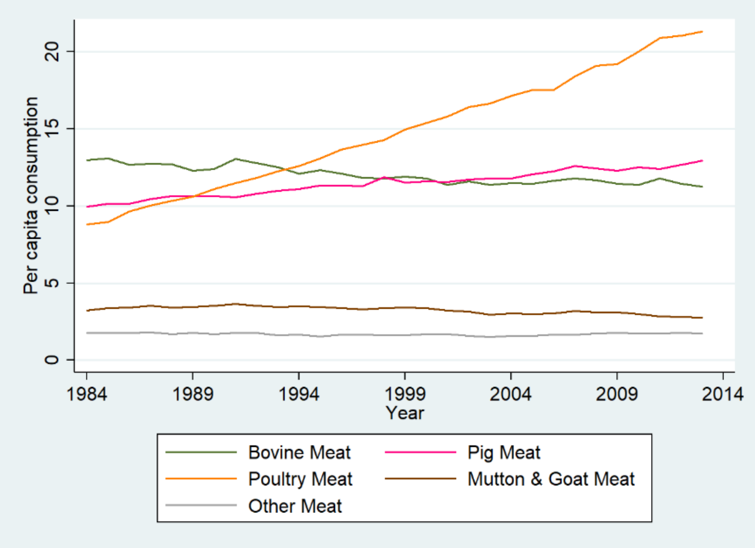

Figure 2: Global development of per capita consumption of different meat categories, in kilogram, for the years 1984-2013.

Before the results regarding β-convergence are presented and discussed, I provide descriptive[84] evidence to gain first impressions and interpretations regarding the dynamics within the data. σ-convergence describes a decline in cross-sectional dispersion of a variable and provides a basic indication for existing convergence. A common measure is the coefficient of variation (CV), describing a potential decline in inequality between countries. Figure 3 shows the CV for all countries and the period 1984-2013. It shows a relatively constant decline in dispersion, with increasing acceleration. In the first years there is no significant change, but rather an increase, up until a decline between the 1991 and 1992. From there on, it increases again in spikes in 1998 and 2001. From 2001 on, up until 2011, the CV declines steep and even, before it indicates to start a plateau in the last years. The data suggests that the inequality in meat consumption between countries decreases over time, indicating that the global levels of consumption move towards a more similar one. σ-convergence is thus suggested.

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[84] For pairwise correlations of the variables see Table A.2 in Appendix.

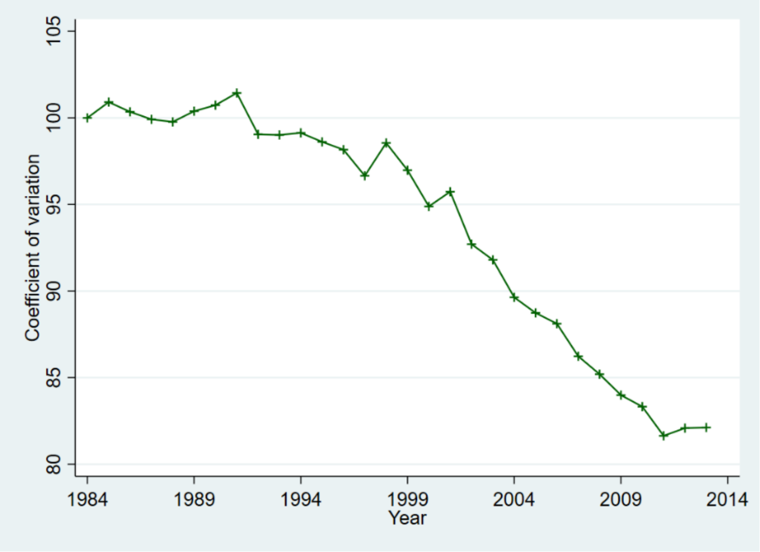

Figure 3: Coefficient of variation (CV) of meat consumption.

Note: The CV is calculated as the cross-sectional standard deviation divided by the cross-sectional mean of the respective year, both in logarithm. The CV is normalized to the value 100 in year 1984.

Figure 4 and Table 1 investigate the potential existence of unconditional β-convergence, describing that the growth rate of a variable depends primarily on its initial level[85]. In Figure 4 the initial log level of meat consumption in 1984 is plotted against the average annual growth rate of meat consumption, for the period 1984-2013. The negative slope indicates that countries with a higher level of initial consumption tend to show lower rates of future consumption growth.

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[85] See e.g. Barro and Sala-i-Martin (1992) for a more detailed description of convergence concepts.

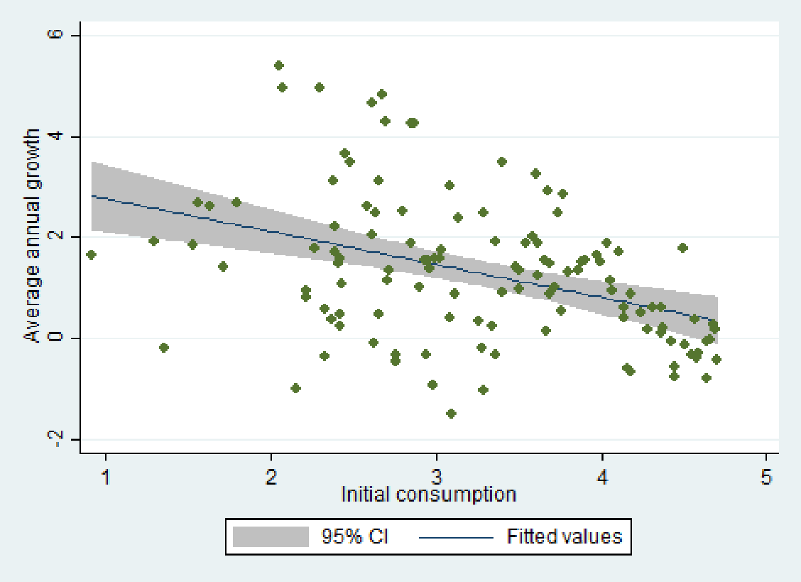

Figure 4: Scatter plot of β-convergence of meat consumption.

Note: The initial meat consumption of 1984 in log levels is plotted against the average annual growth rate of meat consumption between 1984 and 2013.

3.3.2 Convergence Analysis

Table 1 shows two regressions strengthening the suggestion of unconditional β-convergence. The first row shows the results of an OLS regression, in the second column the results of a robust regression are given. Both results indicate that the initial level of meat consumption negatively influences future annual average consumption growth rates. The higher the initial consumption, the lower the average annual growth rates.

Table 1: β-Convergence Regression of meat consumption and growth of meat consumption.

VARIABLES	(1) OLS	(2) Robust Regression
Initial Meat Consumption	-0.651***	-0.606***
	(0.130)	(0.136)
Constant	3.419***	3.206***
	(0.494)	(0.458)
Observations	121	121
R-squared	0.161	0.143

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note: Regression of the average annual growth rate on the initial meat consumption of 1984 in log levels.

The results so far suggest that there could be sigma as well as beta convergence, indicating that first, the level of meat consumption tends to globally move to a more similar one and that the consumption dispersion between countries is potentially declining, and second, that the initial level of consumption is a significant determinant of future consumption development, with higher levels of consumption being associated with lower rates of future growth. Vice versa this means, that lower initial consumption levels are associated with higher future consumption growth. These results can be interpreted as that countries that are currently consuming less meat per capita, potentially "catch-up" during time and reach consumption levels of countries located higher at the global spectrum. The indications of those results are mainly in line with the literature. Regmi and Unnevehr (2005) and Allievi et al. (2015) also suggest sigma convergence and nearly all referenced studies suggest the existence of beta convergence. These results provide interesting insights into the dynamics, are, however, not very resilient and meaningful in the presence of transitional heterogeneity. As discussed by Phillips and Sul (2009), the slope coefficients of regressions assuming homogenous coefficients are potentially biased and negative coefficients can occur even under divergence (Phillips and Sul, 2009).

Table 2 shows the results of the preferred convergence analysis, the convergence (clubbing) algorithm by Philips and Sul (2007). The first group contains the whole set of countries, to test for overall convergence. This is clearly rejected by the t-statistic <-1.65. However, beside this general group, two distinct clubs are identified by the algorithm. For both, club convergence is suggested by the t-statistic. The magnitude of the coefficients identifies growth convergence since both are clearly below 2, which thus rather rejects convergence in levels.

The two identified clubs further show some specific characteristics with respect to the clustered countries. Club 1 contains 69 of the overall 120 countries grouped. Those are primarily located in Europe (28%) and South / Central America (23%). Countries from Asia and Africa are less represented (with 17% and 10% respectively). The average economic development state[86] tends to be relatively high, especially in comparison with Club 2. In Club 1 29% of the countries are developed economies and 46% high, 36% upper-middle, 16% lower-middle and 0% low-income countries. Although 70% are developing economies, Club 1 contains almost all of the developed economies in the sample[87], of which 23 are OECD members. Club 2 in contrast is

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[86] The classification was conducted employing the Statistical Annex of the UN World Economic Situation and Prospects (WESP) 2022, clustering countries according to their developmental state and income (see EAPD (2022)). Information gaps were filled with data/information from The World Bank.

[87] Only Bulgaria is not captured by Club 1.

dominated by African (61%) and Asian countries (27%), followed by South/Central American ones (10%). Of those, 98% are developing economies and only one country a developed one, which is an OECD member. Regarding income levels, Club 2 tends towards the lower spectrum, with 0% high, 18% upper-middle, 51% lower-middle and 31% low-income countries.

Table 2: Convergence and convergence clubs within meat consumption.

Group	Country	Log t Test
All	All	-0.3124 (-7.7057)
Club 1	Albania, Angola, Antigua and Barbuda, Argentina, Australia, Austria, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Brunei Darussalam, Cabo Verde, Chile, China, Colombia, Costa Rica, Cuba, Cyprus, Denmark, Dominica, Dominican Republic, Ecuador, El Salvador, Finland, France, French Polynesia, Gabon, Germany, Greece, Grenada, Guyana, Honduras, Iran, Ireland, Italy, Jamaica, Japan, Jordan, Malaysia, Malta, Mauritius, Mexico, Mongolia, Morocco, Myanmar, Namibia, Netherlands, New Zealand, Norway, Panama, Philippines, Portugal, Republic of Korea, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Samoa, South Africa, Spain, Suriname, Sweden, Switzerland, Trinidad and Tobago, United Kingdom, United States, Uruguay, Vietnam	0.262 (3.354)
Club 2	Algeria, Bangladesh, Benin, Botswana, Bulgaria, Burkina Faso, Cameroon, Central African Republic, Chad, Congo, Côte d'Ivoire, Egypt, Eswatini, Fiji, Gambia, Ghana, Guatemala, Guinea-Bissau, Haiti, India, Indonesia, Iraq, Kenya, Kiribati, Laos, Lesotho, Madagascar, Malawi, Mali, Mauritania, Mozambique, Nepal, Nicaragua, Niger, Nigeria, Pakistan, Paraguay, Peru, Rwanda, Senegal, Sierra Leone, Solomon Islands, Sri Lanka, Thailand, Togo, Tunisia, Türkiye, Uganda, Vanuatu, Zambia, Zimbabwe	0.114 (1.148)

Note: The log t-test coefficients are given with the respective t-statistic in brackets. Hong Kong was not convergent and could not be clubbed by the algorithm. As a robustness check the clubbing process was also performed with a share variable of meat consumption and GDP per capita.

The descriptive statistics in Table 3 make apparent the differences in meat consumption between the two clubs. Club 1 clearly is assigned with the higher level of meat consumption, of around 60 kg of yearly meat consumption per capita, in comparison to around 18 kg in Club 2. This relationship stays consistent when looking at the 1984 and 2013 consumption levels and the average yearly per capita growth rate of consumption. The latter is roughly twice as high in Club 1 as in Club 2, with a roughly 10 times higher average GDP per capita in the respective countries.

Table 3: Descriptive statistics convergence clubs.

Group	Mean meat consumption [kg per capita and year]	Mean meat consumption 1984 [kg per capita]	Mean meat consumption 2013 [kg per capita]	Mean GDP pc [in constant 2015 U.S. dollars]
All	43.25	36.75	50.04	10747
Club 1	60.86	50.72	70.30	17173
Club 2	17.90	16.81	20.59	1722

Note: Mean meat consumption refers to the average meat consumption per capita in kg, for each Group. The columns for 1984 and 2013 describe the average for the respective year only. Mean growth rate describes the average yearly growth rate of meat consumption over the full sample period.

Performing a clubbing-algorithm, however, overall convergence for all countries is rejected. This means that no general convergence towards a common level of consumption is suggested, independent of the countries. This contradicts at least the conclusion of Allievi et al. (2015), that suggest a global convergence by developing and developed countries moving to a similar pattern of consumption. This is not clearly confirmed here. Rather two distinct clubs of countries, that differ in their state of economic development and income, and that are indicated to move towards club-specific equilibrium levels. The clubbing algorithm provides important insights as an overall convergence is clearly rejected and the implication from the ß-convergence regression is opposite with respect to the two convergence clubs found by the algorithm.

3.3.3 Ordered Logit Regression

Besides a potential clustering of countries into clubs, the determinants of this clubbing are of relevance. To gain a deeper understanding of what may influence and lead to rather higher or lower levels of meat consumption, further analysis is needed. Table 4 shows the results of an ordered logit regression. This explores the effect of variables on the probability to belong to a specific club (Kerner and Wendler, 2022). Given are the marginal effects calculated at the mean on the probability of belonging to Club 1 for all variables. Included are the initial observations of each variable (t = 1984). Column 1 shows the estimations for each individual variable, Column 2 shows a specification including GDP per capita for each variable, controlling for a potential dominant effect of income increase. The coefficients express the respective effect of initial variable levels on the probability of belonging to Club 1, i.e. the "higher" club regarding meat consumption. The analysis aims to give indication about correlation, not causality. Table A.2 shows the correlation matrix for all incorporated variables. This gives a first impression of correlations. Meat consumption itself is relatively high positive correlated with GDP, Demographics and Urbanization. And GDP is positively correlated with Demographics, Urbanization and Education.

Basis and reasoning for the employed variables is given in section 3.2.2. GDP per capita is incorporated since the assumption is that meat consumption increases with increasing income (Kearney, 2010; Nam et al., 2010; Recanati et al., 2015; Sengul and Sengul, 2006). Beside GDP per capita, urbanization is incorporated as a variable, since it is found as a determining factor for increasing meat consumption (East et al., 2005; Milford et al., 2019). Its impact is primarily suggested via the offering of greater food choices in cities (Kearney, 2010). However, another effect that could be indirectly captured by the urbanization variable is the westernization of diets (Azzam, 2021). Besides income growth, the expansion of the western culture is seen as a prime cause for the increase of animal product consumption in Asia (Nam et al., 2010), for example. Religious backgrounds are considered potentially relevant (Mensah et al., 2022; Nam et al., 2010). Besides a general religious belonging within a country, as the overarching measure of religious orientation, specific variables that control for Christianity, Hinduism, Buddhism and Islam are incorporated, to control for specific religious effects. Demographics is added as a variable, to capture potential effects of populational and socio-demographic developments. The educational level within countries is also a factor considered. Since studies suggest that geographic location also determines dietary patterns (Mayén et al., 2014), like in the example of the mediterranean diet, the proximity to the sea[88] is assumed to influence food culture and choices. A tendency towards higher meat consumption in countries further away from sea is expected. Since meat production requires a high amount of land (Gerbens-Leenes and Nonhebel, 2002; Goldewijk, 2001; Machovina et al., 2015), agricultural area and land area in

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[88] And rivers.

general are incorporated as variables to control for its potential effect on meat consumption and to investigate if the initial level of agricultural area effects the consumption. The assumption here is that countries with larger available (and potential) agricultural area have a comparative advantage in producing meat, leading to lower prices (Milford et al., 2019), what could affect consumption behaviours, also within countries. The interdependencies between those variables must be assumed rather multifaceted and complex. The disentangling of such effects in this setting should thus be treated with due caution (Kerner and Wendler, 2022).

In the following, the results of the ordered logit regression are evaluated and compared[89], to identify the potential effect of added GDP per capita. Countries with higher initial levels of GDP per capita, population age, urbanization, and an educational mean, tend to rather belong to a higher club. While a general religious belonging does not seem to have a significant effect, a major part of the population belonging to Christianity seems to have a positive effect on belonging to Club 1 and a major part of the population of a country belonging to Islam seems to have a decreasing one. The results furthermore suggest that a higher land area and a higher distance to sea decrease the probability of belonging to Club 1. The share of agricultural area is not found significant. Adding GDP per capita, the effect of most of the population belonging to Islam and a higher educational mean remain significant, with a reduced effect. Religious belonging becomes significantly negative. All other variables become or remain statistically insignificant. In all estimations, countries with initially higher GDP per capita are found to rather belong to Club 1. For some variables GDP per capita seems to be the actual driving force, capturing the significant effect of the variables.

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[89] For correlation coefficients see Table A.2 in Appendix.

Table 4: Ordered logit regression results.

VARIABLES	(1) Single Variable	(2) With GDP per capita
GDP per capita	.383***	
	(.0804025)	
Agricultural Area	-.054	.079
	(.2081297)	(.287858)
GDP per capita		.384***
		(.082512)
Demographics	12.001***	6.124
	(2.693078)	(4.896209)
GDP per capita		.265*
		(.1390477)
Urbanization	1.868***	.526
	(.29105)	(.4205739)
GDP per capita		.310***
		(.1047881)
Religious belonging	-27.191	-21.472**
	(20.98172)	(9.657468)
GDP per capita		.324**
		(.1400334)
Christianity	.345***	.013
	(.0940372)	(.1336341)
GDP per capita		.380***
		(.0799871)
Islam	-.406***	-.271*
	(.1012312)	(.1521969)
GDP per capita		.368***
		(.080442)
Buddhism	-.004	.278**
	(.1935)	(.1178)
GDP per capita		.153***
		(.0784)
Hinduism	-.247	.159
	(.2771)	(.1373)
GDP per capita		.386***
		(.0823)
Educational Mean	3.004***	2.482***
	(.5279741)	(.6708141)
GDP per capita		.177**
		(.0861273)
Land Area	-.021*	-.008
	(.0108665)	(.0133418)
GDP per capita		.377***
		(.0806257)
Distance to sea (+river)	-.096***	-.037
	(.0313923)	(.0318065)

GDP per capita	.363*** (.0822951)

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note: The marginal effects are calculated at the means. All variables are measured as initial conditions (year = 1984). GDP per capita, Land Area and Distance to sea are in natural logarithm. The religious variables Christianity, Islam, Buddhism and Hinduism are dummy variables, associated with the primary religion of each country. For Judaism no variable was incorporated, since none of the sample countries has Judaism as its primary religion. Agricultural Area, Demographics, Urbanization, Religious belonging and Educational mean are in percentage shares.

GDP per capita on its own is found to significantly increase the probability to belong to Club 1. If GDP per capita increases 1%, the probability of a country to belong to Club 1 increases about 38.3 percentage points. For agricultural area no significant effects are found, which is counterintuitive but in line with other studies (Milford et al., 2019). Regarding the results, the share of agricultural area of a country does not affect the belonging to a club, i.e. the consumption of meat. The inconclusiveness of the effect of demographics persists in my results. Without GDP per capita a higher proportion of elderly population is suggested to increase the probability of higher meat consumption. This doesn´t persist, however, when GDP per capita is added. Regarding urbanization the positive effect in the first estimation is also in line with the literature (Milford et al., 2019), which does not persist however when adding GDP per capita, indicating that the primary effect of urbanization is potentially associated to higher income levels of urban populations (Luo et al., 2020; Sulemana et al., 2019). Overall Religious belonging is not found significant on its own, but significantly reduces the probability of higher meat consumption when GDP is added. When looking at the specific control variables for the religions, only for Islam a persistent effect is found. Regarding these results, having Islam as the primary religion of a country, reduces the probability to belong to Club 1 about 27.1 percentage points. While Hinduism is not significant, Buddhism becomes significantly positive when GDP is added. Hinduism is a referred to example in the literature. However, as mentioned by Fillipini and Srinivasan (2019) the respecting of traditional values becomes decreasingly strict, why also Hindu increasingly eat meat. Buddhism being the primary religion of a country increases the probability to belong to the higher Club about 28.7 percentage points. The findings on the significant reducing effect of Islam are in line with the literature (Mensah et al., 2022; Milford et al., 2019). This is most likely to be due to the Islamic principles that forbid certain types of meat (Mensah et al., 2022), that also seem to persist even after e.g. migrating to another culture (Bonne et al., 2008). While most religions have some restricting components, Christianity is an exception (Bonne et al., 2008), what is at least reflected by the first estimation, but vanishes in the second one. Overall religious belonging only becomes significantly negative in my second estimation, suggesting that besides income the belonging to a religion in general decreases the probability to belong to club 1, i.e. the group of higher meat consumption levels. That high levels of educational mean are associated with an increase the probability of higher meat consumptions tends against the initial assumption, but is in line with e.g. the findings of Min et al. (2015) that find increasing educational levels associated with increasing meat consumption for China. In literature, results regarding the effect of education are described as rather inconclusive, putting such findings in perspective. The first estimation suggests that populations near to the sea or major rivers potentially tend to consume less meat, what would be intuitive, since the access to sea is assumed to shape dietary patterns. The significantly negative effect of the distance to sea does not persist in my second estimation. The ordered logit model does not establish assumptions about the causalities (Kerner and Wendler, 2022). Considering this, the counterintuitive results regarding some variables could be due to dynamic interrelationships with the general state of economic development. A higher educational mean e.g., is likely to be rather given in more developed countries. This macroeconomic effect of development could trump the potential probability reducing effect of education on an individual or microeconomic level. Further analysis is needed, to identify the causal effects and gain deeper insights into the dynamics between those determinants more strictly.

3.4 Conclusion

This study analyses the potential convergence of meat consumption, on a global scope, for 121 countries and the years 1984-2013. Growing consumption levels of meat are observed and are regularly linked to increasing incomes – increasing income leads to increasing meat consumption, is the general assumption. Since the production of meat, besides all ethical questions, entails a variety of negative effects on the environment, like driving biodiversity loss and climate change, the question of convergence becomes increasingly relevant in the light of increasing incomes in developing countries. To answer this, different types of convergence were analysed and as the main one the Philips and Sul (2007) clubbing algorithm was employed. The former gives indication on sigma and beta convergence regarding meat consumption, insofar as that the difference in consumption between countries decreases and that the initial consumption level might influence future consumption growth. The latter identifies two distinct clubs of countries, of which one groups rather developed and the other rather developing countries. By forming two distinct clubs the algorithm rejects a global convergence, and identifies two distinct clubs, converging towards a group-specific steady state equilibrium. This suggests that not all countries are moving towards the same level of consumption, but to different ones. To gain further understanding of potential meat consumption influencing factors, an ordered logit model was performed, with different control variables. While most of them significantly affect the probability of higher levels of meat consumption on their own, their effect vanishes, when GDP per capita is added. Especially religious backgrounds, with a persistent probability reducing effect of Islam, is found significant. Education is indicated to significantly increase meat consumption levels.

The results of the clubbing algorithm suggest that not all countries move towards the same level of meat consumption. A globally shared level is based on this analysis thus not suggested. This strengthens the assumption, that certain factors potentially influence meat consumption, which might differ between countries or regions. While potentially biased, the regular convergence regression indicates that lower initial consumption levels could be associated with higher growth rates in the future. This could indicate a potential catch-up effect of countries initially consuming less meat. However, the club algorithm provides a more nuanced picture, which hints that the difference between developed countries and developing countries is even set to increase, while the countries within these groups converge. Overall, the results of the ordered logit regression strengthen the assumption of GDP per capita, i.e. income, as an important driving factor of meat consumption. The analysis shows that higher income levels are tendentially accompanied by higher levels of meat consumption. Also does the incorporation of GDP per capita capture most of the significant effects of the control variables, suggesting that GDP per capita is a relevant and determining factor for growing meat consumption.

This study provides new insights into the convergence dynamics of meat consumption. To identify the concrete specificities and effects of determining factors, future research is needed. Further efforts should be undertaken to investigate the compositions and their reasonings of the identified clubs. This should be connected to a more detailed analysis of the country specific characteristics and resulting determining factors. An analysis of countries with a societal stronger anchored specific cultural and religious factor could be valuable. Furthermore, a potential substitution of meat types should be investigated in more detail. Bovine meat is assumed to be the type associated with the biggest environmental impacts. Since its consumption has decreased between 1984 and 2013, and poultry consumption has increased, a potential substitution could entail environmental benefits, if not trumped by overall growth effects. If certain factors are powerful enough to prevent destructive levels of consumption in developing countries despite growing income is questionable and probably must be evaluated country specific. The power of those factors against increasing income must be doubted and cannot be relied on. Political interventions and programs are integral and future macroeconomic policies must address sustainable production and consumption patterns holistically to ensure food systems within our planetary boundaries (Bowles et al., 2019) and ethical food security developments (Henry et al., 2019).

The impacts of meat consumption on our nature and climate are of great importance to understand, as well as consumption patterns, in the light of growing income and development. This matter is of high importance for future research, to understand and develop adequate countermeasures to protect Nature, biodiversity, climate and in the end us – the humanity.

3.5 Appendix

Table A.1: Description of variables

Variable Name	Original Data Unit	Source
Meat consumption	Kg/per capita/year	Food and Agriculture Organization of the United Nations
GDP per capita	Constant 2015 US$	The World Bank
Agricultural Area	Agricultural land (% of land area)	The World Bank
Religious Belonging	% of population belonging to a certain religion	World Religion Database
Christianity	% of population belonging to Christianity	World Religion Database
Islam	% of population belonging to Islam	World Religion Database
Buddhism	% of population belonging to Buddhism	World Religion Database
Hinduism	% of population belonging to Hinduism	World Religion Database
Educational mean	Literacy rate, adult total (% of people ages 15 and above)	The World Bank
Urbanization	Urban population (% of total population)	The World Bank
Demographics	Population ages 65 and above (% of total population)	The World Bank
Distance to Sea	Distance from centroid of country to nearest coast or sea-navigable river (km)	Geography Dataset Harvard
Land Area	Land Area in km^2	Geography Dataset Harvard

Table A.2: Pairwise correlation of variables

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(1)	1.00												
(2)	0.69	1.00											
(3)	-0.06	-0.13	1.00										
(4)	0.70	0.70	0.07	1.00									
(5)	0.66	0.60	-0.08	0.61	1.00								
(6)	0.25	0.12	0.05	0.05	0.15	1.00							
(7)	-0.22	-0.27	0.02	-0.37	-0.36	0.26	1.00						
(8)	0.61	0.50	-0.06	0.50	0.51	0.07	-0.41	1.00					
(9)	-0.33	-0.27	-0.09	-0.48	-0.33	-0.26	0.04	-0.30	1.00				
(10)	0.37	0.26	0.02	0.27	0.26	-0.04	-0.25	0.38	-0.01	1.00			
(11)	-0.13	-0.08	0.07	-0.06	-0.17	0.07	0.01	-0.09	0.06	-0.24	1.00		
(12)	-0.09	-0.07	-0.07	0.02	-0.15	-0.05	0.07	0.15	-0.19	-0.37	-0.04	1.00	
(13)	-0.35	-0.22	0.02	-0.30	-0.16	-0.05	0.22	-0.45	0.19	-0.75	-0.08	-0.12	1.00

Note: Due to space use, the variables have been numbered: (1) Meat Consumption, (2) GDP per capita, (3) Agricultural Area, (4) Demographics, (5) Urbanization, (6) Land Area, (7) Distance to Sea, (8) Educational mean, (9) Religious belonging, (10) Christianity, (11) Hinduism, (12) Buddhism, (13) Islam

Chapter 4

The Impact of Environmental Innovation on Carbon Dioxide Emissions

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Abstract

This paper examines the effects of environmental innovation on carbon dioxide emissions in the EU-27 countries between 1992 and 2014. We utilize the Generalized Method of Moments in a dynamic panel setting. Patent counts of environmental patent applications are used as indicator for environmental innovation. We find that environmental innovation did contribute to reductions of carbon dioxide emissions, while general innovative activity does not cause decreases in emissions. However, this effect is found to be comparatively small to the effects of increased economic activity. Further, we find the effect of innovation to differ across countries, with less developed economies showing a higher level of heterogeneity.

Keywords Dynamic panel, Carbon dioxide emissions, Environmental innovation, Patent data, Sustainable development, Green technological change

JEL Classification O33; O44; Q01; Q54; Q55

Publication

This article is co-authored by Tobias Wendler and Daniel Töbelmann. It has been published as an original research article: Töbelmann, D., Wendler, T. (2020). The impact of environmental innovation on carbon dioxide emissions. Journal of Cleaner Production, 244, 118787. It is available at: https://doi.org/10.1016/j.jclepro.2019.118787. Minor formal changes have been made, compared to the published version.

4.1 Introduction

Since approximately 1750 the atmospheric greenhouse gas (GHG) concentration and the global mean temperature have been dramatically increasing (Boeker and Van Grondelle, 2011). About that time the industrial revolution started. There is general consensus that those processes are interlinked. To allow for industrialization and general development humans have harnessed non-anthropogenic sources of energy (Cordes, 2009), mainly fossil fuels and biomass which release GHG during combustion (Boeker and Van Grondelle, 2011). The natural greenhouse effect that is essential for the formation and preservation of life on planet Earth (Boyes and Stanisstreet, 1993), has been significantly intensified since human activity showed an impact on environment, leading to climate changes and globally rising temperatures. As carbon dioxide (CO_2) is emitted in high quantities and has a high concentration in the atmosphere, it is internationally of most interest. This global warming will potentially have a multidimensional impact on the Earth's ecosystem and humanity, like e.g. intensifying dry-seasons, causing great challenges regarding food and drinking water supply, raising sea levels, causing changes in the Earth´s geography, increasing the fire frequency, increasing desertification (Solomon et al., 2009), and increased frequency and intensity of storm disasters (Reuveny, 2007). These developments combined are expected to increase migration, entailing the potential for violent-conflicts, and friction between globally leading powers (Reuveny, 2007), potentially leading to future wars (Hopwood et al., 2005).

The urgency to handle these problems has led to a higher priority on political agendas. The idea of unlimited economic growth has been increasingly questioned. Influential reports, especially *The Limits to Growth* (Meadows et al., 1972) have helped to bring environmental problems into political debates. In the following years the generic term *Sustainable Development* was adopted to describe a general development towards a system and system structures combining a range of environmental and socio-economic issues (Hopwood et al., 2005). A central approach to facilitate this development is a techno-centered one. Therein, technology plays a key role in encountering future problems, by either substituting natural resources (Solow, 1974) or helping to protect the environment (Hopwood et al., 2005). In general, this focuses on the idea of shifting the current and rather fossil fuel-based technologies towards more ecologically friendly ones. It is claimed that those new technologies will provide wider economic, social and environmental benefits (Hopwood et al., 2005), and thereby somehow help to overcome those "limits to growth".

The European Union (EU) has set different climate political minimum targets to encounter current and future environmental developments, like a 40% reduction in CO_2, an increase in the share of renewable energy of 32%, and an increase in energy efficiency of 32.5%, compared to the levels of 1990 (European Commission, 2019). The long-term aim is to make the EU a resource-efficient, green and low-carbon economy that is internationally competitive (European Commission, 2011). One central instrument in that mission is the strategic promotion of green technologies and ecologically relevant innovations, implemented by the Eco-Innovation Action Plan. By systematically fostering environmental innovations[90], a new technological level based on those green technologies is to be created in the long term. Those technologies are expected to be more carbon and resource efficient and thus allow for sustained economic activity and wealth, decoupled from ecological deteriorations. Thus, a political strategy, aimed at fostering such a *green technological change*, seems to be a proper approach to encounter environmental problems. To quantify and evaluate the actual effect of those green technologies is the aim of this study.

Although there is a substantial amount of literature dealing with means to foster those green technologies and their potential effects, studies investigating the concrete effect are only scarce (Barbieri et al., 2016). The present study aims at identifying the effect of environmental innovation (EI) on carbon dioxide emissions. Since EI is hypothesized as a solution approach, it is essential to analyze and evaluate its effect, and thus its ability to encounter global warming and related problems. This analysis is based on the EU-27 countries. These countries are chosen because they are both economically and politically strongly connected, given the shared EU framework (European Commission, 2011, 2010) and due to the above mentioned program. This study especially contributes to this literature twofold. First, to the best of our knowledge, it provides the first cross-country analysis on the national level on the impact of EI. Second, all analysis is based on the absolute levels of measures, not relative ones that could be considered a drawback of many earlier studies to a certain degree. Within the Kyoto Protocol framework, environmental measures are evaluated by the percentage reduction of the total CO_2 level (Friedl and Getzner, 2003). Furthermore, relative measures can decrease, while the absolute level is still increasing. Therefore, this study aims at the absolute impact of EI and its potential to tackle environmental problems and climate change. Hence, both aspects are contributing to the

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[90] In the following, the terms environmental innovation and environmental innovative activity will be used interchangeably. The latter term refers primarily to our empirical operationalization of the innovation process.

literature and quality of insight into the effects and relevancy of EI, as a realistic and reliable means to base future economic and policy decisions on.

The paper is structured as follows. Section two will review the relevant background literature and theoretical ideas regarding environmental innovation. Furthermore, an overview of the relevant empirical studies will be given. Section three presents the dataset and section four the methodology. The estimation results and robustness checks will be given in section five and will be discussed and concluded in section six.

4.2 Literature review

This paper draws upon the literature on the environmental effects of EI, as well as on the literature concerning determinants of CO_2 emissions. First, we will provide considerations on how environmentally innovative activity is interrelated with environmental regulation and the adoption of green technologies. Second, we will review previous papers on the environmental effects of EI. Lastly, we will review the literature on the determinants of CO_2 emissions to consolidate our empirical decisions.

Incremental and radical improvements in technologies are a key component of the international agenda to encounter environmental problems and climate change. The concept of *technological change* is widely discussed in the literature (Acemoglu, 2002; Acemoglu et al., 2012; Jaffe et al., 2002; Popp et al., 2011, 2010) as a means to achieve the long-term goal of sustainable economic growth (Popp et al., 2010), since the existing and upcoming environmental problems are not adequately addressable with the current technological level (Popp et al., 2010).

Environmentally innovative activity (EI) only relates to improvements in environmental performance when technologies are diffused and applied (Popp et al., 2010; Sarr and Noailly, 2017). EI can affect environmental performance through different channels (Barbieri et al., 2016), for example via spillovers to other regions and sectors (Cainelli and Mazzanti, 2013; Corradini et al., 2014; Costantini et al., 2013; Dechezlepretre et al., 2014). Although EI is not equivalent to adoption, these processes are highly interlinked. Incentives, such as regulation, affect any stage of the innovation process, including development and diffusion (Popp, 2005). Regulation and external pressure have been shown to foster the adoption of environmental technologies (Blackman and Bannister, 1998; Kemp, 1998; Kerr and Newell, 2003; Popp, 2010;

Popp et al., 2007; Snyder et al., 2003), with the adoption potentially being quickly conducted in response (Lovely and Popp, 2007). While the most recent environmental technologies may rather be applied in response to regulatory pressure, technological advances can support the adoption of existent environmentally favorable technologies (Popp, 2006). However, even in presence of weak policy stimulus EI may be spurred by firms (Ghisetti and Quatraro, 2013). In order to adopt a technology, domestic innovation is often needed to match the local market (Popp, 2006). At the firm level such technological activities improve absorptive capacities, facilitating the diffusion of external technology (Fisher-Vanden et al., 2006).

Environmentally innovative activity[91] is at the core of the interrelation between regulation and adoption. The anticipation of higher regulation is likely reflected in a heightened innovative activity (Carrión-Flores and Innes, 2010). Innovative activity in turn induces a further tightening of standards (Carrión-Flores and Innes, 2010) and is likely associated with the adoption of already existent[92] environmental technologies by firms (Popp, 2010). Further increases in regulatory stringency facilitate the adoption of the latest and most advanced technologies[93] (Popp, 2010), which then can allow a further tightening of standards. In the same vein the initial increase in regulatory standards likely results in the expectation of increasing standards, which then again heighten innovative activity.

Hence, we consider EI as indicative for internal and/or external pressure to develop and adopt new technologies, alongside the technological capabilities (Costantini et al., 2017) to create and adapt environmentally favorable technologies.

Environmental innovation can easily be linked to environmental relievements and emissions reduction. Innovations within the area of renewable energy production like solar or wind energy reduce energy consumption related emissions. New types of bio-fuels or more efficient vehicles may reduce mobility related emissions. Those simple examples intuitively suggest a positive[94] effect of EI. Clarity concerning the concrete impact of EI is not yet given and empirical studies investigating this effect are still scarce. Nevertheless, an increasing number of recent studies enable insights into potential effects. Concerning environmental productivity, EI is suggested

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[91] Measured by environmental patent applications.

[92] Already existent environmental technologies refer to technologies which have already been adopted by some actors, and are now adopted by latecomers. The environmental performance of these latecomers is improved by applying these technologies.

[93] Latest and most advanced technologies refer to technologies which are just developed and now raise the technological possibilities.

[94] Positive here refers to the fact that reducing emissions by EI is the desired outcome. However, in the course of this study we will now speak of a reducing or negative impact as from the statistical point of view this effect is shown by a negative coefficient of our EI variable.

to contribute to less emissions per unit of output. This is supported by Weina et al. (2016), finding a significant impact of EI on environmental productivity, hence reducing emissions per unit of output, as well as Costantini et al. (2017) finding a significantly negative effect on sectoral environmental intensity. Ghisetti and Quatraro (2017) support these results, finding a positive impact on the environmental productivity of regions sectors. A study feeding into these results is Wurlod and Noailly (2016) finding a negative impact of EI on the energy intensity of industrial sectors in OECD countries. Assuming constant emission intensity of energy use, EI is thus suggested to have a negative impact on emissions. The effect of EI on the absolute level of CO_2 emissions is more inconclusive. Carrión-Flores and Innes (2010) find that first, tightened pollution targets have an impact on the cost-saving benefit of innovation activity, and second, environmental innovations do have a significantly negative impact on pollution emissions for US manufacturing industries. Wang et al. (2012) find that fossil fuel-related innovations do not have a significant effect on the reduction of emissions, while the effect of carbon-free energy innovations is unclear. Only at the regional level a significantly negative effect is partially found, while on the national level no significance is evident. Weina et al. (2016) do not find a significant effect on the total level of CO_2 at all, while Zhang et al. (2017) find a reducing effect on CO_2 per capita in Chinese provinces.

There is a vast amount of literature dealing with the determinants of CO_2 emissions. Economic growth is said to be one of the main drivers of CO_2 (Friedl and Getzner, 2003; Hossain, 2011; Sharma, 2011). When an economy grows[95], the rate of flow of matter and energy through the economy increases, more resources are extracted from nature and more waste is released to it (Daly, 1987) – in this case in the form of CO_2. Economic growth is closely interconnected to energy usage, why its production and consumption are regularly described as a further major determinant (Hossain, 2011; Iwata et al., 2012; Sharma, 2011). The more energy is consumed, the more fossil fuels are needed to generate that amount of energy and consequently more CO_2 is emitted to the atmosphere. While economic growth captures a variety of structural changes and effects, energy consumption represents a more direct determinant of CO_2. Both measures represent the physical scale of the economy. Since earlier studies tend to suffer from an omitted variable bias, recent studies include a variety of further hypothesized climate relevant determinants (Kasman and Duman, 2015). Based on the importance of changes in the energy structure of an economy towards less carbon intensive sources, renewable energy technologies are seen as an important aspect of environmental sustainability (Dincer, 2000; Dogan and Seker,

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[95] Ceteris paribus

2016; Panwar et al., 2011). The industry sector is assumed to be more emission intensive than the service sector, due to more energy and resource intensive processes (Carattini et al., 2015). The economic structure and the share of industry are thus hypothesized to determine the economy´s emissions (York et al., 2003). Trade is also said to have an influence (Ertugrul et al., 2016). The trade volume increased dramatically during the last decades and a vast amount of goods and services, even whole industries were shifted over time (Ertugrul et al., 2016). The concrete expected effect of trade on the environment is somehow inconclusive, since trade does capture different opposed effects. The most substantial is the so-called *carbon-leakage*, meaning that emission intensive industries and productions are shifted from developed economies - to improve their environmental conditions - to developing ones deteriorating environmental conditions there, such that the global emissions remain unchanged. A further potential force is the globally occurring change in the population structure from rural living environments to urban ones (He et al., 2017; Martínez-Zarzoso and Maruotti, 2011; Sadorsky, 2014). The concrete effect of this development on emissions is inconclusive. Urbanized areas are more population dense requiring more energy than rural areas and are facilitating economies of scale in production in the form of industrial concentration that requires additional transportation (He et al., 2017; Martínez-Zarzoso and Maruotti, 2011). However, the increased agglomeration and centralization facilitate a more centralized and monitored carbon emission control and enforcement of environmental regulation as well as low carbon mobility, based on a centralized and environmentally friendly energy production.

4.3 Dataset

We construct a panel dataset on the EU-27 countries[96], spanning a period from 1992 to 2014. We restrict our dataset to this time due to data availability of our dependent variable, i.e. CO_2 emissions. Given the upheavals in the wake of the Soviet Union`s breakdown, we can retrieve a balanced sample of our dependent variable from 1992 onwards, thus avoiding issues stemming from the redefinition of countries, e.g. Germany or Czechoslovakia. 2014 is the last year for which we could gather CO_2 data.

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[96] Croatia is not included in our dataset, as it joined the EU in 2013.

The CO_2 data is provided by the Carbon Dioxide Information Analysis Centre (CDIAC) located in Tennessee, USA. It is one of the most reliable, comprehensive and current databases for CO_2 data , containing emission data from 1751-2014 for every country in the world at a global, national and regional basis (Boden et al., 2017; Doda, 2014). Captured sources of CO_2 emissions are the burning of fossil fuels and the manufacture of cement. The data derived capture CO_2 based on the "territory principle", as used in the context of the Kyoto Protocol (Usubiaga and Acosta-Fernández, 2015). An alternative way would be to account by the "residence principle". Given our focus on the effects of innovation within a country we consider the "territory principle" superior for our analysis.

Our main explanatory variable is Environmental Innovation (EI). We capture EI by relying on patent applications as a proxy. Patents are considered to be the most appropriate proxy for innovation (Haščič and Migotto, 2015), as they measure intermediate output, they are quantitative and widely available, and provide a wealth of information due to disaggregation into technological classes. While some drawbacks of patent data are extensively discussed in the literature (Haščič and Migotto, 2015; Johnstone et al., 2010; Lanjouw and Mody, 1996; Popp et al., 2011), patent data is considered as a preferable indicator for innovation (Dernis and Khan, 2004; Griliches, 1998).

To meet the issue of differing propensity to patent, as well as large value differences in patents we rely on patent applications at the European Patent Office (EPO) meaning multinational patent applications. Multinational patents are considered to indicate inventions of higher value as only the expected commercial profits justify the relatively high application costs (Johnstone et al., 2010). We include only the first patent of a patent family to avoid double counts of the same technology. Further, relying on one patent authority mitigates the issues stemming from differing patent regimes[97]. We assign the country based on the applicant data (Ghisetti and Quatraro, 2017) as we are interested in the utilization of an invention. We count the number of patents per country and year, where at least one of the applicants comes from the country concerned. We use patent applications instead of granted patents and include them based on their earliest filing year, to timely capture the whole innovative effort that has been undertaken (Costantini et al., 2017). Using patent applications is common (Costantini et al., 2017; Ghisetti and Quatraro, 2017; Wang et al., 2012; Weina et al., 2016) to capture the whole innovative effort independent of the sole economic market value (Costantini et al., 2017). The earliest filing year

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[97] It should be noted that given our model (First Difference model) differences in countries propensity to patent should not bother too much, as the change in patenting activity within one country is of interest, not the relation between different countries.

is the closest to the actual date of invention (Carrión-Flores and Innes, 2010; Costantini et al., 2017), not dependent on administrative procedures as the publication year is.

To distinguish environmental and non-environmental innovation we rely on the technological classes of patent applications, namely the International Patent Classification (IPC) and the Cooperative Patent Classification (CPC). Those have been made available to allow the discrimination between green and non-green technologies (Ghisetti and Quatraro, 2017). Our search strategy used to construct our main explanatory variable is combining the technological classes from the OECD EnvTech and the WIPO Green Inventory (Haščič and Migotto, 2015; WIPO, 2012) that are widely applied in the literature to capture green technologies (Albino et al., 2014; Costantini et al., 2017; Ghisetti and Quatraro, 2017; Kruse and Wetzel, 2014).

We include a variety of variables to control potential aspects that affect carbon dioxide emissions, different than green innovation. We include GDP and energy consumption as proxies for the scale of the economy. Data on GDP is retrieved from Cambridge Econometrics European Regional Database[98] (ERD). Data on energy consumption is retrieved from Eurostat (see Carattini et al., 2015). Beside these explanatory variables we control for several further factors. Structural changes in the composition of an economy are considered to potentially influence emissions (Carattini et al., 2015), hence we calculate - based on the gross value added data from the European Regional database (ERD) - the share of the industry sector in the value added of an economy. Next to the economic structure, especially the energy supply structure may have an effect on the environmental impact of an economy (Weisz et al., 2006). Due to this we control for the share of renewable energy in the energy consumption of a country, also retrieved from Eurostat. Technological improvements may not only result from domestic innovation, but can also stem from the import of foreign technologies. Hence, we control for the net inflows of foreign direct investment (FDI) as a share of GDP. In a similar vein, trade openness[99] is considered to capture the potential of outsourcing of environmentally intensive production, leading to so-called carbon leakage (Carattini et al., 2015). Lastly, the population structure may indicate differences as the urban population may be more prone to lead a certain fossil fuel based industrial lifestyle (Shao et al., 2017). Therefore, we use the share of the urban population as a proxy. The data for our variables on FDI, trade openness and urban population is retrieved from the World Bank. A list on data source, units and descriptive statistics on all our variables can be found in Table A1 in the Annex. Stationarity of the variables was tested using unit root

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[98] The data is publicly available at https://urban.jrc.ec.europa.eu/t-pedia/#/

[99] Trade Openness is calculated as the sum of Imports and Exports as share of GDP.

tests. Relying on the Fisher-test with drift, all variables are stationary except for the share of renewable energy (see Table A2 in the Annex). A more detailed discussion of emission and patent data is provided in the Annex (A3).

4.4 Methodology

A dynamic panel data approach is employed in this study, since it is assumed that CO_2 is depending on itself from the last period. This is due to assumed gradual changes in the production structure of an economy (Ibrahim and Law, 2014).

$$(1)\quad CO_{2,i,t} = \sum_{j=1}^{J} \delta_j CO_{2,i,t-j} + X'_{i,t}\beta + \mu_i + \psi_t + \varepsilon_{i,t} \quad with\ i = 1, \dots, N\ and\ t = 1, \dots, T$$

$CO_{2,t-1}$ represents the lagged dependent variable (LDV), X' is a $1\ x\ k$ vector of regressors, β denotes the $k\ x\ 1$ vector of coefficients, μ the country fixed effects, ψ the time fixed effects and ε the error term. The subscript i denotes the cross-sectional unit (country) and t denotes the time.

Employing the well-known Fixed-Effects estimator (FE), aiming to eliminate the country fixed effects, leads to endogeneity problems caused by the presence of the LDV (Baltagi, 2008). The FE estimator fails to eliminate all sources of endogeneity, known as the Nickell-Bias, which leads to inconsistent estimates (Nickell, 1981). Although this bias decreases with T increasing, it was shown that even with $T = 30$ the bias can be around 20% of the true coefficient value (Judson and Owen, 1999). A way to avoid this bias and general endogeneity problems is to utilize instrumental variable (IV) estimation methods.

Due to the given data structure this study employs the one-step difference Generalized Method of Moments (GMM) estimator, as proposed by Arellano and Bond (1991), widely known as the Arellano-Bond estimator (AB). This is in line with econometric literature suggesting the usage of this estimator, since it outperforms other methods in long panels (Hwang and Sun, 2018; Judson and Owen, 1999).

Starting point of the AB estimator is given by first-differencing the equation:

$$(2)\quad \Delta CO_{2,i,t} = \sum_{j=1}^{J} \delta_j \Delta CO_{2,i,t-j} + \Delta X'_{i,t}\beta + \Delta\psi_t + \Delta\varepsilon_{i,t}$$

This eliminates μ_i but causes that the LDV again is correlated with the error, due to $\Delta y_{i,t-1} = y_{i,t-1} - y_{i,t-2}$ and the existence of $\varepsilon_{i,t-1}$ in $\Delta\varepsilon_{i,t} = \varepsilon_{i,t} - \varepsilon_{i,t-1}$ (Baltagi, 2008). This problem is encountered by the utilization of IV, in which the first-differenced variables are instrumented by their own lags. Those are highly correlated with the LDV, but not correlated with the error. These estimators allow the inclusion of endogenous, predetermined and exogenous regressors. Endogenous regressors are influenced by the contemporaneous error term, while predetermined regressors may be influenced by the error term in previous periods. In this manner, the strictly exogenous variables are instrumented by themselves and the endogenous or predetermined by their lagged levels (Castro, 2013). Basis and suggested advantage of the GMM procedure is the comprehension of the orthogonality conditions, existing between y_{it} and ε_{it} that are the imposed moment conditions.

$$(3)\quad E\left[CO2_{i,t-s}\Delta\varepsilon_{i,t}\right] = 0 \quad and \quad E\left[X_{i,t-s}\Delta\varepsilon_{i,t}\right] = 0$$

$$for\ t = j+2, \dots, T \quad and \quad s \geq j+1$$

The procedure requires that no second-order autocorrelation in the differenced equation is present, while first-order autocorrelation is uninformative. Autocorrelation of order higher than one in the differenced equation would render some instruments invalid,[100] requiring later lags to be used as instruments causing a loss of observations (Roodman, 2009). If second-order autocorrelation would be present, this would generate inconsistent estimates (Castro, 2013).

Further, for the the validity of GMM exogeneity of the instruments is needed. If the number of regressors k is equivalent to the number of instruments j, then the model would be exactly identified, making detection of invalid instruments impossible. However, if the model is overidentified due to $j > k$, the validity of instruments is tested with the Sargan specification test (Castro, 2013; Roodman, 2009).

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[100] Even after estimation with forward orthogonal deviations the test is run on residuals in differences (Roodman, 2009).

4.5 Empirical results

We start by proving the soundness of AB estimation for our model and with the determination of the lag structure on our innovation variable. Further, we test a variety of determinants that have been considered in the literature for inclusion and determine our main model for further analysis. We then turn to test the robustness of our results by analyzing different samples of our dataset, testing an alternative green innovation search strategy, and exploring whether EI actually has a unique effect on carbon dioxide emissions or whether regular innovations provide a similar effect. Finally, we provide evidence that the effects of EI may differ across countries.

4.5.1 Main results

We start by specifying a baseline model for our analysis (see Table 1), including the LDV, our main explanatory variable environmental innovation (EI), and the relevant scale variables, namely GDP and Gross Inland Energy Consumption (Energy) (Carattini et al., 2015).

Table 1: Baseline model with OLS, FE and AB and different lags of EI

	(1)	(2)	(3)	(4)	(5)
Model	OLS	FE DK	AB	AB	AB
Dep. Var.	CO_2	CO_2	CO_2	CO_2	CO_2
L1. CO_2	0.958***	0.338***	0.579***	0.540***	0.581***
	(0.0101)	(0.0568)	(0.143)	(0.170)	(0.161)
Environmental Innovation				0.00168	
				(0.00578)	
L1. Environmental Innovation	-0.00569**	-0.0120***	-0.0137**	-0.0132*	-0.0131**
	(0.00279)	(0.00423)	(0.00572)	(0.00661)	(0.00631)
L2. Environmental Innovation				-0.00360	-0.00340
				(0.00464)	(0.00474)
Energy	0.0289***	0.748***	0.501***	0.543**	0.486**
	(0.0107)	(0.0660)	(0.178)	(0.219)	(0.202)

GDP	0.0145*	0.125***	0.141**	0.131	0.146*
	(0.00827)	(0.0341)	(0.0680)	(0.0905)	(0.0787)
Time-effects	Yes	Yes	Yes	Yes	Yes
Observations	577	577	550	526	533
No. of Countries	27	27	27	27	27
R-squared	0.999	0.8806			
AR1-Test			-2.79	-2.70	-2.88
			[0.005]	[0.007]	[0.004]
AR2-Test			-1.43	-1.43	-1.39
			[0.152]	[0.152]	[0.166]
Sargan-Test			13.68	10.18	10.98
			[0.550]	[0.808]	[0.754]

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

To assure the soundness of AB estimation the coefficient on the LDV should lie within the range, or nearby the coefficient in OLS (upward biased) and fixed effects (downward biased) (Roodman, 2009). This is precisely the case in our analysis. Further, both the AR2-test and Sargan-test indicate that our results are econometrically sound, as argued in section 4. We further employ different lags of our innovation variable as potential regressors in line with similar work (Wang et al., 2012). However, we find that only the first lag is significant, which is both plausible from a theoretical perspective (see section 2) and the results on our other relevant variables do not change significantly from only including the first lag. Hence, we will continue our further analysis by using the first lag of the innovation variable in our model.

Our findings within the baseline model indicate that EI, GDP and Energy have a significant impact on the carbon dioxide emissions. Our main variable of interest, i.e. EI, exerts a reducing effect on carbon dioxide emissions. The coefficient lies at ~ -0.01, indicating that a 1% increase in environmentally innovative activity is associated with a 0.01% decrease in emissions.

The results concerning Energy and GDP show that both affect carbon dioxide emissions positively, indicating that increases in either variable cause emissions to rise. With regard to the scale aspect that these variables capture, these results are not surprising (Carattini et al., 2015). However, it is obvious that the effect of Energy is much larger, roughly three to four times as high as the effect of GDP. This indicates that Energy is more strongly related to carbon dioxide emissions, as a 1% increase in Energy raises emissions by 0.5%. Given the direct linkage of energy consumption with emissions due to the burning of fossil fuels, this is not surprising (Carattini et al., 2015). GDP then captures only a residual part of the scale effect as a major aspect of growing GDP can be an increase in energy consumption. However, our results still indicate that GDP affects emissions with a coefficient of ~ 0.15, meaning a 1% increase in GDP to raise emissions by 0.15% beyond the effect of increased energy consumption.

We now turn to our estimations with inclusion of further control variables. As outlined in the data section we consider Renewable Energy, FDI, Trade Openness, Urban Population and the Industrial Intensity as control variables. We expect the following relationships:

Renewable Energy (-): The share of renewables in the energy supply structure should influence carbon dioxide emissions in a negative way, as the fossil fuel burning for energy is a strong direct link to emissions and the effect of the energy supply structure should not be partially captured by any other variable.

FDI (-): We consider FDI as a robustness check on our innovation variable, as we basically include only domestic green innovation into our model. A domestic innovative basis has been considered to be pivotal, as domestic innovation is directly related with regulatory pressure and the need for sustainable governance (Costantini et al., 2017; Popp, 2006). Yet, especially in transition economies foreign direct investment may lead to the spilling over of new and advanced technologies, potentially raising the efficiency of production. Thus, we consider FDI relevant to capture this potential technological upgrading. We expect FDI to reflect import of foreign technology, improving the technological level and thus reducing emissions.

Trade Openness (-): Trade openness has been thoroughly used in the relevant literature, especially in the context of carbon leakage. Given our data, we cannot control for carbon leakage in our measure of carbon dioxide emissions. Hence, we consider trade openness, due to being related with trade liberalization, specialization, and displacement of polluting activities and technology transfer (Carattini et al., 2015). Therefore, we expect trade openness to reduce carbon dioxide emissions.

Industrial Intensity (±): The economic structure is considered a relevant determinant of emissions (Carattini et al., 2015), as the industrial sector is generally understood to be more environmentally intensive (Carattini et al., 2015; Weisz et al., 2006). As in our setting the main relation may be mediated via Energy, we also expect that the Industrial intensity does not exert a relevant effect.

Urban population (±): The structure of the population is considered to reflect differences in lifestyle, with urban population living under a different socio-metabolic mode (Shao et al., 2017). However, given the inclusion of energy consumption we expect this variable to not exert a significant impact.

The results of the inclusion of our controls is reported in Table 2. The inclusion of Renewable Energy in the model shows a relevant impact. This inclusion leaves the effects and size of green innovation and energy consumption unchanged. While the size of the coefficient of GDP remains stable, it loses its significance. Renewable Energy shows by far the largest coefficient, being significant at the 1% level. The coefficient lies at ~ -1.8. As expected a higher share of renewable energy in the energy supply structure decreases the amount of emissions. Given that we had to include Renewable Energy in first differences, due to its non-stationarity in levels, leads to the following interpretation. The coefficient shows that a one percentage point increase in the growth of the renewable energy share leads to a 1.8% reduction of carbon dioxide emissions. It is interesting that the coefficient on EI remains significant and of a similar magnitude, indicating that the effect of EI is beyond the increase of renewable energy in the energy structure of an economy.

None of our further control variables shows to be significant. As argued above, however, this seems reasonable in all cases, including the share of the industrial sector as energy consumption may mediate the emission raising effect of this variable. Trade openness and urban population also do not show any significant impact. The inclusion of FDI seems most relevant, to check the robustness of the impact of green innovation. We included FDI with one lag, as we expect a time-lag from the financial investment to the actual implementation of new technology resulting in environmental effects. FDI is insignificant and does not take away the effect of EI. For further testing we combine trade openness and FDI in one specification to secure that we separate the effects of technology import and carbon leakage. The magnitude and significance of EI remains unchanged, while both trade openness and FDI remain insignificant.

Table 2: Inclusion of controls into baseline model

	(1)	(2)	(3)	(4)	(5)	(6)
Model	AB	AB	AB	AB	AB	AB
Dep. Var.	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2
L1. CO_2	0.645***	0.571***	0.601***	0.608***	0.514***	0. 579***
	(0.148)	(0.140)	(0.140)	(0.137)	(0.167)	(0. 170)
L1. Environmental Innovation	-0.0109**	-0.0132**	-0.0132**	-0.0131**	-0.0131**	-0.0104**
	(0.00498)	(0.00590)	(0.00582)	(0.00601)	(0.00566)	(0.0050)
Energy	0.425**	0.512***	0.482**	0.475**	0.547**	0.474**
	(0.183)	(0.179)	(0.176)	(0.173)	(0.203)	(0.206)
GDP	0.103	0.129*	0.127*	0.125	0.157**	0.112
	(0.0614)	(0.0735)	(0.0746)	(0.0792)	(0.0755)	(0.075)
D1. Renewable Energy	-1.749***					-1.640***
	(0.336)					(0.308)
Trade Openness		0.00749				0.0019
		(0.0185)				(0.024)
Urban Population			-0.0218			
			(0.176)			
Industrial intensity				0.0214		
				(0.0937)		
L1. FDI					-0.00456	-0.0061
					(0.00372)	(0.0038)
Time-effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	550	548	550	550	522	522
No. of Countries	27	27	27	27	27	27
AR1-Test	-2.80	-2.80	-2.85	-2.88	-2.64	-2.65
	[0.005]	[0.005]	[0.004]	[0.004]	[0.008]	[0.008]
AR2-Test	-0.19	-1.42	-1.41	-1.41	-1.51	-0.41
	[0.848]	[0.157]	[0.159]	[0.159]	[0.130]	[0.682]
Sargan-Test	16.11	13.79	13.67	13.35	13.31	17.15
	[0.374]	[0.541]	[0.550]	[0.576]	[0.579]	[0.310]

Robust standard errors in parentheses, *** $p<0.01$, ** $p<0.05$, * $p<0.1$

The obtained results cause us to include renewable energy into our further modelling to avoid misspecification. Thus, we will now continue with this model to check the robustness of our results.

4.5.2 Robustness checks

We now continue to analyze our main model, including green innovation, GDP, energy consumption, and the share of renewable energy more indepth. At first we will conduct a variety of classic robustness checks, by restricting our time-period to the time after the Kyoto Protocol, excluding the years of the financial crises 2008 and 2009, and excluding the three smallest countries of the European Union with less than one million inhabitants, namely Luxembourg, Malta and Cyprus (see Table 3). Then we will explore our main explanatory variable more specifically by testing an alternative environmental innovation patent search strategy, and compare the results obtained for green innovation with the results for overall innovation and non-green innovation to verify whether EI exerts a unique environmental effect. Lastly, we will explore country heterogeneity concerning the effect of EI.

Table 3: Robustness checks by restricting the sample

	(1)	(2)	(3)
Model	AB	AB	AB
Dep. Var.	CO_2	CO_2	CO_2
Restriction	Year>1997	Excl. 2008 & 2009	Excl. MT, LU, CY
L1. CO_2	0.537***	0.604***	0.667***
	(0.165)	(0.138)	(0.124)
L1. Environmental Innovation	-0.0115**	-0.0124**	-0.0103*
	(0.00431)	(0.00544)	(0.00542)
Energy	0.520**	0.482***	0.376**
	(0.231)	(0.163)	(0.153)
GDP	0.174**	0.0841	0.0993
	(0.0679)	(0.0547)	(0.0792)
D1. Renewable Energy	-1.452***	-1.784***	-1.762***
	(0.315)	(0.380)	(0.340)
Time-effects	Yes	Yes	Yes
Observations	417	496	492
No. of Countries	27	27	24
AR1-Test	-2.19	-2.75	-2.84
	[0.029]	[0.006]	[0.005]
AR2-Test	-0.06	-0.01	-0.24
	[0.949]	[0.990]	[0.807]
Sargan-Test	19.18	17.99	17.41
	[0.206]	[0.263]	[0.295]

Robust standard errors in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

The results in Table 3 show the robustness of our main results on all variables, except for GDP. While GDP turned insignificant in our regular sample it turns significant at the 5% level when focusing on the time after the Kyoto Protocol.

Table 4: Robustness concerning green patent search strategy

	(1)	(2)	(3)	(4)
Model	FE DK	AB	FE DK	AB
Dep. Var.	CO_2	CO_2	CO_2	CO_2
EI search strategy	Green Inventory	Green Inventory	Green Inventory + OECD EnvTech	Green Inventory + OECD EnvTech
L1. CO_2	0.405***	0.647***	0.403***	0.645***
	(0.0552)	(0.144)	(0.0560)	(0.148)
L1. Environmental Innovation (GI)	-0.0120**	-0.0123**		
	(0.00488)	(0.00526)		
L1. Environmental Innovation (GI + OECD)			-0.0105**	-0.0109**
			(0.00445)	(0.00498)
Energy	0.672***	0.423**	0.672***	0.425**
	(0.0692)	(0.178)	(0.0693)	(0.183)
GDP	0.108***	0.107*	0.106***	0.103
	(0.0345)	(0.0610)	(0.0349)	(0.0614)
D1. Renewable Energy	-1.369***	-1.762***	-1.359***	-1.749***
	(0.111)	(0.337)	(0.113)	(0.336)
Time-effects	Yes	Yes	Yes	Yes
Observations	574	547	577	550
No. of Countries	27	27	27	27
R-squared	0.8957		0.8946	
AR1-Test		-2.80		-2.80
		[0.005]		[0.005]
AR2-Test		-0.21		-0.19
		[0.836]		[0.848]
Sargan-Test		15.77		16.11
		[0.397]		[0.374]

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4 shows the results of using different patent search strategies. As our main variable we have merged the OECD EnvTech (OECD) with the Green Inventory (GI) to obtain a comprehensive list of green technologies. Defining EI narrowly may reduce the potential issue of including irrelevant patents, which is considered to be more severe for potential biases[101] (Lanjouw and Mody, 1996). Our comprehensive list of EI avoids the danger of not capturing all green technologies, which would lead to only a result for the analyzed subgroup of green technologies. However, including too many technologies as green ones may lead to biased results. The results might be downward biased if the included technologies have no similar effect as the green technologies on our dependent variable (Wurlod and Noailly, 2016). Since the WIPO Green Inventory (GI) is considered to be narrower (Ghisetti and Quatraro, 2017) we choose for a robustness check to only include the GI IPC codes. When using the Green Inventory the coefficient, indeed, gets a little larger in magnitude, remaining significant at the 5% level.

Given the political pursuit of green innovation (European Commission, 2011), we are interested in whether the shift from non-green to green technologies is actually leading to an improvement of environmental performance. Therefore, we now use Total Innovation and non-environmental innovation besides EI. The results of these specifications are reported in Table 5. As innovation is generally about improving efficiency, and given the fact that regular innovations may also provide environmental benefits (Kemp and Pearson, 2007) we test for total innovation first. However, the coefficient stays insignificant, not showing any reductional impact of general innovative activity. Next, we test for both our stricter definition of EI (GI) and our comprehensive definition (GI + OECD). First, for reference purposes, only the inclusion of EI, and then a specification including both EI and non-green innovations are displayed. Thus, we avoid potential omission issues coming along with excluding technologies. The results show that EI maintains its reducing effect on emissions when we include non-green innovation. Non-green innovations on the other hand do not exert any significant impact on emissions. This is in line with what we expected. General innovations, which shall improve efficiency and result in economic benefits are not equally expected to reduce emissions, as the reduction of emissions is largely about reducing negative externalities. However, we also do not find that regular innovations increase the amount of emissions, e.g. by facilitating the use of non-green technologies. These results are also not sensitive to the choice of our EI definition. We consider this as a strong robustness check, that we have identified an actual effect of EI. We have used

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[101] Given that our model calculates in first differences, having too low absolute numbers is not too much of an issue, as the change rates are relevant for obtaining results.

both a narrower and a comprehensive definition of EI with very similar effects, to avoid the issue of having selected too few or too many patents. As we have shown that neither total innovation nor non-green innovation exert an effect, we can assure that EI has a unique effect on emissions.

Table 5: Comparison of Total, Green and Non-green innovation

	(1)	(2)	(3)	(4)	(5)
Model	AB	AB	AB	AB	AB
Dep. Var.	CO_2	CO_2	CO_2	CO_2	CO_2
Patent search strategy	All patents	Green patents (Green Inventory)	Green and Nongreen patents (Green Inventory)	Green patents (Green Inventory + EnvTech)	Green and Nongreen patents (Green Inventory + EnvTech)
L1. CO_2	0.778***	0.647***	0.670***	0.645***	0.663***
	(0.128)	(0.144)	(0.162)	(0.148)	(0.166)
L1. Total Innovation	-0.000864				
	(0.00824)				
L1. Environmental Innovation (GI)		-0.0123**	-0.0113**		
		(0.00526)	(0.00542)		
L1. Non-Environmental Innovation (GI)			0.00301		
			(0.00944)		
L1. Environmental Innovation (GI+OECD)				-0.0109**	-0.0102**
				(0.00498)	(0.00470)
L1. Non-Environmental Innovation (GI+OECD)					0.00265
					(0.00893)
Energy	0.275*	0.423**	0.404*	0.425**	0.411*
	(0.156)	(0.178)	(0.201)	(0.183)	(0.207)
GDP	0.0747	0.107*	0.0608	0.103	0.0557

	(0.0770)	(0.0610)	(0.0847)	(0.0614)	(0.0868)
D1. Renewable Energy	-1.839***	-1.762***	-1.812***	-1.749***	-1.792***
	(0.405)	(0.337)	(0.340)	(0.336)	(0.337)
Time-effects	Yes	Yes	Yes	Yes	Yes
Observations	582	547	543	550	546
No. of Countries	27	27	27	27	27
AR1-Test	-2.79	-2.80	-2.78	-2.80	-2.77
	[0.005]	[0.005]	[0.005]	[0.005]	[0.006]
AR2-Test	0.41	-0.21	-0.11	-0.19	-0.10
	[0.680]	[0.836]	[0.914]	[0.848]	[0.917]
Sargan-Test	11.15	15.77	15.94	16.11	16.74
	[0.742]	[0.397]	[0.386]	[0.374]	[0.335]

Robust standard errors in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Although the development of technologies is likely related with diffusion, differences of environmental effects of EI between countries may arise from a variety of aspects. Amongst other factors structural differences or the presence of absorptive capacity (Keller, 1996) to use technologies may cause the effects of EI, measured by patent applications, not to be homogenous across countries. While technology development in companies may be driven by international programs and competition the national effects could be moderated, for example, by preferences of citizens, which may be dependent on the developmental level of a country (Stern, 2004).

Hence, we now continue by providing analyses based on these considerations in multiple ways. First, we exclude countries based on their average GDP per capita during our time-period (1992 to 2014). Thereby we aim to evaluate whether the developmental level of a country influences EI effects. Next, we exclude countries which have a strong domestic availability of fossil resources. To identify these countries we rely on material flow data[102] (UNEP, 2016) to construct an indicator of `domestic resource dependency` (DRD) meaning the share of fossil

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[102] Material flow data has been extracted from the Global Material Flows Database publicly available at https://www.resourcepanel.org/global-material-flows-database. We derived data on the so-called Direct Material Input (DMI) which is equivalent to adding-up materials extracted domestically and materials which were imported.

materials extracted in the home-country versus all fossil materials entering the socio-economic system (Fischer-Kowalski et al., 2011; Weisz et al., 2006). Lastly, we will show how the exclusion of individual countries affects the coefficient of EI.

When excluding countries based on their developmental level the results show a clear tendency (compare Table 6). When excluding the three richest countries, namely Denmark (DK), Luxembourg (LU), and Ireland (IE), the coefficient of EI changes from -0.0109 to – 0.00797, indicating a reduced negative effect of EI. The opposite is the case when excluding the three poorest countries, Bulgaria (BG), Romania (RO), and Latvia (LV). The coefficient increases in magnitude to -0.0143. This tendency holds when excluding the seven richest and poorest countries. Excluding the seven richest countries[103] causes EI to lose its significance, with the coefficient dropping in magnitude to -0.00615, while for the seven poorest countries[104] the coefficient increases further to -0.0164. These results can be seen as an indication that within the richer countries the effect of EI is stronger than in the EU-27 average, while poorer countries seem to have a weaker negative effect. However, these results motivate the idea that EI effects seem not to be homogenous across countries but could depend on the developmental level, with rich countries profiting more from domestic green innovation. This could be interpreted in various ways. Explanations could range from issues with absorptive capacity in less developed countries to the stronger diffusion of green technologies in developed economies due to e.g. preferences and purchasing power of the citizens. Further, for less developed economies domestic innovation may be less important compared to imported technologies, while developed economies more heavily rely on domestically provided green technologies (Lema and Lema, 2012).

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[103] Which are Denmark (DK), Luxembourg (LU), Ireland (IE), Netherlands (NL), Sweden (SE), Austria (AT) and the United Kingdom (UK).

[104] Which are Bulgaria (BG), Romania (RO), Latvia (LV), Poland (PL), Lithuania (LT), Estonia (EE) and Slovakia (SK).

Table 6: Robustness of Results to systematic exclusion of country groups

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Criterion	EU27	3 Richest	3 Poorest	7 Richest	7 Poorest	DRD > 80%	DRD > 75%
Model	AB	AB	AB	AB	AB	AB	AB
Dep. Var.	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2
Countries excl.	None	DK & LU & IE	BG & RO & LV	DK & LU & IE & NL & SE & AT & UK	BG & RO & LV & PL & LT & EE & SK	EE & PL	EE & PL & CZ & RO
L1. CO_2	0.645***	0.646***	0.590***	0.681***	0.389**	0.645***	0.664***
	(0.148)	(0.141)	(0.159)	(0.161)	(0.172)	(0.143)	(0.137)
L1. Environmental Innovation	-0.0109**	-0.00797*	-0.0143**	-0.00615	-0.0164**	-0.0147**	-0.0197***
	(0.00498)	(0.00410)	(0.00612)	(0.00396)	(0.00674)	(0.00582)	(0.00630)
Energy	0.425**	0.404**	0.475**	0.374*	0.867***	0.412**	0.391**
	(0.183)	(0.162)	(0.219)	(0.187)	(0.279)	(0.182)	(0.178)
GDP	0.103	0.0984	0.126	0.107**	-0.102	0.111*	0.137**
	(0.0614)	(0.0625)	(0.0882)	(0.0501)	(0.195)	(0.0590)	(0.0560)
D1. Renewable Energy	-1.749***	-1.632***	-1.613***	-1.918***	-1.366***	-1.728***	-1.684***
	(0.336)	(0.296)	(0.348)	(0.358)	(0.294)	(0.326)	(0.373)
Time-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	550	484	501	396	430	512	473
No. of Countries	27	24	24	20	20	25	23
AR1-Test	-2.80	-2.78	-2.59	-2.58	-2.05	-2.80	-2.80
	[0.005]	[0.005]	[0.010]	[0.010]	[0.041]	[0.005]	[0.005]
AR2-Test	-0.19	-0.21	0.55	-0.45	0.69	-0.02	0.01
	[0.848]	[0.836]	[0.579]	[0.650]	[0.491]	[0.984]	[0.989]
Sargan-Test	16.11	14.67	18.57	15.48	12.53	14.38	18.28
	[0.374]	[0.475]	[0.234]	[0.417]	[0.639]	[0.497]	[0.248]

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Another aspect is the effect of countries which have a high-level of DRD for fossil fuels. High levels of fossil DRD could relate to structural barriers impeding the establishment of more sustainable technological systems. Our results indicate that countries with a higher level of DRD have a less negative effect of EI on emissions. Estonia (EE) and Poland (PL) have the highest levels with more than 80% of used fossils being extracted in the country itself.[105] Excluding Estonia and Poland leads to an increase of the coefficient to -0.0147. Romania (RO) and the Czech Republic (CZ) follow with more than 75% of fossils extracted domestically. Without these countries the coefficient of EI increases again, almost reaching -0.02. Hence, the exclusion of countries based on this criterion causes a more pronounced change of the EI effect than excluding countries based on their developmental level.

As a final check we drop each country individually and report the coefficient of EI. As can be seen in Figure 1 below most countries do not cause substantial changes. However, Poland (PL), Romania (RO), Latvia (LV), Cyprus (CY), and Slovenia (SI) cause a strong decrease in coefficient size, reaching -0.012 and less. Poland causes the strongest decrease of the coefficient reaching almost -0.014. The strongest increases in coefficient size are caused by excluding Lithuania (LT) where the coefficient changes to -0.0085, followed by Bulgaria (BG, -0.0089), Slovakia (SK, -0.0096), and Luxembourg (LU, -0.0096). Two aspects are striking in this graph. On the one hand, with Poland, Romania, and Czechia three of the four countries with very high DRD of fossils are also among the six countries which individually lead to the strongest decrease in the coefficient size. Further, both the countries leading to the strongest increase but also decrease of the coefficient belong to the non EU-15 countries. EU-15 countries do not cause such strong changes in the coefficient size. Hence, this could be interpreted in the way that among less developed economies the effects of EI on emissions seem to be much more heterogeneous than among the higher developed economies, which also share a longer common institutional history, due to the European Union framework.

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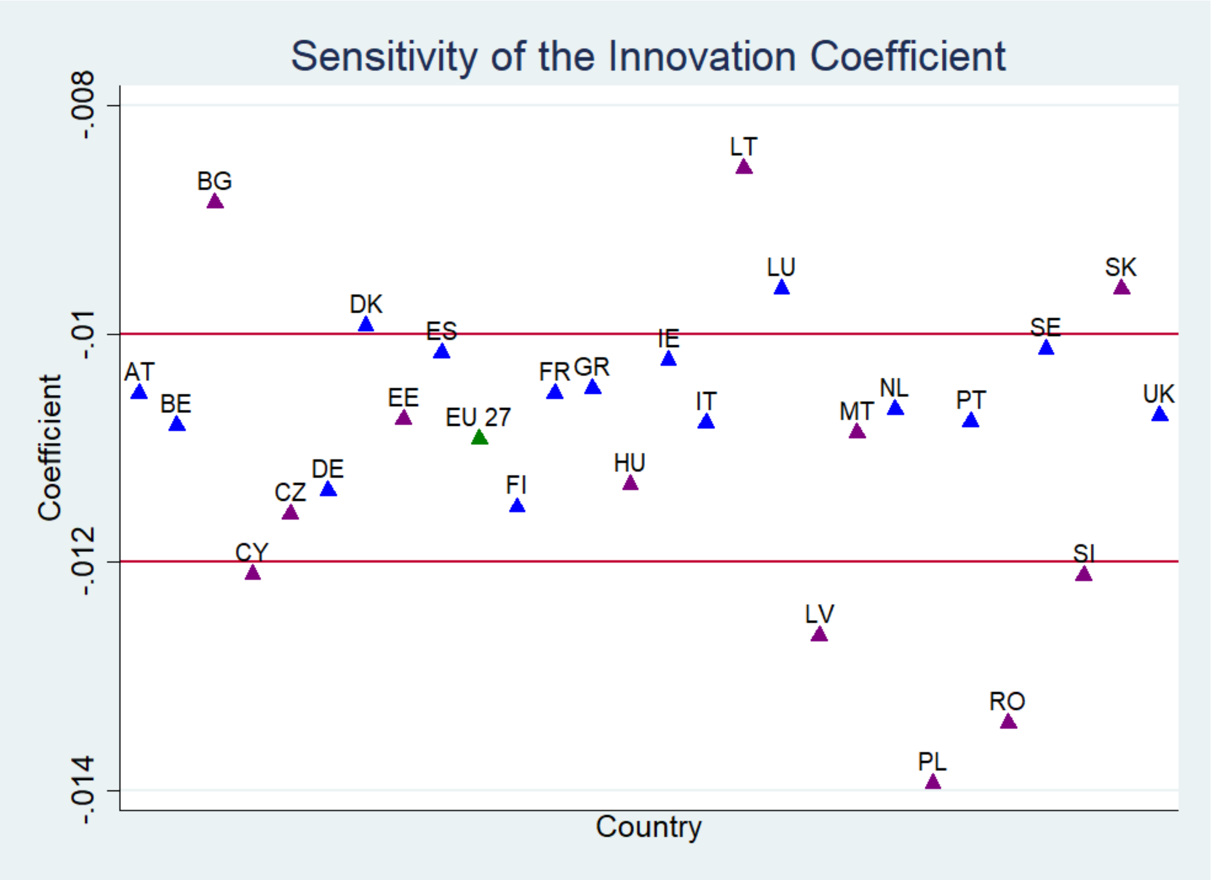
[105] On average during our observed period.

Figure 1: Development of the Coefficient of EI



Note: *Individual countries were dropped and the coefficient reported. Blue triangles refer to EU-15 countries. Purple triangles refer to non-EU-15 countries. The green triangle shows the baseline model with all 27 countries. The country codes indicate the country omitted. The red lines mark deviations of the coefficient which surpass an increase or decrease of the coefficient by ~0.001 or more, compared to the result of EU-27.*

Source: Own calculations.

4.6 Discussion and conclusion

Green technologies are considered as a practical and realistic means to encounter global warming and environmental issues. In this paper we aimed to identify the effect of green technologies on carbon dioxide emissions in European countries. Using a dynamic panel data model we analyzed the EU-27 countries between 1992 and 2014. To the best of our knowledge we thus provide the first cross-country analysis at the national level looking at the environmental effects of EI.

Past studies have shown that at a sectoral level the contribution of EI to reductions of emissions and energy usage is given (Carrión-Flores and Innes, 2010; Costantini et al., 2017; Ghisetti and Quatraro, 2017; Wurlod and Noailly, 2016). At the regional-national level, however, the results are more divergent, dependent on the specific empirical setting (Wang et al., 2012; Weina et al., 2016; Zhang et al., 2017).

Our findings indicate that EI does have a reducing effect on emissions. This effect is unique to EI, as general innovation is not associated with emission reduction. The developmental stage of countries seems to play a role for the magnitude of the EI effect, as our results suggest that within higher developed economies EI more strongly contributed to emission reduction than in less developed countries. For the latter, we find a higher level of heterogeneity as all countries that strongly influence the EI coefficient size belong to the non-EU-15 countries. Furthermore, we find that countries with a high domestic availability of fossil fuels seem to be less receptive towards the reducing effects of EI.

Our further findings show that Energy and GDP are associated with increases in carbon dioxide emissions, whereby Energy has a larger effect. However, the energy supply structure has a strong influence on our dependent variable. We find that increases in the growth of renewable energy utilization are associated with disproportionally high decreases in emissions. Hence, a strong reducing effect of EI may lie in the expansion of renewable energy usage. Given the systemic nature of changes in the energy supply system it seems difficult to appropriately and directly capture the effect of EI on renewable energy expansion (Popp et al., 2011). However, EI is obviously related to reducing the energy unit costs of renewable energy, thus supporting the further diffusion of renewable energy. This likely strong reducing effect of EI cannot be sufficiently measured via our innovation variable.

Further research is needed to consolidate our findings and to clarify open questions. Firstly, if emissions occur in another country, they are not captured as CO_2 emissions in our dependent variable which is due to the territorial principle of accounting CO_2. Interesting insights could be provided by looking at similar contexts using other data, for example including upstream requirements in CO_2 data.[106] Secondly, as a fundamental concern a national system boundary should be questioned when assessing technology effects, given that these are of a holistic nature and often go beyond direct and short-term empirically accessible impacts (Hepburn et al., 2018). Lastly, given differences in EI effects across countries, an interesting new line of

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[106] This is usually attempted via global multiregional input-output tables (MRIO).

research would be to conduct in-depth research on EI effects in different countries and the role which countries' specificities play.

At a global scale, despite strong improvements in emission efficiency, a strong decline in absolute levels has not yet been observed. Thus, the necessary reduction in CO_2 intensity to stay within the absolute limits (Rockström et al., 2009) for emissions is far from being reached by technological development. Further, there are fundamental concerns on the limits of improving the efficiency of economic activity given inevitable limits (Georgescu-Roegen, 1971; Meadows et al., 1972; Schramski et al., 2015). The solution approach towards encountering environmental degradation needs to be a holistic one as the effects of technologies are of a holistic nature, too. Pure reliance and concentration on technological progress is not sufficient, but a holistic reform and transformation of all fundamental system aspects is needed.

To face future environmental problems technological innovation must be embedded and used as a supplementary tool within a systemic transformation.

4.7 Appendix

Table A1: Descriptive statistics[107]

Variable	**Unit**	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**	**Source**
CO_2 Emissions	Thousand Metric Tons (TMT)	621	142108.6	190913.3	2024.184	891975.4	Carbon Dioxide Information Analysis Centre (CDIAC)
Energy Consumption	Thousand Tons of Oil Equivalent (TTOE)	621	63760.06	85075.38	621.3999	352856.9	Eurostat
GDP	Billions of Euro[108]	621	401.9651	627.0884	3.168	2601.824	European Regional Database (ERD)
Environmental Patents (GI + OECD, EPO, Applicant, Whole counting)	Count	621	353.6006	901.8494	0	6639	PATSTAT 2017b
Environmental Patents (GI, EPO, Applicant, Whole counting)	Count	621	269.9469	664.0224	0	4863	PATSTAT 2017b
Non-Environmental Patents (GI + OECD, EPO, Applicant, Whole counting)	Count	621	1583.559	3702.332	0	23214	PATSTAT 2017b
Non-Environmental Patents (GI, EPO, Applicant, Whole counting)	Count	621	1667.213	3936.98	0	24806	PATSTAT 2017b
Total Patents (EPO, Applicant,	Count	621	1937.159	4591.022	0	28693	PATSTAT 2017b

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[107] For the used sample in initial units for the years 1992 to 2014.

[108] In constant 2005 prices.

Whole counting)							
Renewable Energy: Share of GIEC	Share	621	.0937323	.0866182	0	.3715844	Eurostat
Industrial Intensity[109]: Sector Share in Gross Value Added	Share	621	.276535	.0598955	.1141474	.4698775	European Regional Database (ERD)
Trade Openness[110]	Share	609	1.047754	.5871905	.350209	3.822915	World Bank
Urban Population	Share	621	.7197536	.1177277	.4913	.97818	World Bank
Foreign Direct Investment (FDI): Net inflows share of GDP	Share	586	.089589	.3331599	-.5832288	4.517155	World Bank

Table A2: Unit Roots

	Fisher ADF Inv. X2	**Fisher ADF** Inv. N	**Fisher ADF** Inv. L	**Fisher ADF** M. Inv. X2
CO$_2$ **Emissions**	122.1942 [0.0000]	-4.9443 [0.0000]	-5.1288 [0.0000]	6.5620 [0.0000]
Energy Consumption	166.1549 [0.0000]	-7.9549 [0.0000]	-8.2985 [0.0000]	10.7921 [0.0000]
GDP	187.0374 [0.0000]	-9.2752 [0.0000]	-9.7489 [0.0000]	12.8015 [0.0000]
Environmental Patents (GI + OECD)	144.4375 [0.0000]	-7.4048 [0.0000]	-7.3532 [0.0000]	8.7024 [0.0000]
Environmental Patents (GI)	146.2144 [0.0000]	-7.5126 [0.0000]	-7.4692 [0.0000]	8.8733 [0.0000]
Non-Environmental Patents (GI + OECD)	187.4035 [0.0000]	-9.1537 [0.0000]	-9.7391 [0.0000]	12.8368 [0.0000]
Non-Environmental Patents (GI)	190.0388 [0.0000]	-9.2292 [0.0000]	-9.8733 [0.0000]	13.0903 [0.0000]
Total Patents	174.7351 [0.0000]	-8.6519 [0.0000]	-9.0280 [0.0000]	11.6177 [0.0000]
Renewable Energy	38.6815 [0.9425]	4.0921 [1.0000]	4.5691 [1.0000]	-1.4740 [0.9298]
Δ **Renewable Energy**	274.5258 [0.0000]	-12.115 [0.0000]	-14.324 [0.0000]	21.2201 [0.0000]
Industrial Intensity	121.8800 [0.0000]	-4.8743 [0.0000]	-5.1821 [0.0000]	6.5318 [0.0000]

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[109] Share of the Industry Sector in Gross Value Added.

[110] Trade Openness is equivalent to the sum of Imports/GDP and Exports/GDP.

Trade Openness	124.6579 [0.0000]	-6.1107 [0.0000]	-6.0688 [0.0000]	6.7991 [0.0000]
Urban Population	100.7640 [0.0001]	-3.6333 [0.0001]	-3.7019 [0.0002]	4.4999 [0.0000]
FDI	227.1148 [0.0000]	-11.002 [0.0000]	-12.004 [0.0000]	16.6580 [0.0000]

Notes: Variables used are in logarithm or share.

Fisher-ADF: The Fisher-type unit-root tests are based on augmented Dickey–Fuller (Fisher-ADF) tests with drift and one lag; the null hypothesis is that "all panels contain unit-roots"; the test does not require a balanced panel. Statistics and respective p-values (in square brackets) are reported for each type of Fisher test: inverse chi-squared, inverse normal, inverse logit and modified inverse chi-squared.

Δ is the first difference operator.

A3: Descriptives on emissions and patents

We will now explore in more detail our data for our sample period 1992 to 2014. Concerning CO_2 emissions at a country level, the largest emitters are Germany, the United Kingdom (UK), Italy, and France. Germany is by far the largest emitter in absolute terms with a mean value between 1992 and 2014 of ~812,500 thousand metric tons (TMT) followed by the UK with ~518,000 TMT on average. The smallest emitter of CO_2 is Malta with ~2,430 TMT followed by Cyprus with ~6,800 TMT. Luxembourg and Latvia also remain below the 10,000 TMT threshold. The largest and smallest values across the whole sample also occur within the largest and smallest emitter countries. In 1992 both the largest value (~892,000 TMT in Germany) and the smallest value (~2,000 TMT in Malta) are observed. It is apparent that the absolute levels of CO_2 emissions largely correspond with the size of the countries and their level of economic development, as Germany (~2.3 trillion), the UK (~1.8 trillion), France (~1.7 trillion), and Italy (~1.4 trillion) have the largest mean values of GDP, while Malta(~5 billion) followed by Estonia (~9 billion), Latvia (~12 billion), and Cyprus (~14 billion) have the lowest mean values of GDP. Hence, it may be more informative to look at a relative measure accounting for the economic size of a country to get an impression of the environmental impact of the countries. For this purpose we compute a measure of environmental intensity, namely the amount of CO_2 emissions (in TMT) per unit of GDP (in billion). There are other countries at the top and bottom of the ranking. Five countries, namely Bulgaria (~7.7), Estonia (~7.6), Poland (~7.2), Romania (~7.2), and the Czech Republic (~7.1) caused on average more than 7 TMT CO_2 per billion GDP. The most environmentally friendly countries on the flipside are Sweden (~5.2), France (~5.4), Denmark (~5.5), and Austria (~5.6). The highest intensity can be found in Bulgaria in

1993 with 8.29 TMT CO_2 per billion GDP, while Sweden provides the lowest value in 2014 with only 4.79 TMT CO_2 per billion GDP.

Figure A3 below shows the development of all our key variables over the whole range of time observed. EI[111] as well as GDP are increasing over this period, with recognizable drops. CO_2 is rather constant and decreasing towards the end of our time-period. The CO_2 intensity of GDP is consequently decreasing. All variables were summed up for all countries in our dataset. The time series are normed to the year 2003, where all variables are equal to 1. Hence, it is visible that across EU-27 countries the CO_2 intensity has decreased from more than 1.2 times of the 2003 value in the early nineties to less than 0.8 times of the 2003 value in 2014.

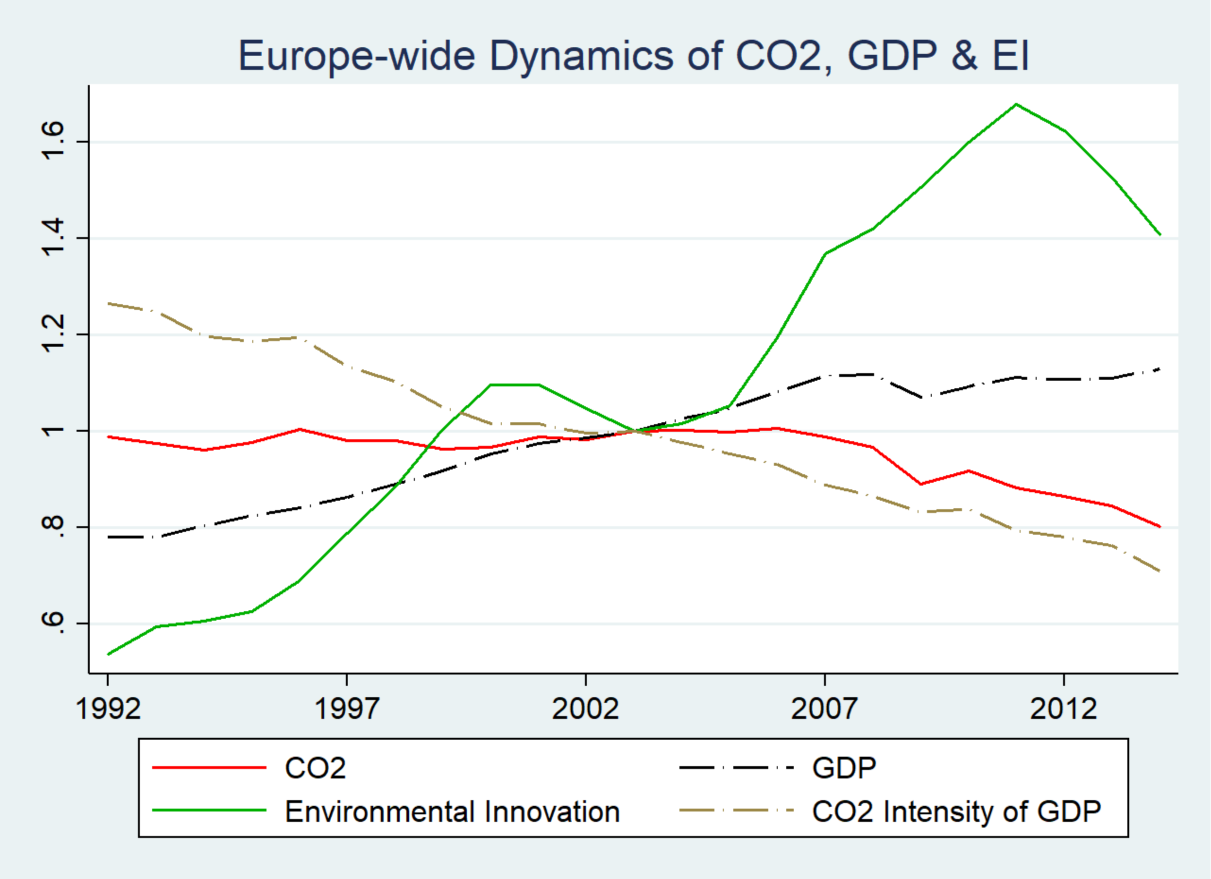

Figure A3: Aggregate Dynamics of key variables in the EU-27 countries between 1992 and 2014.

Note: All variables are normed by their 2003 value.

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[111] We used the patent counts of our main explanatory variable, namely EI defined by combining the WIPO Green Inventory and the OECD EnvTech.

Concerning our main explanatory variable of interest, i.e. green patenting, we find the following patterns: The largest mean values of green patents per year are found for Germany (4,397) and France (1,345), followed by the UK (834), the Netherlands (700), and then Italy (514). The smallest average values of green patent applications per year are found for Lithuania (2.26) and Latvia (2.39) followed by Bulgaria (3.52), Malta (3.56), and Romania (3.7). Again, these numbers are strongly bound to the overall size of the respective economy. A completely different picture appears when computing the share of green patent applications among all patent applications. In these terms, Slovakia (0.29), Lithuania (0.27) and Bulgaria (0.27) have the highest share of green patents, while Latvia (0.12), Italy (0.14) and Sweden (0.14) show the lowest share of green patent applications, according to our classification of environmental technologies. However, the numbers above may be strongly driven by the different magnitudes in innovative activity and patterns over time. Within the EU-15 countries the mean value of patent applications is about 60 times higher than for the eastern European countries. Hence, while the share of green patents ranges between 0 and 1 for eastern European countries, it ranges between 0.06 and 0.53 in the EU-15. Further, even within the EU-15 these extreme values are both found for Greece in 1996 respective 1993. For a large mature economy, namely Germany, the share of green patents ranges between 16 and 24% throughout the whole time period.

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Appendix A: Personal contributions to the papers of the cumulative dissertation

On the tension between natural resource extraction and biodiversity – do governance characteristics matter? (Chapter 2)

This paper was written by me, as a sole author.

Global convergence of meat consumption – Is income growth an insurmountable force? (Chapter 3)

This paper was written by me, as a sole author.

The Impact of Environmental Innovation on Carbon Dioxide Emissions (Chapter 4)

This paper is joint work with Tobias Wendler. It was designed and conducted jointly from the beginning, with both authors contributing equally to all steps in the process.

Acknowledgement

My co-author and me are thankful for advice from different sources of which the papers have benefited, including presentations at meetings, discussions with colleagues, or recommendations from editors and reviewers who read previous draft versions.

Acknowledgement

I dedicate this work to the idea of creating a future in harmony with nature, transformation towards coexisting systems of humanity and its living environment, and the chance for our children, grandchildren and many generations to come, to enjoy the beauty and fascination of wild animals and diverse flourishing ecosystems, out of which we as humans evolved and within which we have lived and strived the major part of this evolution. We need to stop to see our human system somehow disconnected from nature and start to implement again the reality of the existing strong connection with and dependence on nature into our perceptions and actions. In the end, we not grown out of nature as a species. We are still part of it. So I dedicate this work to the idea of reconnection.

This work is the result of my years as an external doctoral candidate at the University of Bremen. However, my journey at the University of Bremen began much earlier, with the start of my Bachelor in economics, followed by my Master in business economics. Along the way I have encountered many good, intelligent and motivated people, that all together had collective influence on this dissertation. Especially grateful, however, I am for the sheer endless support of and believe in mine, by my supervisor Jutta Günther. She was by my side the whole time – from my early years in Bachelor to now – and always encouraged me with and her undefeatable believe in my abilities. She has not only passed academic knowledge but also live lessons to me, I still apply and think about regularly, and of which I participate now, implementing them in the professional arena. I am endlessly thankful for her support and her strong leadership.

Within my study years, I have immensely participated from critical discussions, challenging comments and above all the always open-minded and holistic viewpoints and impulses from Torben Klarl, Christian Cordes, and Michael Rochlitz. While being an external doctoral candidate, I nevertheless had the pleasure to be connected and involved into the department activities. Here, I had the luck to meet people, that became friends in the course of time. I am very grateful for meeting Tobias Wendler, with which I share a lot of interests and viewpoints. He was and is always available for insightful and challenging discussions and support – not only in academia but in life. Philip Kerner always inspired me with his relentless meticulousness and aspiration of highest levels of academic professionalism.

This thesis would, however, not exist without all the people that supported and influenced me and my plans along the way of life. First of all, my parents, Susanne and Bernd, supported me my whole life in all my endeavours, regardless of what it was. They provided me with the foundation for all to come, that is invaluable. I cannot articulate in words, the values and support they have given and still give to me. My grandfathers showed and taught me the value of respect and hard work. Their words and lessons will resonate with me for the rest of my life. My uncle Matthias from early on challenged me to think more critical and non-conforming, especially in terms of ecological questions and own behaviours. My sister Daria again and again proves to me that finding the own individual way in life is the most important. I also want to thank my friends Paul Haak, Thore Twisterling, and Nick Hein, for being available and supportive for the major part of our joint lives.

Last, but most important, I want to thank my loved wife, Julia, and my daughter, Lea. Julia has not only supported me unconditionally in all my ideas and plans, but also always provided me with her relentless positive attitude and solution-oriented guidance, even and especially in turbulent and hard times. I could not imagine a better partner both in the trenches and the sweet times of life. My daughter Lea despite her young age has already taught me so many lessons about joy, being oneself, compassion and love. She keeps me grounded and continuously reminds me of what really matters in my life.