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Tobias Heimann, M.A.

aus Köln

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Abbreviations

AI	Aggregated Income
AEZ	Agro-Ecological Zone
BE	Bioeconomy
BMBF	Bundesministerium für Bildung und Forschung
BMEL	Bundesministerium für Ernährung und Landwirtschaft
BAU	Business-as-Usual
CFP	Common Fishery Policies
CGE	Computable General Equilibrium
CES	Constant Elasticity of Substitution
CET	Constant Elasticity of Transformation
CPI	Consumer Price Index
DDGS	Dried distillers grains with solubles
DART	Dynamic Applied Regional Trade
EU	European Union
FIFO	Fish-In Fish-Out
FAO	Food and Agriculture Organization
GG	German Government
GAIN	Global Agricultural Information Network
GBS	Global Bioeconomy Summit
GTAP	Global Trade Analysis Project
GHG	Greenhouse Gases
GDP	Gross Domestic Product
HCS	High Carbon Stocks
ILUC	Indirect Land-Use Change
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
JCR	Journal Citation Ranking

LCA	Life-Cycle Assessment
LES	Linear Expenditure Function
OECD	Organization for Economic Co-operation and Development
PE	Partial Equilibrium
RED	Renewable Energy Directive
SBE	Sustainable Bioeconomy
SDG	Sustainable Development Goals
TBT	Technical Barrier to Trade
TAC	Total Allowable Catch
TFP	Total Factor Productivity
UN	United Nations
UCO	Used Cooking Oil
UCOME	Used Cooking Oil Methyl Ester
WTO	World Trade Organization

1 Introduction

According to geologists who divide time by the Earth's state, today's world finds itself in a human-dominated geological epoch, the so-called Anthropocene (Lewis & Maslin, 2015). An important attribute of this epoch is the Industrial Revolution shaping modern society since the 18th century (ibid.). However, the thereon founded economic development is marked by a rapid increase in the use of fossil resources, and the associated pollution of the environment that causes the climate change we are experiencing today (IPCC, 2014). With increasing awareness that climate change is taking place, governments develop policies and political concepts to fight climate change and reduce the pollution of the environment. One of those political concepts is the bioeconomy, which is at the focus of this dissertation.

Bioeconomy has no unique definition, and governments and international organizations have different conceptions of this political concept (Staffas, et al., 2013; Bugge, et al., 2016; FAO, 2016). For instance, in the definition of the European Union (EU) *the bioeconomy encompasses the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy* (European Commission, 2012, p.5), whereas the OECD defines bioeconomy *as a world where biotechnology contributes to a significant share of economic output* (OECD, 2009, p.22). Thus, some concepts mainly focus on the biotechnology sectors, others are export promotion programs for domestic agricultural products, and an increasing number of concepts understand the bioeconomy as a holistic economy-wide concept for an economic paradigm change (German Bioeconomy Council, 2018). According to the most fundamental definition, bioeconomy aims to turn the fossil-based economy into a bio-based economy, building on renewable biological resources (Bugge, et al., 2016).

While in general, the term bioeconomy is associated with sustainability, the various political concepts of the bioeconomy cast doubts on the actual sustainability coherence of these policies (Pfau, et al., 2014; FAO, 2016). The discussion on the sustainability of the bioeconomy motivated the first paper of this dissertation, called *"Bioeconomy and Sustainable Development Goals (SDGs): Does the bioeconomy support the achievement of the SDGs?"*. Starting to work on the bioeconomy I found it difficult to understand what the term bioeconomy means and how it relates to sustainability, due to the various concepts from different actors as depicted above. The scientific literature on bioeconomy also reflects this pluralism in definitions. Some studies highlight the potential of the bioeconomy and certain bioeconomy policies for sustainable development, while others criticize possible negative trade-offs that would violate the sustainability of the concepts. The evaluation varies from study to study and heavily relies on how the authors define bioeconomy, and which assumptions they make for its future development. However, there was no systematic study that assessed the sustainability of individual bioeconomy concepts at this point, and the first paper of my dissertation fills this research gap. This paper examines the bioeconomy concepts of the European Union (EU) (European Commission 2012), the OECD (OECD 2009), and the German government (BMBF 2010; BMEL 2014). Potential bioeconomy activities planned by these actors are derived from the official concept reports, and then assessed against the UN Sustainable Development Goals (SDGs) which serve as sustainability benchmark (UN, 2015). The core of this analyzes is a literature search of studies that have already examined effects of potential bioeconomy activities on factors that are captured within the SDGs. As a result, this paper identifies trade-offs between the two political concepts of bioeconomy and SDGs, and reveals which aspects of sustainability are addressed and neglected by policy makers formulating bioeconomy concepts. The paper is single authored and published in *Earth's Future (2019), 7(1), p.43-57*.

The availability of biomass is a major bottleneck in developing the bioeconomy (Scarlat, et al., 2015). Biological resources need to be produced somehow, and their production is dependent on natural resources such as land and water. The competition for natural resources is already addressed in the Water-Energy-Food Nexus debate, which aims at mapping the complex interlinkages in resource availability and demand of these crucial components for global development and sustainable livelihoods (Bhaduri, et al., 2015; Biggs, et al., 2015; Leck, et al., 2015; Albrecht, et al., 2018). Concern about the bioeconomy is related to this topic, as the bioeconomy entails a higher demand of biomass for material and energetic use, and thus fortifies the trade-offs analyzed in this nexus debate. In the following two papers of my dissertation we assess how policies and developments within the bioeconomy framework interfere with agricultural markets and affect the competition for the natural resource land.

The second paper *"Yet another reform of the EU biofuel policies: Impacts of the latest reform of the European Union's Renewable Energy Directive"* quantifies the effects of an EU bioeconomy policy on global energy and agricultural markets, as well as land use. In this paper, we analyze the implications of the EU biofuel policy stated in the latest renewable energy directive (RED II). This policy is currently expected to be the only EU bioeconomy policy that has the scope to affect global markets until 2030 (Delzeit et. al., 2021a). To quantify the effects of the RED II, we employ the computable general equilibrium (CGE) model DART-BIO (Delzeit et. al., 2021b). A crucial aspect of this paper is the evaluation of the palm oil biodiesel phase-out, conditioned by the regulations within the RED II. Due to the expansion of palm fruit production into land with high carbon stocks, the RED II demands a phase-out of the utilization of palm oil-based biodiesel until 2030. However, with our model, we show how the substitution and feedback effects of global agricultural markets undermine a policy meant to protect tropical ecosystems, and acts as a technical barrier to trade (TBT) potentially discriminating certain regions. The results provide valuable insights for policy makers to design more effective regulations. The paper is authored by Ruth Delzeit, Tobias Heimann, Franziska Schünemann and Mareike Söder. Each author contributed to the construction of the database for this study. Most of the modelling exercise was done by Ruth Delzeit and me, and each author engaged in writing the paper, while I contributed the major share. The paper is submitted to the European Journal of Agricultural Economics.

The third paper takes a focus on aspects of the blue bioeconomy. The bioeconomy can be separated into four major parts, defined by the respective relevant biotechnology sectors: medical (red biotechnology), agriculture (green biotechnology), hydrology (blue biotechnology), and industrial applications (white biotechnology) (Scarlat et al. 2015). The blue bioeconomy encompasses economic activities that use renewable aquatic resources, such as aquaculture fish production (EUMOFA, 2020). The third paper is named "*Land for Fish: A scenario based CGE analysis of the effects of aquaculture consumption on agricultural markets*" and is the first study that explicitly focuses on aquaculture production in a CGE model. Here we develop the DART-BIOFISH model to analyze the effects of rebuilding sustainable wild fish stocks and of plant-based fodder consumption by the aquaculture sector on agricultural markets, land use, and welfare. In the second paper we explicitly model the vegetable oil processing industry, accounting for the production of oilseed meals as a co-product from vegetable oil production. As these oilseed meals are the main source for animal feed, accounting for this co-production allows us to derive a precise fish feed composition for an aquaculture sector. We exploit this attribute in the DART-BIOFISH model, for which a fishmeal, capture fish and aquaculture fish sector are added to the original DART-BIO model.

In this study we analyze feedback effects of substituting fishmeal and plant-based feed in aquaculture production and their implications on agricultural markets under various scenario assumptions. Additionally, we look at the economic consequences of rebuilding sustainable fish stocks to achieve SDG 14 *"Life under Water"*. Further, we explore resource economic linkages between capture and aquaculture fisheries within an applied CGE model, which have been yet studied in theoretical models (Anderson, 1985; Naylor, et al., 2000; Mullon, et al., 2009; Tacon & Metian, 2009; Merino, et al., 2010; Merino, et al., 2012; Regnier & Schubert, 2017; Bergland, et al., 2019). The paper is co-authored by Ruth Delzeit. All research steps have been carried out by me, while Ruth Delzeit provided valuable support during the entire process, and contributed to result selection, interpretation and formulation. The paper is submitted to the American Journal of Agricultural Economics.

Each of the three papers provides a valuable contribution to the scientific literature. The first paper provides an easy entry for scholars and policy makers into the complex topic of bioeconomy and sustainability. The second paper contributes to the debate of whether climate policies can be misused as technical barrier to trade and reveals shortcomings in the RED II policy of the European Union. Finally, the third paper shows the results of the first CGE model that explicitly focuses on the fish sector. As being based on applied scientific methods, all three papers deliver recommendations for policy makers in step with actual practice.

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2 Bioeconomy and Sustainable Development Goals (SDGs): Does the bioeconomy support the achievement of the SDGs?

Tobias Heimann[1]

[1] Kiel Institute for the World Economy

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Abstract:

This paper evaluates how bioeconomy activities, stated in the concepts of the EU, OECD, and German government, potentially affect the targets of the Sustainable Development Goals (SDGs). The aim of the bioeconomy is to substitute the use of fossil resources by renewable resources, while the SDGs set targets for a holistic sustainable global development. A literature-based influence analysis on empirical studies is employed to derive three bioeconomy scenarios (business-as-usual, bioeconomy, sustainable bioeconomy) and to quantify their effects on the individual SDG targets. It is shown that the bioeconomy scenario has positive as well as negative effects on the SDG targets. While targets for cleaner industrial production are strongly supported, socio-economic targets are subject to mixed effects and environmental targets significantly hurt. This paper outlines which SDGs need special attention when implementing a bioeconomy according to the above-mentioned concepts. The results add to the debate on SDG trade-offs and on the substitutability of SDG targets. Without regulations, policies, and investments ensuring sustainability, or in case the substitutability of SDG targets is not allowed, the bioeconomy concepts have the potential to jeopardize the achievement of several SDGs. In contrast, the sustainable bioeconomy scenario assumes strong sustainability measures that reveal the extensive potential of the bioeconomy to support the achievement of the SDGs.

2.1 Introduction

Mankind is still unsustainably consuming natural resources and services, beyond rates at which these resources can reproduce, regrow, and regenerate, exerting thereby increasing pressures on climate, ecosystems, habitats, and biodiversity (Global Footprint Network, 2016). Yet, the role of the environment and natural resources for development, wealth, and particularly poverty reduction has remained poorly acknowledged in national and international policy designs so far (Griggs et al., 2013). A tipping or even turning point towards the design of more sustainable national and international policies could be the 2030 Agenda for Sustainable Development. These Sustainable Development Goals (SDGs) have been adopted by the United Nations General Assembly in September 2015 and consist of 17 goals containing 169 specific targets (UN, 2015).

The global SDG framework has not been implemented into a white spot of the global policy landscape but interacts with various existing regulations and initiatives at the regional, national, and supranational level. One prominent example for an already existing regulatory framework relates to the development and intensification of the bioeconomy. In contrast to the unique SDGs, there are several bioeconomy concepts which are formulated individually by countries and international organizations, defined according to their political agendas (FAO, 2016; Staffas et al. 2013). The German government (GG) defines its bioeconomy concept *as a sustainable bio-based economy oriented on the natural life-cycle of materials which can provide us with high quality products from natural resources and sufficient healthy food to satisfy the global demand"* (BMBF, 2010, p.3). According to the EU *the bioeconomy encompasses the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy* (European Commission, 2012, p.5), whereas the OECD thinks of a bioeconomy *as a world where biotechnology contributes to a significant share of economic output* (OECD, 2009, p.22). Notably, sustainability is addressed in the concept papers of the EU and the German government while the OECD strongly considers the bioeconomy as a driver for economic growth. However, even in the concepts of the EU and Germany, the commitment to ensure sustainability of the bioeconomy remains vague, raising the highly relevant research question to which extend exiting bioeconomy policy frameworks are in line with the achievement of the SDGs. Here, we present a literature-based scenario analysis to approach this question and to assess to which extent the bioeconomy concepts of the European Union (EU) (European Commission 2012), the OECD (OECD 2009), and the

German government (BMBF 2010; BMEL 2014) support the achievements of the SDGs, identifying meanwhile key requirements to make bioeconomy development sustainable.

The sustainability of bioeconomy policies has been already discussed in the literature (Birch et al. 2010; GBS, 2015; Juerges & Hansjürgens, 2016; Pfau et al. 2014; Sheppard et al. 2011; Smolker, 2008). These studies and reports mainly criticize that measure and strategies ensuring sustainability are missing in most of the bioeconomy concepts. The final report of the Global Bioeconomy Summit (GBS) 2015 distinguishes between bioeconomy and sustainable bioeconomy. The authors argue that for achieving a sustainable bioeconomy, the planet's natural capital needs to be improved, and that besides technological also social innovations are crucial (GBS, 2015). This statement underlines that measuring the effects of the transition towards bioeconomy requires particular evaluation over "their" sustainability, especially regarding social and ecological implications. Moreover, while imagining a society based on renewable resources, it is important to remember that renewable resources like biomass must be given the time and opportunity to renew, thus they must be managed sustainable (Zilberman et al. 2013). Pfau et al. (2014) argue that the bioeconomy concepts are not already sustainable by default. They emphasize that the main goals are rather the reduction of the dependence on fossil resources, followed by reducing green-house gases (GHGs) emissions and the carbon footprint. Policy makers anticipate the increasing price and environmental risks of resource extraction, as well as the dependence on potentially geopolitical unstable regions, where the remaining resources are predominantly located (Pfau et al. 2014). Thus, from their point of view the primary motivation for establishing a bioeconomy is political and economic, and then environmental. While the final report of the GBS already acknowledges the potential of the bioeconomy to support the achievement of some SDGs, the other studies analyze the sustainability of bioeconomy policies in general, using different sustainability concepts and definitions.

Accordingly, this paper goes beyond these studies by directly analyzing the relationship between bioeconomy policies and the SDGs, which, in turn, provide the first global political approval of sustainable development. Most closely related to this study is the work of El-Chichakli et al. (2016). They briefly describe which SDGs might be positively affected by the bioeconomy and provide policy recommendations for supportive measures. However, the policy recommendation only scratches on the surface of the bioeconomy SDG relation and is not based on a systematic literature research. This study analyses the magnitude and relevance of the effects from bioeconomy activities on SDG targets, and indicates which effects strongly support or jeopardize the achievement of the SDGs. It adds to the literature by identifying the most negative and positive effects of a bioeconomy, and delivers a foundation for discussions on the sustainability of the bioeconomy as well as for optimizing the bioeconomy concepts to minimize their negative effects on SDG targets. Thus, the results of this work can be used as a guideline for policymakers to concentrate their efforts on the most important issues that may emerge from implementing the bioeconomy concepts.

The just mentioned bioeconomy activities are measures which are conducted to achieve the aims of the bioeconomy, according to the respective concepts of institutions and governments. Considering the aims, the bioeconomy concepts and SDGs are overlapping in some aspects, and some aims of the bioeconomy activities are complementary or even identical to SDG targets. However, the bioeconomy activities can enable as well as hinder the achievement of SDG targets, especially by triggering trade-offs with SDG targets whose aspects are not considered in the bioeconomy concepts. In order to evaluate if the bioeconomy activities support or contradict the SDGs, each level of activities needs to be considered. As an example, consider the three connected aspects: increased biomass production *(aim),* farm productivity *(aim),* use of marginal land *(activity).* Increased biomass production can have income and job market effects while increased farm productivity may have, amongst others, income and environmental effects, and the use of marginal land can have negative effects for the local population and biodiversity. Thus, all three aspects are complementary but affect different SGDs. Moreover, the use of marginal land is only one of many possible activities to achieve the aim of increased biomass production, and the effects on the SDG targets from other activities may differ significantly. An important asset of this study is that it considers various activities for each major aim of the bioeconomy concepts, and evaluates their potential effect on the respective SDGs.

A literature-based scenario analyses is employed, because econometric approaches and CGE (computable general equilibrium) models are unable to cover such a wide range of dimensions that must be considered to draw a holistic picture of the bioeconomy effects on the SDGs. Up to now, comparable quantitative evaluations capture only a limited number of dimensions, concentrating on e.g food security, productivity and land use change (Delzeit et al., 2018), or water (Howarth, 2008), or changes in biodiversity (Sheppard et al., 2011). To provide a multidimensional overview on the different affected SDGs, this study bundles the results of quantitative evaluations dealing with the respective dimension of the SDGs. Such a holistic approach, in terms of SDG dimensions, has not yet been conducted by econometric or CGE approaches due to missing data as well as due to the complexity of the required multidimensional models. However, this study delivers a summary of the potential effects, and can be used as a foundation for the selection of dimensions and the design of scenarios for future quantitative analyses.

This paper is structured as follows. Section 2 explains the literature-based scenario analysis where we use the bioeconomy definition of the German Government, the EU, and the OECD to define our scenario space. Section 3 presents the results, discussing for the SDGs 1 to 3, 6 to 9 and 12 to 15 the interaction with the bioeconomy and the implication of the different bioeconomy policy scenarios. Section 4 brings about the discussion and the conclusion.

2.2 Method

This ex-ante evaluation is based on a review of scientific literature. The bioeconomy concepts are not yet fully implemented and data on effects of bioeconomy activities is not available. However, several measures which are considered to be used for the bioeconomy have been implemented individually, and research on the effects of these measures already exists. Furthermore, scholars, governments as well as international organization have published their anticipation of effects from bioeconomy activities (BMBF, 2010; BMEL, 2014; Deininger, 2013; European Commission, 2012; FAO, 2016; GBS, 2015; Levidow et al. 2012; Zilberman et al. 2013). Since this paper does not claim to judge on the probability that those expectations occur, all expectations that are formulated based on common scientific reasoning, which means that authors need to provide or refer to scientific evidence supporting their claims, are included. The literature review collects papers with information on effects resulting from potential bioeconomy activities on aspects which are considered in the SDG targets. However, in rare cases the evidence for the same measure differs, which may have various reasons, such as different study design, study area, or estimation techniques. One study may find a significant evidence for an effect and another does not. Since only high-level papers are included, it is assumed that the evidences in the papers are valid. Only if a majority of the high-level papers make strong arguments rejecting the evidence for an effect, the effect is excluded.

It needs to be noted that this is not a systematic meta-analysis, which is useful when evaluating several papers analyzing one specific hypothesis (Baumeister & Leary, 1997). Instead, this work aims at linking several studies on various topics, and therefore is a narrative literature review providing an overview on findings on various related topics (Snyder 2019). Conducting a systematic meta-analysis on each bioeconomy SDG interaction would presumably deliver evidence for multiple individual studies. As Snyder (2019) states, narrative literature reviews are useful for synthesizing knowledge on multidimensional complex topics, as they concentrate on the narratives of the studies rather than the exact effect size. On the downside, narrative literature reviews are prone to inherent selection bias and subjectivity introduced by the reviewer (Randolph, 2009; Grant & Booth, 2009). Therefore, narrative literature reviews must be interpreted carefully considering their respective context.

To select a subset of relevant articles, selection criteria are defined. Criteria such as study group characteristics or research design are not useful for this review, because the various topics that are jointly considered in this review are necessarily analyzed using heterogenous study approaches. Since, in contrast to a systematic meta-analysis, the absolute effect size found in the studies does not play a crucial role in this literature review, it is decided to use research quality as selection criteria to assure that only scientific valid narratives based on high scientific standards are considered. In this study research quality is assessed against the number of citations as explained below. Note that considering the quality of research articles as selection criteria for the literature is a contended topic among researchers (Randolph, 2009). The criterion "journal citation report rank" may include a publication bias towards stronger positive results. However, Murtaugh (2002) states that the quality of research design and execution is correlated to the effect size stated in individual studies and argues that high level journals publish on average higher quality research. Even if this might imply that high quality articles also find a higher effect size, this does not prevent using this selection criteria since the effect size does not play a significant role in this study. This study focuses on the narrative regarding the existence of a potential effect, and a publication bias resulting from the focus on high quality articles does not have such a big influence than including false positive effects based on weak study design. Therefore, research quality is considered a valid and useful exclusion criterion for this analysis.

For the literature-based influence analysis, the scientific search engine "Web of Science" is employed. A list of search words can be found in the appendix. Among the identified articles, articles from journals ranked at least in the 2nd quartile of their Journal Citation Reports (JCR) Categories were selected for the review of influences. For key words yielding more than 30 journal articles within this criterion, only articles in the category "highly cited papers" were considered. This selection let to 128 articles that were then screened for their relevance for this study, and papers that cover evidence on potential effects of bioeconomy activities on SDG targets were extracted. In addition, articles and reports cited within these selected articles were also considered if relevant, which is a common procedure in literature reviews (Randolph, 2009). In total a number of 56 documents were used for this analyzes. Table 1 provides an overview on the literature consulted for the evaluation of the bioeconomy considering the respective SDGs.

Table 1: Literature used for evaluation by SDGs

SDG	***Literature***
SDG 1	Cotula et al. (2008); Landis et al. (2008); OECD (2009); Varshney et al. (2011); EU (2012); McMicheal (2012); Tscharntke et al. (2012); Deininger (2013); Hertel et al. (2013); Swinnen & Riera (2013); BMEL (2014)
SDG 2	Moschini & Lapan (1997); Johns & Eyzaguirre(2007); Cotula et al. (2008); Danielsen et al. (2008); Landis et al. (2008); Smolker (2008); OECD (2009); Stein (2009); Tilman et al. (2009); Blakenye (2010); Meenakshi et al. (2010); Banward (2011); Chapell (2011); Varshney et al. (2011); Sheppard et al. (2011); EU (2012); McMicheal (2012); Tscharntke et al. (2012); Deininger (2013); Hertel et al. (2013); Swinnen & Riera (2013); BMEL (2014); Lewandowski (2015); Juerges & Hansjürgens (2016)
SDG 3	Alavanja et al. (2004); Kamel (2004); McCauley et al. (2006); OECD (2009); Jamaludin et al. (2013); BMEL (2014); GBS (2015); Rojas Fabro et al. (2015); Wongsanit (2015); Larsen & Noack (2017)
SDG 6	OECD (2009); Robertson (2009); Smaller & Mann (2009); Cotula (2011); Gheewala et al. (2011); Moraes et al. (2011); Raghu et al. (2011); EU (2012); Deininger (2013); Rosegrant et al. (2013); Zilberman et al. (2013); BMEL (2014)
SDG 7	OECD (2008); OECD (2009); EU (2012); BMEL (2014); Bruckner et al. (2014)
SDG 8	Grossman (1995); Stern (2004); Cotula et al. (2008); Deininger (2013); OECD (2009); EU (2012); McMicheal (2012); BMEL (2014)
SDG 9	Cotula et al. (2008); Deininger (2013); OECD (2009); EU (2012); BMEL (2014)
SDG 12	OECD (2009); Giljum et al. (2011); EU (2012); Galli (2012); BMEL (2014); Hoekstra (2014)
SDG 13	Danielsen et al. (2008); Fargione et al. (2008); Searchinger et al. (2008); Kim et al. (2009); OECD (2009); Varshney et al. (2011); EU (2012); BMEL (2014); UN (2015)
SDG 14	Beman (2005); Howarth (2008); OECD (2009); Robertson & Vitousek (2009); EU (2012); BMEL (2014)
SDG 15	Beman (2005); Cotula et al. (2008); Howarth (2008); OECD (2009); Robertson & Vitousek (2009); Banward (2011); Ferdinands et al. (2011); Raghu et al. (2011); Sheppard et al. (2011); Chapell (2012); EU (2012); Deininger (2013); Hertel et al. (2013); BMEL (2014); Lewandowski (2015); Juerges & Hansjürgens (2016)

To examine the effects of bioeconomy activities on the SDGs, one needs to acknowledge which SDGs are relevant. This way, based on the literature review it is possible to analyze which targets of the various SDG are potentially affected by the actions and plans stated in the concepts of EU, OECD and the German government. Based on this analysis, the goals 1, to 3, 6 to, 9 and 12 to 15 were identified to be influenced by bioeconomy activities (Figure 1). The goals *"No Poverty"*, *"Zero Hunger",* and *"Decent Work and Economic Growth"* (SDG 1, 2, 8, respectively) are affected by the socio-economic outcomes of the bioeconomy. The bioeconomy affects the job market, the agricultural commodity market, and agricultural activities in general. Therefore, employment, food security and poverty need to be considered, as reflected by these three goals. The goal *"Good Health and Well-Being"* (SDG 3) is, amongst others, affected by investments into biotechnology research promoted by the bioeconomy concepts.

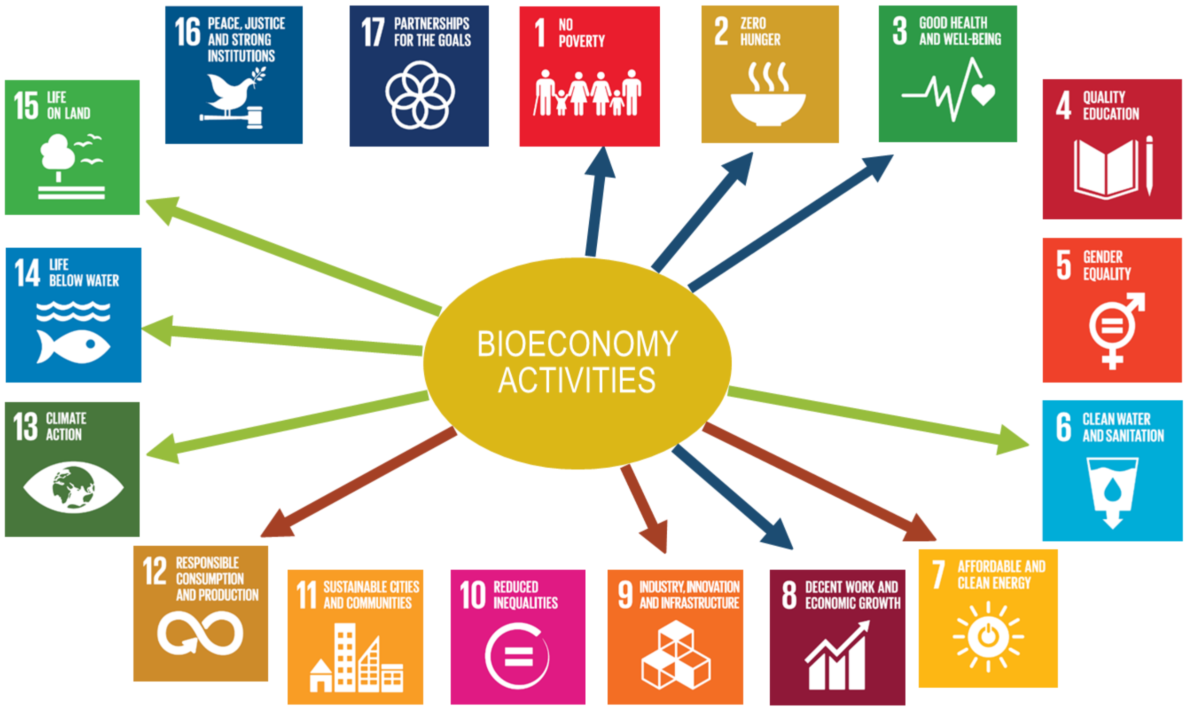

Figure 1: SDGs affected by bioeconomy activities. Blue arrow: Socio-economic targets; Green arrow: Ecological targets; Red arrow: Clean industry & economic targets.

According to the OECD, in 2009 about 80 percent of biotechnology research investments by private and public sector went to health applications (OECD, 2009). *"Clean Water and Sanitation"*, *"Climate Action"*, *"Life below Water",* and *"Life on Land"* (SDG 6, 13, 14, 15, respectively) are affected by the ecological dimensions of the bioeconomy. They capture the effects of industry and agriculture on water, the atmosphere, the oceans and land. Finally, the SDGs *"Affordable and Clean Energy"*, *"Industry, Innovation and Infrastructure",* and *"Responsible Consumption and Production"* (SDG 7, 9, 12, respectively) reflect the bioeconomic production of goods and energy, relating in turn to the sustainable use of global resources in general. Summarized, the SDG bioeconomy relations can be bundled into three groups, with a socio-economic, ecological, and industrial & economic dimension, whereby health is sorted to the socio-economic dimension.

Quantification method

For the quantification of the potential bioeconomy effects on SDGs, two major challenges must be addressed: i) the magnitude of the effects on the SDGs is highly sensitive and depends on how the bioeconomy is implemented, and ii) the weak definition of "bioeconomy measures" makes it very difficult to evaluate their outcomes. As an example, the EU states that *"The goal is to provide agriculture and forestry with the required knowledge and tools to support productive, resource-efficient and resilient systems that supply food, feed and other bio-based raw-materials without compromising ecosystems services, while supporting the development of incentives and policies for thriving rural livelihoods"* (European Commission, 2012, p. 19). The statement declares ambitious goals, but remains silent on how to achieve them. There are various applicable modern agricultural techniques, like sustainable intensification, conservation agriculture, or precision agriculture, each having its advantages and disadvantages. To evaluate the potential effect of the bioeconomy on the SDGs, the outcomes of all those possible approaches must be considered in course of this analysis.

Thus, since there are different possibilities for an implementation of a bioeconomy, three scenarios are employed. Scenario one describes the business-as-usual (BAU) without any implementation of the bioeconomy concepts. The demand for biomass would only grow according to population growth and anticipated preference changes through increased incomes. Also, investments into biotechnology, cleaner industries, environmental protection, and climate change mitigation remain to have a constant share of total investments.

The bioeconomy scenario (BE) is based on the concepts of the EU and OECD (European Commission, 2012; OECD, 2009). In terms of biomass, demand would increase much stronger than in the BAU scenario, but no further sustainability measures are employed. As a result, in the BE scenario, both positive and negative effects of biomass demand become more intense compared to the BAU scenario. Therefore, in line with the bioeconomy concepts, investments into biotechnology, cleaner industries, and climate change mitigation are strongly promoted and supported.

The sustainable bioeconomy scenario (SBE) is similar to the bioeconomy scenario, but sustainability measures and regulations are additionally implemented, which particularly dampen the negative effects of increased biomass demand. Some sustainability aims are taken from the concept of the German government (BMEL, 2014), but since this concept is still neglecting serious issues, further sustainability aims and measures from the literature review are considered. It needs to be noted that the sustainable bioeconomy draws an idealized sustainable world in which global regulations and measures ensuring the sustainability of the bioeconomy activities would be in place.

To evaluate the potential effect of the three scenarios on the SDGs, the following steps are taken:

1) Determine the *BaseValue*: The effects of the bioeconomy activities are taken from the literature and matched to the respective targets of the SDGs. Those effects receive a *base value* denoting the relevancy of them for the SDG targets. The classification of the *base values* is illustrated in Figure 2. The scale is related to the work of Nilsson et al. (2016).

-2 Contradicting	-1 Counteracting	+1 Promoting	+2 Complementary

Figure 2: Base Values. The base value reflects the relevancy of an effect on specific SDG targets. The assignment of the value to the effect is based on the literature and the wording of the SDGs. If the effect is directly mentioned in a target or can be matched perfectly, it gets one of the extreme base values. The values in the middle are assigned to effects which are related to the SDG, but only weakly or indirect. For instance, the bioeconomy activity "development and cultivation of climate change resilient crops" is directly mentioned in SDG Target 2.4 and therefore receives an extreme value for SDG 2. However, this activity may also secure income of farmers in climate change prone regions, and hence affect targets within SDG 1. But as this is a side effect of securing food security and this certain bioeconomy activity is not directly reflected in SDG 1, it receives only a medium value when evaluating SDG 1. Sensitivity analyses are conducted showing the robustness of this approach.

2) Determine the *ScenarioValue*: The second dimension accounts for the magnitude of the effect in each of the three scenarios. Thereby, the magnitude of this *scenario value* takes an integer between 0 (no effect) and 3 (strong effect). The scale is selected due to the possibility to assign a different non-zero level to each of the scenarios. Further, it is important to note that an effect can be related to multiple targets and one target can be subject to multiple positive and negative effects.

Equation 1 and 2 describe the calculation of the effect score for one SDG (E_{sg}) by adding the average positive and average negative effect for this specific SDG. Equation 3 calculates impact factor over all SDGs. The equations are:

$$E_{vsg} = \frac{1}{N_{vsg}} \sum Base\ Value_{i,vsg} * Scenario\ Value_{i,vsg} \qquad for\ v = \{p, c\} \tag{1}$$

$$E_{sg} = E_{psg} + E_{csg} \tag{2}$$

$$E_s = \sum_{g=1}^{N} E_{psg} + \sum_{g=1}^{N} E_{csg} \tag{3}$$

,where *i* indicates the effect, *p* denotes a positive effect, *c* a negative effect, *s* the scenario and *g* the respective SDG. One of the core principles of the SDGs is equal weighting of all SDGs (UN, 2015). This principle does not allow the weighting of the mean, and consequently, by adding up the average effects of the SDGs in equation 3, each SDG is weighted the same in the overall evaluation. However, the data in the supplement allow the reader to assign weights to the SDG targets and produce alternative results.

When assigning the scenario and base values, taking the arithmetic mean increases the robustness of the evaluation to subjectivity and assumption errors. Compared to sums or sum of squares, adding and dropping an effect or changing the values brings only comparable small variations if the number of included values is sufficient large. The arithmetic mean is preferred to the geometric mean because the numeric range is the same for each effect, and the focus is on absolute changes not changes in rates. Since the base value and the scenario value are ordinal data, the usual recommended measure are quantiles, such as the median. For ordinal data, quantiles have the advantage that they can be interpreted by categories. However, in this evaluation the effect score is not interpreted categorical but is an indicator for the tendency of the aggregated effect of the bioeconomy. For this purpose, the mean has shown to be more practical than the median, since the median tends to neglect extreme values which are relevant for this evaluation. As a result, this can lead to dubious conclusions. To demonstrate this point, two alternative calculations employing the median as measure can be found in the supplement.

Calculating and adding the average positive and average negative effects, as in equation 1 and 2, also bears two shortcomings. First, one strong effect becomes extenuated by including many weak effects when calculating the averages in equation 1. This is a high-priced trade-off for the sake of robustness. Second, if the number of positive and negative effects per SDG is neglected when calculating the effect score in equation 2, we have a domination of strong effects. One strong positive (negative) effect can dominate many weak negative (positive) effects. This condition describes the imperfect substitution elasticities of the effects. An example that demonstrates their existence is that groundwater depletion can only be combatted by more efficient farming techniques to a certain degree. In case the groundwater is totally depleted, even the most efficient farming technique would not be applicable and helpful anymore. Thus, the strong negative effect cannot be equalized by many positive effects from efficient farm management.

For this evaluation several sensitivity analyses have been conducted. An alternative approach is accounting for the number of positive and number of negative effects per SDG. In principle, considering the number of effects is highly relevant because it provides valuable information on how strong the SDG is affected. Bioeconomy activities can affect one SDG through several channels, which should be respected when evaluating their impact.

For the alternative approach equation 1 and 2 are substituted by equation 4. If the number of positive and number of negative effects is the same, or close together if large, than the results between the first and the alternative approach are very similar and only differ in scale.

$$I_{sgw} = \frac{1}{N_{sg}} \sum Base\ Value_{i,esg} * Scenario\ Value_{i,esg} \qquad for\ e = p = c \tag{4}$$

The difference between the first and the alternative approach are exemplified at the end of the results section. Furthermore, the calculation of the evaluation, including the sensitivity analyses, can be found in the supplement. The evaluation file lists the score for each effect and scenario, as well as the source of the information and the assumptions made for each effect and scenario.

2.3 Results: Bioeconomy and the SDGs

This section presents the results of the analysis and is structured as follows. The first part explains the aggregated results and provides an overview over all affected SDGs. The second part shows three different outcomes for individual SDGs. SDG 8 delivers an example for a positive case, SDG 15 exemplifies a negative case, and SDG 1 demonstrates mixed effects and represents the results for the majority of the evaluated SDGs. For further information, the results on the other individual SDGs are discussed in the appendix, and the detailed calculations of the effect scores can be taken from the supplement. Finally, the outcomes of the sensitivity analysis applying the second evaluation approach are described.

2.3.1 Aggregated Results

Figure 3a demonstrates that the BE scenario has increased positive as well as increased negative effects compared to BAU scenario, and the effect score increases from -15.1 (BAU) to -5.5 (BE). Thus, the overall impact of the BE scenario on the SDGs is still negative, but the share of positive effects significantly increases, as visualized by Figure 3b.

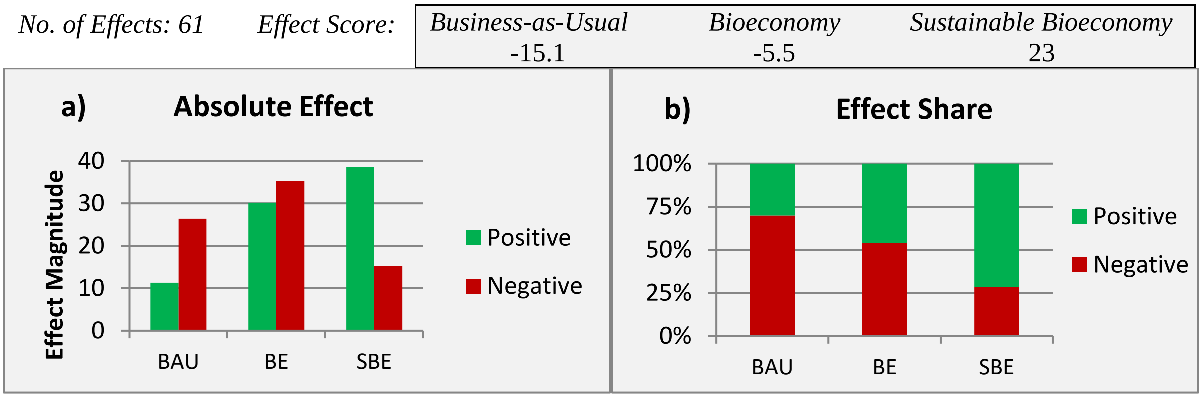

Figure 3: Analysis aggregated over all relevant SDGs. The score of the negative effects is multiplied by -1, and thus showing a positive value.

However, the BE scenario can only be considered superior if we allow for the substitution of effects. This means that the increased negative effects can be outbalanced by the stronger increased positive effects. Without substitution the BE scenario would be worse, since in this case only the change in the negative effects, or the change in positive effects if the negative effects are equal, would count. Figure 4 is mapping the individual SDGs. When substitution is allowed (Figure 4a), compared to the BAU scenario, the BE scenario is only the worse option for SDG 13 to 15. Without substitution the BE scenario is worse for 7 SDGs (Figure 4b).

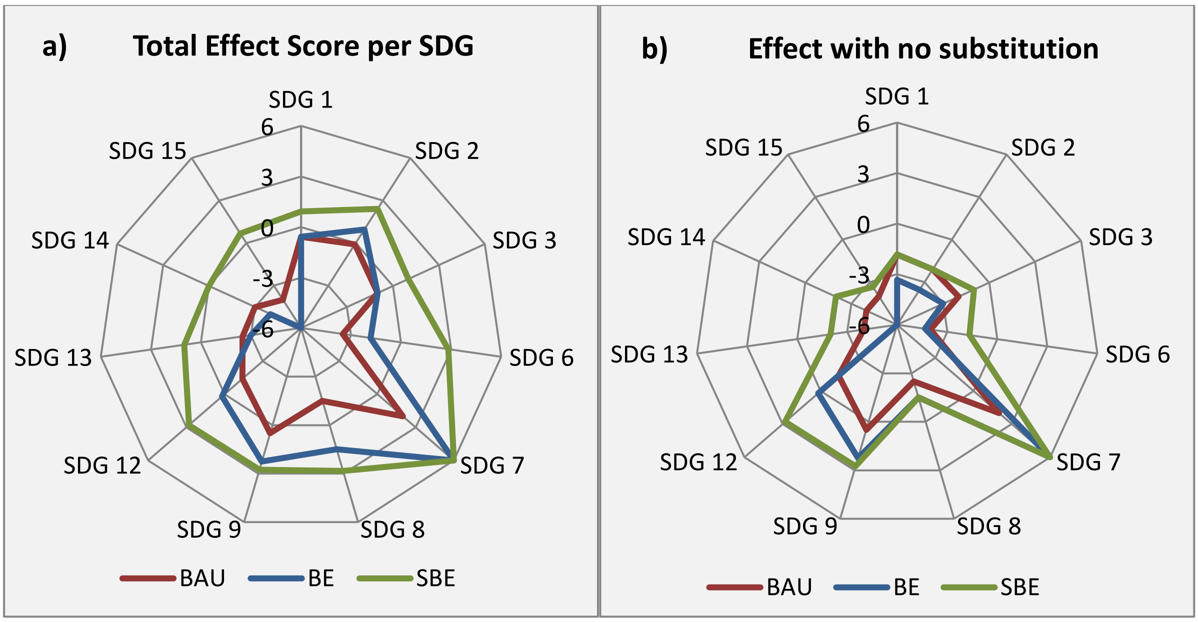

Figure 4: Scores of the individual SDGs.

Separating the results into a socio-economic, an industrial & economic, and an ecological dimension, as displayed in Figure 5, provides a very good impression of the areas where the most conflicts are. While the industrial dimension of the SDGs is strongly supported by the bioeconomy, the socio-economic component shows mixed results. The net effect of the BE scenario is positive, but the increase of the negative effects show that substitution must be allowed to draw this conclusion. Finally, the ecological dimension can be strongly violated if sustainability is not respected. The dimension wise evaluation mirrors the primary aims of the considered bioeconomy concepts, which are mainly concentrating economic factors, like resource efficiency, productivity, and competitiveness, which are to a large share reflected by the clean industry & economic dimension. Also, the strong motivation to reuse waste and residual materials for energy production has a large positive impact on those SDGs. Therefore, going through the concepts, socio-economic and ecological aspects seem to be rather subordinate.

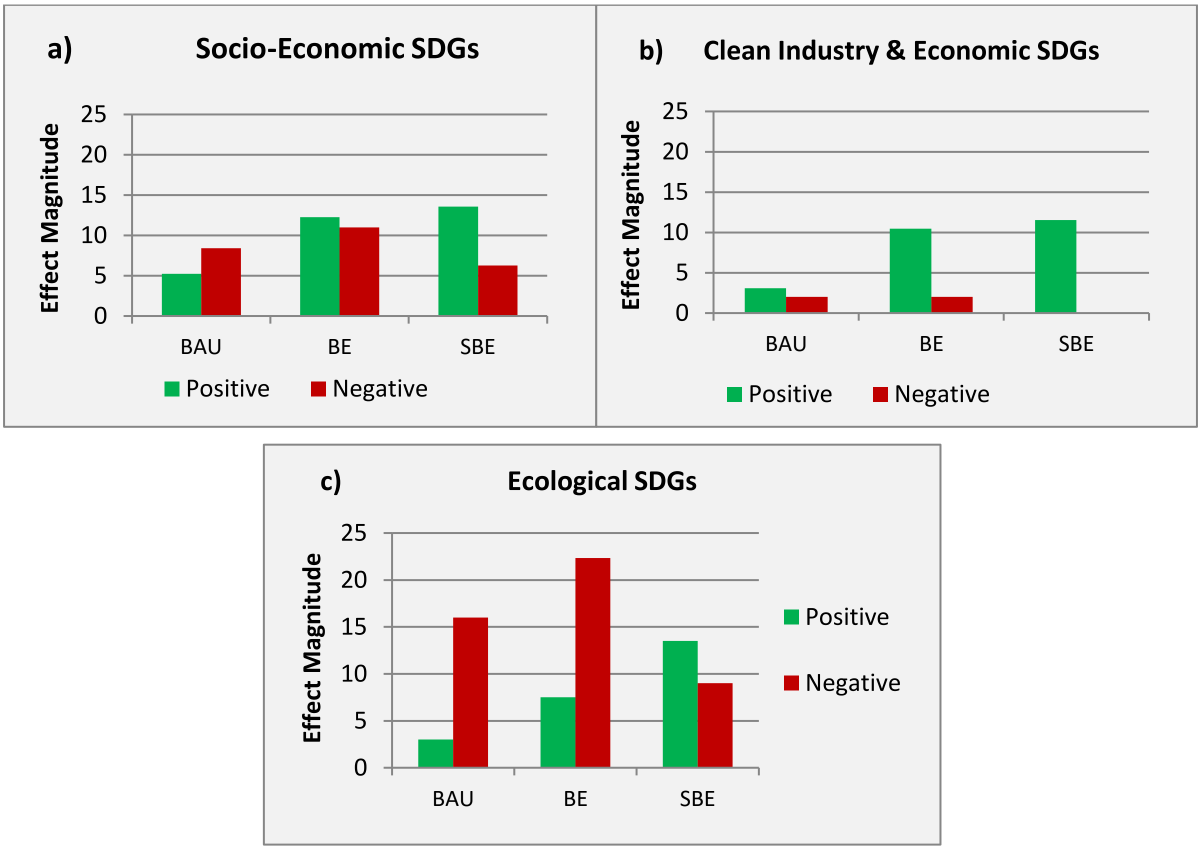

Figure 5: SDGs aggregated by dimension. The score of the negative effects is multiplied by -1, and thus showing a positive value.

For the substitution of fossil resources by natural resources the global agricultural output has to be increased. Therefore, it is intuitive that many interactions between the bioeconomy and

SDGs are similar to interactions between industrial agriculture and SDGs, which mainly affect the socio-economic and ecological SDGs. The bioeconomy concepts of OECD, EU and the German government differ in their approach addressing potential emerging problems. The OECD and the EU consider biotechnological innovations as driver of the bioeconomy and simultaneously as the solution for bioeconomy inherent problems (European Commission, 2012; OECD, 2009). However, this approach has several shortcomings and neglects important issues, which are addressed in the evaluation of the individual SDGs. The German government recognizes and stresses negative effects that cannot be solved by biotechnology. This includes issues on property rights, exploitation rights, biodiversity and distributional aspects (BMEL, 2014). While accounting for such factors would make the bioeconomy sustainable, the concept of the German government does not deliver solutions or binding regulations, yet. Therefore, their bioeconomy concept is located between the BE and the SBE scenario.

2.3.2 Three Case Examples

Improvement: *SDG 8 "Decent work and economic growth"*

No. of Effects:5	*Effect Score*	*Business-as-Usual*	*Bioeconomy*	*Sustainable Bioeconomy*
		-1.5	1.5	2.8

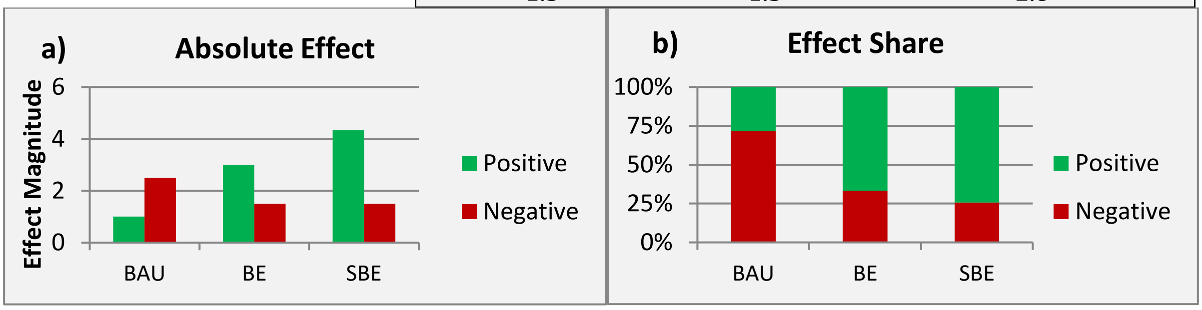

Figure 6: SDG 8. The score of the negative effects is multiplied by -1, and thus showing a positive value.

Figure 6 shows that for SDG 8 the bioeconomy scenario is unambiguously positive compared to the business as usual scenario. Economic development is a main target of the bioeconomy concepts of the OECD, EU and Germany. With investments into new technologies and value-added production, skilled labor jobs are assumed to be created. The FAO estimates that in 2013 all sectors of the bioeconomy in the EU already generated about 18.3 million jobs with an annual turnover 2.1 trillion EURO (FAO, 2016). The difference between the bioeconomy and the sustainable bioeconomy is only caused by stronger efforts to decouple economic growth from environmental degradation in a sustainable bioeconomy. The negative effects are the same for both scenarios and explained below.

There is some criticism questioning if the cultivation of industrialized monocultures actually can provide new jobs at all. For some biomass crops, labor participation per hectare in industrialized monocultures is much lower than in traditional small-holder cultivation. Deininger (2013) states that the cultivation of herbicide-tolerant and pest resistant crops requires less steps in the production processes, and significantly reduces the labor intensity of production. This provides a trade-off between efficiency and labor intensity. If those farmers who lose their jobs, through mechanization and efficient low labor share techniques, do not find new off-farm employment opportunities, e.g. in the value-added production, this can lead to further poverty and migration into urban areas (Cotula et al., 2008; Deininger, 2013).

Thus, the effect on this goal considering developing countries in both bioeconomy scenarios is rather unclear. On the one hand, it is expected that new value-added production possibilities also emerge in those countries (BMEL, 2014; Scarlat et al., 2015). On the other, the bioeconomy concepts of the OECD, EU and Germany predominantly target investments into technology, new production opportunities, and high skilled labor for their own regions. The bioeconomy concepts cannot be considered as development support program for job creation in developing countries in the first instance. This is also the case in the SBE scenario. However, the German government recognizes that *"it must be ensured that the robustly-increasing demand for renewable resources also supports the development-policy objectives in developing countries and emerging economies"* (BMEL 2014, p. 9).

Deterioration: *SDG 15 "Life on Land"*

No. of Effects: 5	*Effect Score*	*Business-as-Usual*	*Bioeconomy*	*Sustainable Bioeconomy*
		-4	-6	0

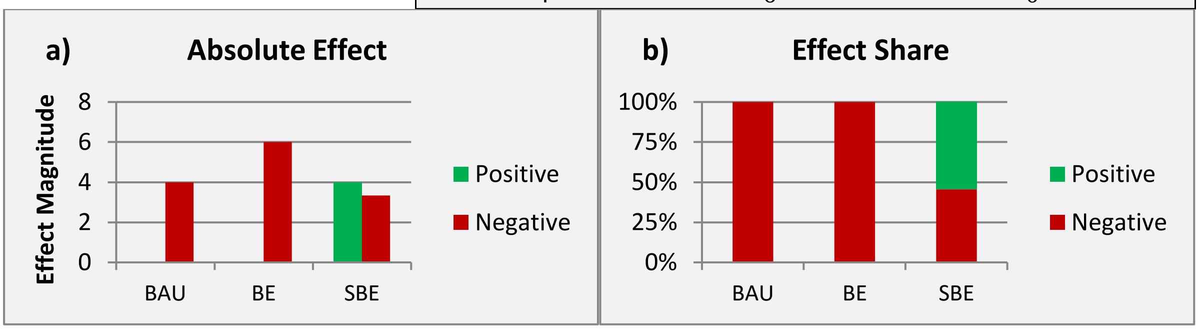

Figure 7: SDG 15. The score of the negative effects is multiplied by -1, and thus showing a positive value.

SDG 15 is an extreme case, since there are no positive effects for the BAU and BE scenario, as shown in Figure 7. The effect score reveals that the BE scenario has the strongest negative impact, for following reason. While e.g. the EU states that the goal of the bioeconomy is to use bio-based raw materials without compromising ecosystems, SDG 15 emphasizes that ecosystems need to be restored. Restoration is however not in the focus of the bioeconomy documents (European Commission, 2012; OECD, 2009). Similar affected is the SDG target considering afforestation and restoration of degraded forests. The bioeconomy concepts recognize trees as a highly valuable biomass resource, in particular for lignin-cellulosic applications like biofuels. The bioeconomy criteria to only use sustainable managed forests promotes the afforestation for commercial use in some regions as well as allows for the deforestation in other regions (BMEL, 2014; European Commission, 2012). Considering this, in addition to incentives to clear forest for crop land in order to satisfy the increasing biomass demand (Deininger, 2013; Henders et al. 2015), the bioeconomy scenario cannot be considered supportive for this SDG target. The SBE scenario therefore fulfills the SDG target 15.2 by promoting the substantially increase of afforestation and reforestation globally (UN, 2015), while taking local factors and ecological requirements into account.

Furthermore, the increased demand for biomass, and thus the increased demand and price for land, may incentivize to unlock new agricultural areas and thereby harm ecosystem services as well as biodiversity (Deininger, 2013). Biodiversity can also be reduced by the extensive cultivation of potential invasive hybrid and GMO crops which may suppress local varieties and contradict target 15.8 (Ferdinands et al., 2011; Sheppard et al. 2011). Moreover, overutilization of land can lead to land degradation and desertification in the worst case (Smolker, 2008). Juerges and Hansjürgens (2016) argue that in the transition towards a bioeconomy the increasing demand for biomass might set incentives to manage soils with a short-term time perspective, while causing negative effects for soil quality in the long-term. They conclude, since short-term costs and benefits of decisions regarding the use of soils often differ from long-term costs and benefits of building up soils, the challenge of managing trade-offs and spillovers over time is increasingly essential in the governance of the transition process.

Since the above-mentioned problems are already well known from the developments in the last decades, a bioeconomy without strong emphasize on sustainability will probably foster, or in the best case maintain, the problems. However, still the sustainable bioeconomy scenario can have severe negative effects on SDG 15. While afforestation, land degradation and restoration of ecosystems would be addressed, issues from land expansion and invasive crops remain adherent. Thus, the net effect of the SBE scenario is neutral for the achievement of SDG 15.

Upscaling Effect: ***SDG 1 "No poverty"***

The effects of the BE scenario on SDG 1 represent the outcome for most of the other SDGs. While in absolute terms the positive and negative effects of the BE scenario increase compared to the BAU scenario, the relative share of the negative effects decreases. Nevertheless, looking at the negative effects in Figure 8a, they increase by 54% from the BAU to the BE scenario.

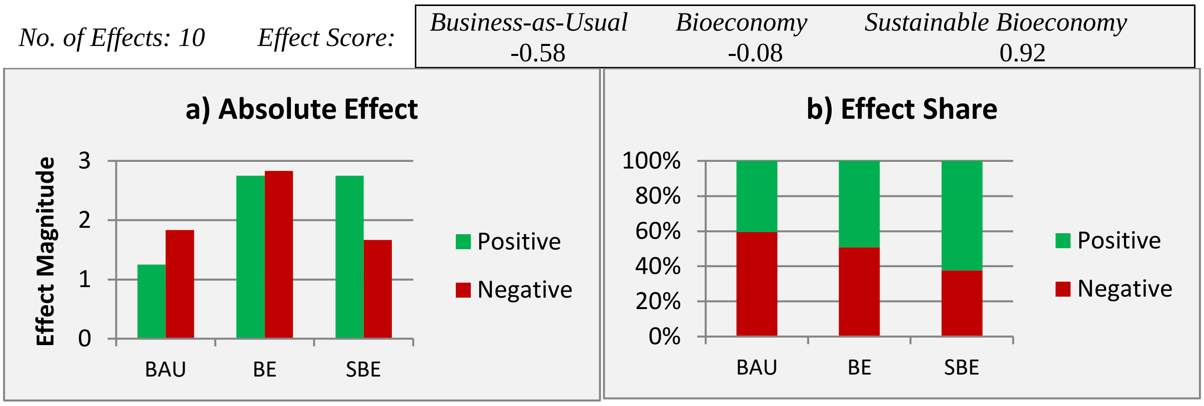

Figure 8: SDG 1. The score of the negative effects is multiplied by -1, and thus showing a positive value.

The potential negative effects of the bioeconomy on poverty are the same as of industrial agriculture and the biomass production for biofuels. The increased demand for land can lead to land grabbing, displacements, unequal distribution of land considering soil quality and loss of communal land. Furthermore, the switch of farmers from food crops towards biomass production for industrial purposes increases their dependencies on international agricultural commodity prices (Cotula et al., 2008).

However, bioeconomy activities can also help to reduce poverty through two channels. On the one hand, increasing demand for agricultural goods can lead to higher prices, and thus higher income of farmers (Cotula et al. 2008). The EU estimates an increase in world food demand of 70% by 2050 and a further steep increase in the demand of biomass for industrial purposes (European Commission, 2012). On the other, producing goods for a bioeconomy may provide new opportunities for value-added industries in developed as well as developing countries (BMEL, 2014; GBS, 2015; Scarlat et al., 2015). Hence, off-farm employments could emerge and help to alleviate poverty.

The SBE scenario assumes that the local population in biomass producing areas is not excluded from the profits of increased biomass production, and regulations hindering displacements and land grabbing are in place. However, the assumed increased production of intensive cash crops, which require a lower labor share than traditional agriculture (Deininger, 2013), and the higher dependency on global agricultural commodity markets (Cotula et al., 2008), lead to the result that in absolute numbers, Figure 8b, the negative effects of the sustainable bioeconomy are not lower than in the BAU scenario. Nevertheless, the ratio of positive and negative effects strongly improves, demonstrating that with sustainability measures, the bioeconomy has the potential to support the achievement of SDG 1 targets.

2.4 Sensitivity Analysis

Considering the aggregated effect over all SDGs, the results are robust and accounting for the number of effects in the evaluation does not really make a difference. In approach one, the bioeconomy scenario would support the SDGs with 46% of its total effect on the SDGs, while according to approach two, 48% of the impact is positive. This demonstrates the robustness of this evaluation, as with both measures the overall share of positive effects is only varying by 2 percentage points. These and further statistics as well as robustness checks are provided in the supplement.

Stronger differences between approach one and two can be found when looking at some individual SDGs, where the number of positive and negative effects strongly differ. SDG 2 provides a very good example to demonstrate differences between the two approaches, as shown in Figure 9. For this SDG the number of negative effects is much larger than of the positive effects, but the base and scenario values of the negative effects are comparable low. This leads to a domination of the positive effects in approach one. However, when accounting for the quantity of positive and negative effects in approach two, the results change significantly and the negative effects now dominate for all scenarios.

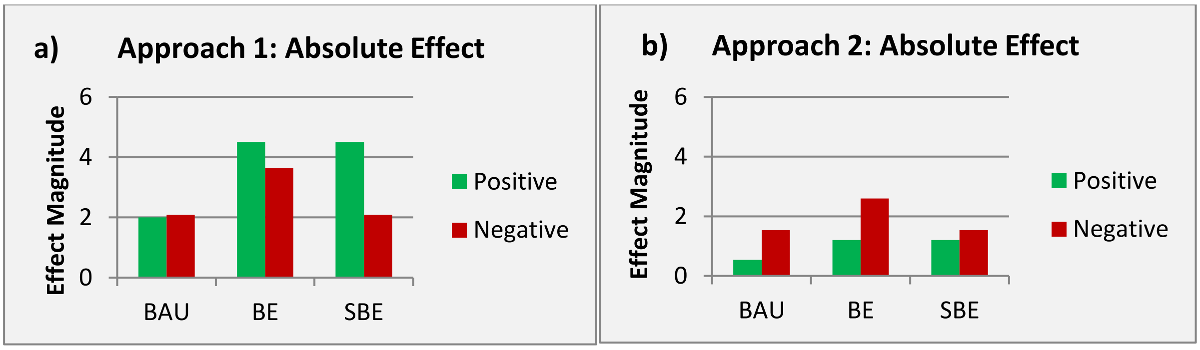

Figure 9: Absolute effects on SDG 2 for approach 1 and approach 2. The score of the negative effects is multiplied by -1, and thus showing a positive value.

Subjectivity can become a factor when accounting for the number of effects. The issue is demonstrated on the positive effect *"Productivity and efficiency increases of farm management* *techniques"*. On the one hand, productivity and efficiency can be considered as complementary and being the result of the same activities and efforts. In other words, when you increase productivity you simultaneously improve efficiency to a certain degree, and vice versa. On the other, one can argue that productivity and efficiency are complementary but still two individual attributes, and thus should be considered as two effects. In this case the sum of positive effects on SDG 2 would increase by about 30% due to the high base and scenario value of this effect. Here, also the reason for taking averages becomes visible, as the average positive effect would only increase by 15%, thus making this approach more robust to changes in the computation base.

Furthermore, as already mentioned in the method section, accounting for the number of effects promotes that a large number of weak effects can compensate a small number of strong effects. This condition has been already exemplified by the means of groundwater depletion in the approach section above.

2.5 Discussion

To evaluate the results of this study, two questions need to be answered. First, does the bioeconomy scenario support the achievement of the SDGs in general, and second can the bioeconomy scenario be regarded as an improvement to reach the SDGs compared to the situation today? Both questions are dependent on the discussion on trade-offs within the SDG concept. For the first question, assumptions on the weighting of SDG targets are relevant, and the answer to second question is conditional on the applied concept of substitutability within the SDG targets.

Assuming that a scenario can only be considered supportive if at least more than 50% of its effects are positive, the answer to the first question is straight forward. In both evaluation approaches the BE scenario tightly misses this target, and only the SBE scenario fulfills that criteria. However, this conclusion neglects the problem of not weighting SDG targets. Maybe the positive affected SDG targets have in reality more impact on the global well-being than the negative affected ones. As already mentioned above, the SDG framework does not allow the weighting of targets (UN, 2015), and thus this research follows this rule. Nevertheless, the data in the supplement provides a framework for policymakers and researchers to assign weights according to their own assumptions. Differences in the results can be used for a discussion on the practical use of the SDG targets.

Answering the second question is more complicated. Under both measurement approaches the score for the negative and positive effects in the BE scenario increase compared to the BAU scenario, while the share of positive effects increases stronger. As a result, the bioeconomy scenario can only be considered superior if substitution between positive and negative effects is allowed. The question to policymakers is, whether it reasonable to strongly increase the negative impacts on SDG targets for the sake of stronger positive impacts. Especially, if there are inequalities in the distribution of the profits. The conceptual non-substitutability of the SDGs and the ideal of a strong sustainability rather disapprove this assumption (Rickels et al., 2016; UN, 2015). However, Rickels et al. (2016) note that strictly applying the non-substitutability might hinder the application of effective policies. They argue that the specification of substitution possibility cannot solely be based on scientific reasoning, but requires normative judgement and decision (Rickels et al., 2016, p.265). The findings of this research support this statement, recommending that trade-offs from bioeconomy activities need to be ferret out, and evaluated on an individual basis.

Compared to the BE scenario, the sustainable bioeconomy scenario shows much more improvement. Thereby, the positive effects of the sustainable bioeconomy on land, the oceans, water and resource use are dominating. The negative effects can be to some degree considered as the inherent trade-offs of the SDGs, which are also highlighted by Pradhan et al. (2017). Supporting one SDG can have unavoidable negative effects on another SDG (Pradhan et al., 2017), and this is also true if the sustainable bioeconomy is used as an approach to fulfill the targets. However, the superiority of the sustainable bioeconomy is caused by the strong assumptions made and it would be appropriate to have some reasonable skepticism. The sustainable bioeconomy scenario builds on innovations which are not yet cost competitive and in different stages of development. Furthermore, it assumes that matters of international cooperation and regulation are addressed to avoid issues like negative spill-overs to other countries or cost advantages of countries which are defaulting from sustainability regulations. This requires strong efforts negotiating agreements and regulations on an international and intergovernmental scale, and thus, depends on the political will in the respective countries.

2.6 Conclusion

In a nutshell, the results of this study are in line with the recent studies on bioeconomy concepts and their sustainability in general. Without additional measures and efforts, the sustainability of the existing concepts is not assured. Furthermore, global socio-economic and ecological effects need special attention. As a net-importer of natural resources, such as land, Germany and the EU have an increased responsibility to implement sustainability criteria for their bioeconomy activities. Through global trade and production spill-over effects, their bioeconomy activities do not only affect their own regions but countries all over the world (BMEL, 2014).

Focusing on the SDGs, this analysis demonstrates that the road which we are going today will leave most of their targets unfulfilled. Also, an unsustainable bioeconomy is certainly not the best solution. Without regulations, policies and investments ensuring sustainability, or in case the increased positive effect of bioeconomy activities cannot outbalance the increased negative effect, the bioeconomy has the potential to rather restrain than support the achievement of the SDGs. However, it is beyond doubt demonstrated that the bioeconomy can have a strong potential to be sustainable if implemented wisely. A sustainable bioeconomy that includes such sustainability measures mentioned above has a strong potential to be a very useful concept to achieve the targets of the SDGs.

Complementarily, the SDGs can and should be used as an appropriate sustainability benchmark for bioeconomy concepts as well as individual bioeconomy activities. This analysis demonstrates that the establishment of the bioeconomy can have wide spread effects, which are very well captured by the wide scope of the SDGs. The German government already recognized this circumstance. In their Bioeconomy Evaluation Report 2017, the federal ministry for education and research recommended to emphasize the relevance of bioeconomy research for the achievement of the SDGs, when distributing future research assistant measures within the bioeconomy research portfolio. On this way the bioeconomy should be brought into line with the national sustainability goals, national climate and environmental protection targets, and the SDGs (Hüsing et al., 2017). This paper provides an overview on the strength and weaknesses of the bioeconomy in terms of the SGDs and highlights aspects that require increased efforts and further research. As a next step, bioeconomy activities need to be analyzed quantitatively to evaluate their individual effects on the respective targets. This work indicates areas to concentrate on by further research.

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A.2 Appendix

A.2.1 Analysis of the individual SDGs

A.2.1.1 SDG 2 “Zero Hunger”

No. of Effects: 15	*Effect Score:*	*Business-as-Usual*	*Bioeconomy*	*Sustainable Bioeconomy*
		-0.1	1	2.4

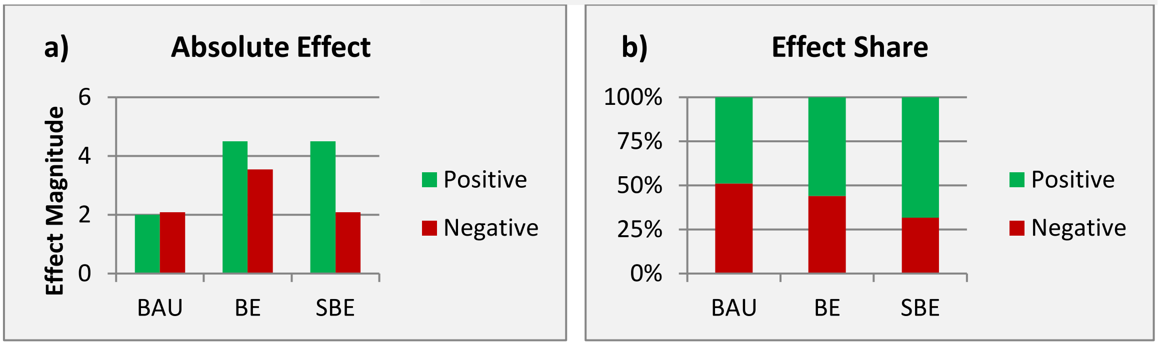

Figure A1: SDG2. The score of the negative effects is multiplied by -1, and thus showing a positive value.

The ratio of positive and negative effects in the bioeconomy scenario is only slightly better than under BAU assumptions, but the effect score strongly improves for the BE and SBE scenario. The higher score of positive effects of the bioeconomy scenarios is mainly caused by assumed investments into agricultural productivity, cultivation of superior and climate resistant crops, and increased incomes. Nevertheless, the concentration on the cultivation of biomass for industrial purposes can have severe negative effects on food security. The domestic reduction of food crop cultivation can lead to a loss of food self-sufficiency, and the local population would be depending on imports which are potentially marked by volatile global market prices (McMicheal, 2012). Furthermore, while increased demand for biomass can lead to higher incomes of farmers, increased food prices hurt poor net food consumers. This trade-off is already observed as a result of the expansive cultivation of biofuel crops (Cotula et al., 2008). The bioeconomy concepts recognize this problem and suggest three solutions. First, intensification and biotechnology shall increase yields per hectare and improve the climate resistance of crops, and investments into storage and transportation should reduce post-harvest losses. Second, marginal land is used for agricultural activities, whereby plant modifications through biotechnology make some varieties more undemanding in terms of soil quality. And finally, wastes and residual material are planned to satisfy a large share of industrial biomass demand (BMEL, 2014; European Commission, 2012).

The industry and biotechnology sector is still developing the above mentioned solutions. Furthermore, especially for the use of marginal land two shortcomings need to be acknowledged. Marginal land unused for large-scale production often only seems to be idle on first sight. In fact this land can have crucial value for other purposes, like for small-scale growers without formal land titles, livestock grazing, biodiversity, and as a source for game and various natural products (Smolker, 2008). Second, large-scale land investments tend to concentrate on relative fertile land. In case small-scale farmers who cultivate food crops are shifted to use less fertile marginal land areas, their yields may be lower, especially if they cannot afford, or get access to, the seeds modified for low soil quality. This leads to less food production and can be a thread for local food security (Cotula et al., 2008).

Similar to SDG 1, the bioeconomy and sustainable bioeconomy have the same positive effects, but the sustainable bioeconomy implements measures to reduce negative socio-economic impacts of bioeconomy activities, like land-grabbing and increased food prices. However, amongst others, the loss of idle land and increased global market dependencies are also expected in a SBE scenario, leading to the result that, in sum even the sustainable bioeconomy scenario does not reduce the score of negative effects compared to the BAU scenario.

A.2.1.2 SDG 3 "Good health and well-being"

No. of Effects: 4	*Effect Score:*	*Business-as-Usual* -1	*Bioeconomy* -1	*Sustainable Bioeconomy* 1

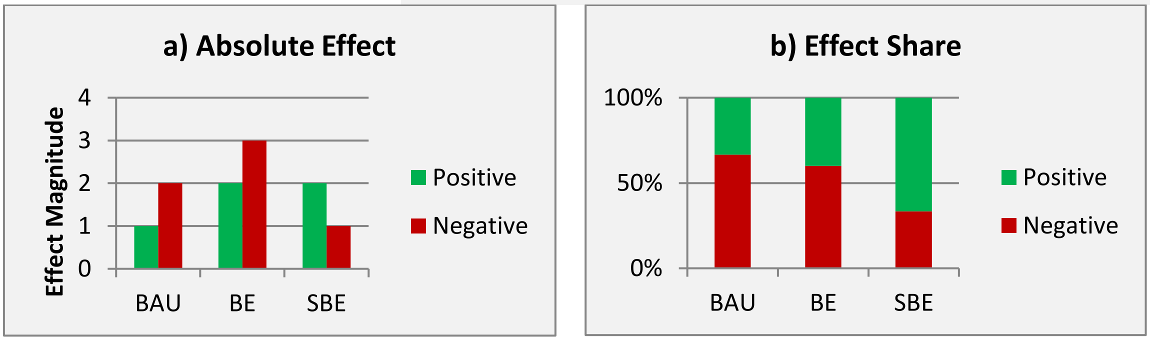

Figure A2: SDG 3. The score of the negative effects is multiplied by -1, and thus showing a positive value.

Only four effects are found to be related to the targets of SDG 3. On the positive side, the bioeconomy aims to reduce air pollution, and thus to reduce the number of health issues caused by air pollution (BMEL, 2014). Second, it is assumed that investments into health biotechnology research and life science will strongly increase in a bioeconomy, which will have beneficial effects on the health of the human population as well (OECD, 2009).

The negative health effects are caused by chemical pollution as side effects from large scale intensive biomass production. Here, direct health issues caused by chemical fertilizers and pesticides are considered, as well as indirect health problems from the consumption of nitrate polluted water (Alavanja et al., 2004; Jamaludin et al., 2013). While increased biomass production in the bioeconomy scenario would also increase the application of chemical inputs and nitrate fertilizers, a sustainable bioeconomy scenario must be based on agricultural practices and inputs which avoid such negative health impacts. Thus, while the positive and negative effects are scaled up in the BE scenario, leading to an unchanged effect score compared to the BAU scenario, in the SBE scenario the negative health effects are reduced due to more sustainable and health-friendly agricultural techniques. As an example, Larsen and Noack (2017) analyse that crop diversity can significantly reduce insecticide use, while its magnitude depends on the crop type.

A.2.1.3 SDG 6 "Clean water and sanitation"

No. of Effects: 5	*Effect Score:*	*Business-as-Usual*	*Bioeconomy*	*Sustainable Bioeconomy*
		-3.5	-1.8	2.8

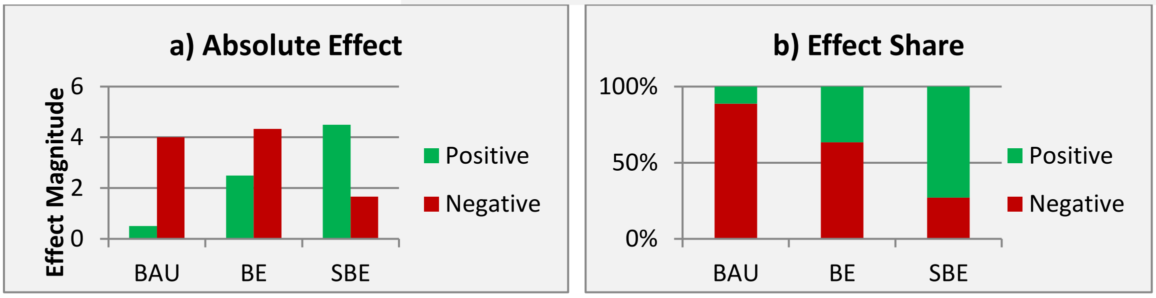

Figure A3: SDG 6. The score of the negative effects is multiplied by -1, and thus showing a positive value.

Water is an essential element for agricultural production and therefore strongly affected by agricultural activities. As already addressed in the bioeconomy concepts, more efficient production methods, varieties with less water requirements, and an in general sustainable and efficient use of water resources by bioeconomy activities can support the achievement of goal 6. Moraes et al. (2011) elaborate applicable policies and instruments improving the sustainability of water use for bioenergy production. However, if the efficiency gains in water consumption do not totally substitute the fresh water demand from increased production, this goal will be negatively affected. As the bioeconomy concepts rely on input-based intensification, the same has to be considered for the absolute amount of fertilizer and pesticide used. If the relative use per hectare or per unit yield decreases but additional areas are cultivated regional water pollution may get more severe (Zilberman et al. , 2013). Therefore, it is assumed that under the BE and SBE scenario more water use efficient methods are implemented, while a large share of the profits thereof are consumed by increased production area.

The sustainable bioeconomy is based on a highly sustainable use of natural resources, as well as reduced water use and pollution due to alternative sustainable agricultural practices. Furthermore, compared to the bioeconomy and BAU scenario, the sustainable bioeconomy scenario does not allow negative effects on the access to water for the local population. This causes the larger share of positive effects in Figure A3a as well as the strongly increased effect score. Biomass production for bioenergy showed that local water users might lose out when biofuel plantations are established through government sales of concessions and access to water for the population has not been established legally (Moraes et al. , 2011). In addition, should a water shortage occur, contractual agreements on water rights between the investor and the local government guarantees him priority access. This can become highly relevant considering long-term contracts and the future effects of climate change on water availability (Cotula L., 2011; Smaller & Mann, 2009). Thus, sustainable socio-economic measures play a crucial role for achieving SDG6, and they are the main factors to distinguish the SBE from the BE and BAU scenario.

A.2.1.4 SDG 7 "Affordable and clean energy"

No. of Effects: 2	*Effect Score:*	*Business-as-Usual* 2	*Bioeconomy* 6	*Sustainable Bioeconomy* 6

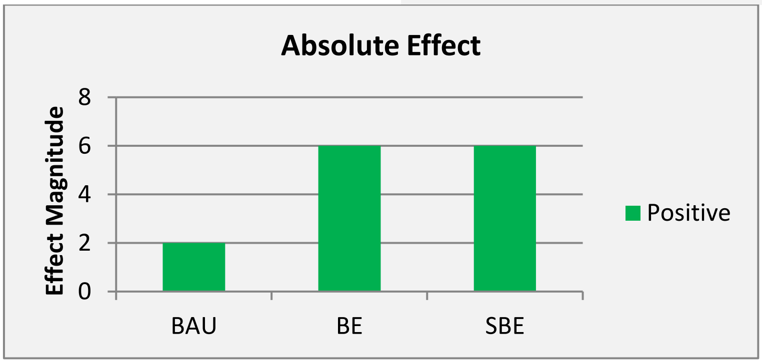

Figure A4: SDG 7. No negative effects for this SDG. Shares are 100% positive.

Targets 7.2 and 7.3 aim at increasing the share of renewable energy in the global energy mix and doubling the rate of improvement in energy efficiency. Both targets are strongly in line with the idea of the bioeconomy and equally reflected in the BE and SBE scenario. The increased and efficient use of renewable energy is a core value of the concepts (BMEL, 2014; European Commission, 2012; OECD, 2009). The literature review did not detect evidences of potential negative effects from bioeconomy activities for this SDG. The large difference between the BAU and the two bioeconomy scenarios is caused by the price competitiveness of fossil resources. Without efforts making bioenergy and other renewables more competitive, fossil resources will remain playing a dominant role in energy production (Bruckner et al., 2014; OECD, 2008).

A.2.1.5 SDG 9 "Industry, Innovation and Infrastructure"

No. of Effects: 4	*Effect Score:*	*Business-as-Usual*	*Bioeconomy*	*Sustainable Bioeconomy*
		0.5	2.25	2.75

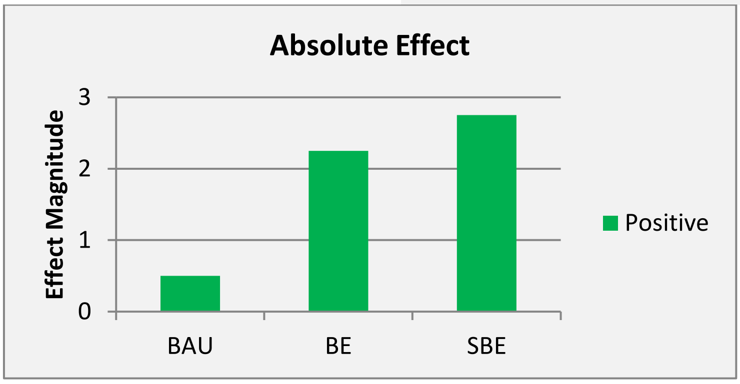

Figure A5: SDG 9. No negative effects for this SDG. Shares are 100% positive

Making industries sustainable, more resource efficient and environmental friendly is a core pillar of the bioeconomy. As well, investments into scientific research and value addition are taking place. Those factors are supporting the targets of SDG 9. Also here, no negative effects from bioeconomy activities have been discovered, and the different scenarios only differ in the intensity of their positive effects. The effects score of the SBE scenario is larger than of the BE scenario, because it is assumed that under the SBE scenario stronger efforts for a sustainable efficient production and use of natural resources are made.

A.2.1.6 SDG 12 "Responsible Production and Consumption"

No. of Effects: 6	*Effect Score:*	*Business-as-Usual* -1.4	*Bioeconomy* 0.2	*Sustainable Bioeconomy* 2.8

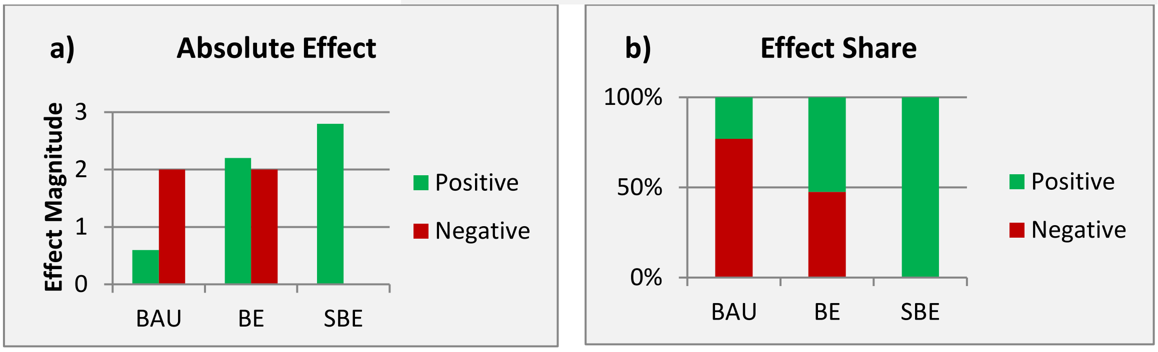

Figure A6: SGD 12. The score of the negative effects is multiplied by -1, and thus showing a positive value.

Targets 12.1 to 12.5 are perfectly in line with the aim of a bioeconomy. As an example, cascade use of resources is a core measure of the bioeconomy, which in turn contributes to the efficient use of resources in target 12.2 and waste reduction in target 12.5. In the same manner life-cycle analysis (LCA) is crucial for the bioeconomy (BMEL, 2014; European Commission, 2012) and simultaneously a good measure to reach the targets of SDG 12. However, here the bioeconomy and the sustainable bioeconomy scenario differ due to a sustainable use of natural resources in a sustainable bioeconomy scenario. The positive effects of the BE and SBE scenario are rooted in the reduction and more environmental friendly management of waste as well as investments into more climate friendly production.

A.2.1.7 SDG 13 "Climate Action & Paris Agreement"

No. of Effects: 3	*Effect Score:*	*Business-as-Usual* -2.5	*Bioeconomy* -3	*Sustainable Bioeconomy* 1

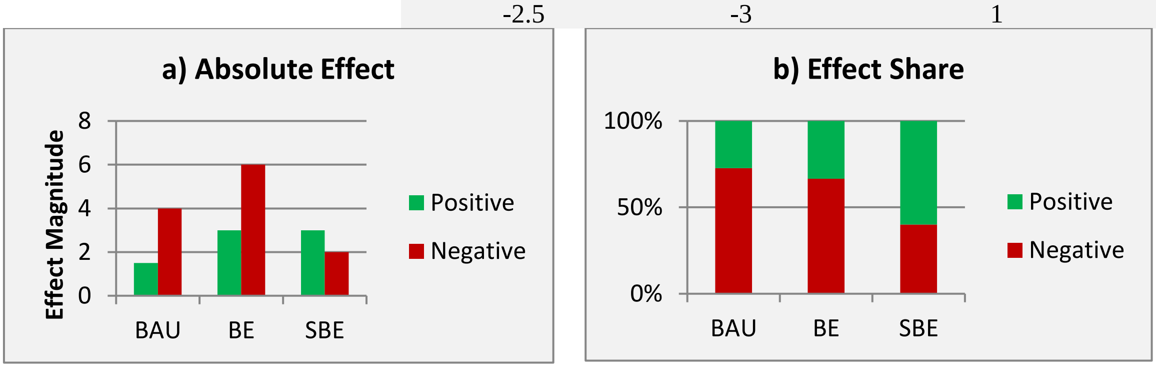

Figure A7: SDG 13. The score of the negative effects is multiplied by -1, and thus showing a positive value.

Target 13.1 aims to strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries. The development of climate resistant crops is part of the bioeconomy and complementary to this target. For other climate related aspects, SDG 13 refers to the UN Framework Convention on Climate Change as the primary international intergovernmental forum for negotiating the global response to climate change (UN, 2015). While leaving out climate effects would mean to neglect a large and important dimension of the bioeconomy, evaluating the effect of the bioeconomy on the Paris agreement would fill a paper by itself. As a compromise, this paper includes the effect of the bioeconomy on article 2 of the Paris agreement, denoting its main purpose.

The negative effects of the bioeconomy and the sustainable bioeconomy differ due to GHG emissions from agricultural activities. Several studies showed that biofuel production can emit more GHGs in the short term than the use of fossil fuels, which is mainly driven by direct and indirect land-use change (Fargione et al., 2008; Kim et al., 2009; Searchinger, et al., 2008). While GHG emissions from agricultural practices in general are addressed by the bioeconomy concepts, only the EU mentions the problems caused by land use change as a potential negative aspect, without suggesting any solution (BMBF, 2010; European Commission, 2012). Since the bioeconomy relies on the cultivation of biomass for industrial purposes, it can be assumed that land-use change and land expansion takes place, having severe negative effects on the targets of the Paris agreement. Therefore, compared to the BAU scenario, the bioeconomy scenario supports the SDG targets through climate resilience and reduced GHG emissions from fossil fuels, but hurt the targets by increased GHG emissions from land-use change leading to a slightly worse effect score. In the sustainable bioeconomy scenario it needs to be evaluated and assured via LCA that replacing fossil resources by biological resources does not lead to higher GHG emissions.

A.2.1.8 SDG 14 "Life below Water"

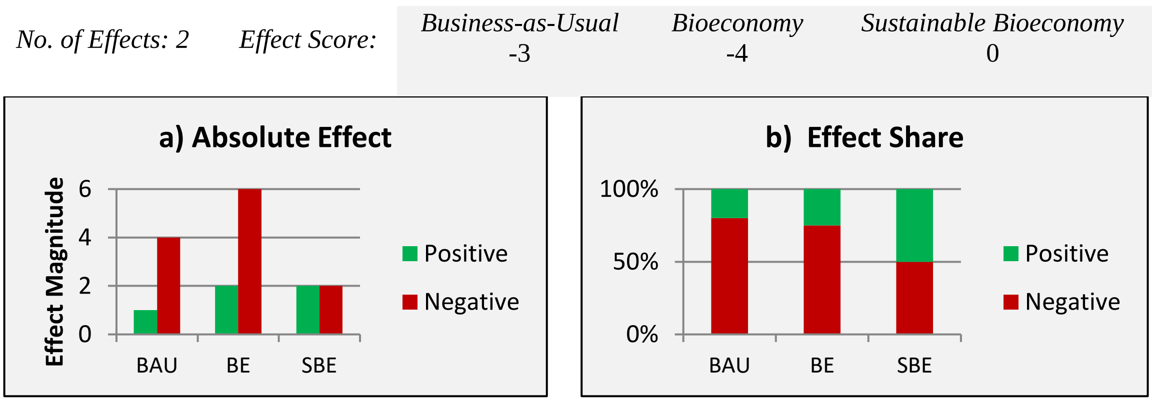

Figure A8: SDG 14. The score of the negative effects is multiplied by -1, and thus showing a positive value.

For SDG 14 we only have two effects. First, agricultural runoff is a serious problem for coastal areas. Coastal eutrophication is predominantly caused by nitrogen pollution resulting from agricultural activities. This can lead to hypoxia and anoxia, habitat degradation, alteration of food-web structure, loss of biodiversity and harmful algal blooms (Howarth, 2008). If the efficiency gains in fertilizer use are smaller than the additional fertilizer use through an increased production area, this goal will be negatively affected. Increasing productivity and production, while reducing the agricultural runoff into rivers and oceans, is a major challenge for reaching SDG 14.

Second, sustainable fishing practices according to the principle of maximum long-term yield play an important role in the bioeconomy as well. All three bioeconomy concepts include the application of the Common Fishery Policies (CFP) in order to maintain wildlife fish-stocks and aquatic biodiversity. Furthermore, technological innovations and biotechnology shall be used to improve aquaculture production, make it more cost efficient and minimize negative environmental effects (BMEL, 2014; European Commission, 2012; OECD, 2009). As an example, aquaculture recycling units, which use waste heat from biogas facilities and reuse the cleaned water, are becoming increasingly economically attractive and can produce less expensive fish on a large scale (BMEL, 2014).

The bioeconomy scenario is not a real improvement compared to the BAU scenario, since the score for positive and negative effects both double, resulting in an increased effect score. The sustainable bioeconomy scenario is superior as it is assumed that strong measures to reduce nutrients run-off into coastal areas are implemented. However, is it not assumed that the SBE scenario can completely relinquish the use and release of nitrogen. As a result, positive effects on SDG 14 from sustainable aquaculture and negative effects from nitrogen pollution cancel out.

A.2.2 Supplementary Material

A.2.2.1 Evaluation Data

Table A1: Data and assumptions for the baseline evaluation

SDG	Type of Effect	Effect	Base Value of Effect	Affected Targets	No. Targets	Scenario Values BAU	BE	SBE	Sources	Assumptions
SDG 1	Positive	Increased biomass demand / Higher prices	1	1.1, 1.2	2	1	2	2	Cotula(2008); Landis(2008); Hertel(2013); BMEL(2014)	Considering the global population growth in the next decades, biomass demand and prices are expected to increase under the BAU scenario. This will be even stronger under both bioeconomy scenarios as they imply additional demand for biomass. Though, the increase of demand will not be fully reflected by the prices, as they will also be affected by increased supply through production and productivity increases.
		Productivity and efficiency increases of farm managment techniques	1	1.1, 1.2	2	1	3	3	Deininger (2013); OECD (2009); EU(2012); BMEL(2014)	High public investments and policies incentivizing private investments into research, especially biotechnology research, as part of the bioeconomy policies, will foster technological developments and advances in resource efficient farm management. This is a core value of the bioeconomy concepts.
		Opportunities for value added production	2	1.1, 1.2	2	1	2	2	Cotula(2008); Deininger(2013); OECD(2009); EU(2012); BMEL(2014)	The conversion of biomass into biofuels already provides new job opportunities in the value-added sector. Under the bioeconomy concepts it is predicted that much more jobs are created in this sector. The creation of value addition opportunities is a fundamental argument of the supporters for a bioeconomy. This can have a strong positive effects on employment and income.

		Climate resistant crops / climate resilience	1	1.5	1	1	2	2	Varshney(2011); OECD(2009); BMEL(2014)	Investments into research should foster development of climate resistant crops under the bioeconomy scenarios.
		Score positive effects				1.25	2.75	2.75		
	Negative	Displacement	-1	1.1, 1.2, 1.4	3	2	3	1	Cotula(2008); Deininger(2013); McMicheal(2012); Tscharnke(2012); BMEL(2014)	Land grabbing and displacements of rural families is already a severe issue today. It will become more severe if land pressure increases as under the EU/OECD scenario. A sustainable bioeconomy needs to respect the local population and let them equally partake in the biomass production, and thus profit from the bioeconomy.
		Land Grabbing	-1	1.1, 1.2, 1.4	3	2	3	1	Cotula(2008); Deininger(2013); McMicheal(2012); Tscharnke(2012); BMEL(2014)	
		Input intensive agriculture with low labor share	-1	1.1, 1.2	2	2	3	3	Cotula(2008); Deininger(2013); McMicheal(2012); OECD(2009)	The current trend in global agriculture is going for further intensification and input - based approaches. Also, both bioeconomy scenarios are building on biotechnology crops, input intensive farm management techniques, and efficient monocultures. As those tend to have a much lower manual labor share as common farm management approaches, strong negative effects on rural employment can be expected.

		Land inequality (soil quality)	-1	1.1, 1.2, 1.4	3		2		3		1		Cotula(2008);		Large scale investors tend to get access to land with a high soil quality, while the local population has to move their fields to areas with low soil quality. This will concern more small scale farms if the pressure on land and the investment activities increase as a result of the bioeconomy. A sustainable bioeconomy has to assure that land distribution does not marginalize the local population. However, total land equality in terms of soil quality between small-scale farmers and large scale investors would be unrealistic, even under a sustainable bioeconomy scenario.
		Loss of communal land	-1	1.4	1		1		2		1		Cotula(2008); Deininger(2013); McMicheal(2012); BMEL(2014)		Already today in many regions communal land is being privatized and sold to investors. This may increase under the bioeconomy scenarios. However, communal land may be crucial for the livlihood of the local population. The sustainable bioeconomy needs to respect this fact.
		Dependencies on global markets	-1	1.1, 1.2	2		2		3		3		Swinnen(2013); Cotula(2008); McMicheal(2012);		With an increased agricultural specialization and concentration on global traded agricultural commodities, countries, regions and farmers make themselves more dependend on the global markets. Thereby price fluctuations and price volatility can become a risk for a secure income.
		Score negative effects					-1.83		-2.83		-1.67				
		Score negative effects * (-1)					1.83		2.83		1.67				
	Effect Score						-0.58		-0.08		1.08				

SDG 2	Positive	Productivity and efficiency increases of farm managment techniques	2	2.3	1	1	3	3	Deininger(2013); OECD(2009); EU(2012); BMEL(2014)	See above.
		Opportunities for value added production	2	2.3	1	1	2	2	Cotula(2008); Deininger(2013); OECD(2009); EU(2012); BMEL(2014)	See above.
		More nutritious crops	2	2.2	1	1	2	2	Johns(2007); Stein(2009); Meenakshi(2010); OECD(2009); EU(2012); BMEL(2014)	Biotechnology provides techniques to improve the nutritious value of food and in particular staple crops. Since first crops have already been developed (e.g. golden rice) some further progress is assumed under BAU. Strong investments into biotechnology research in a BE and SBE scenario would foster the development of such crops.
		Climate resistant crops / climate resilience	2	2.4	1	1	2	2	Varshney(2011); OECD(2009)	See above.
		Score positive effects				2	4.5	4.5		

	Negative	Increased Food Prices	-1	2.1, 2.2	2		2		3		1		Cotula(2008); Landis(2008); Hertel(2013); Tscharnke(2012); EU(2012); BMEL(2014)		As increased prices for biomass benefit farmers, they might hurt consumers. Recent developments showed that biomass production for biofuels led to higher food prices. Thus, a higher demand for biomass in a bioeconomy scenario would lead to even higher food prices. The bioeconomy concepts already emphasize this problem by stating that no food crops should be used for bioeconomy technologies, but preferentially waste materials and plant residuals. However, this will probably not sufficient. As a result, increased demand for biomass will still increase the land rent which makes food production more costly. The bioeconomy concepts offer no conclusive solution to this problem yet. But this is required to make a bioeconomy sustainable.
		Displacement	-1	2.1, 2.3	3		2		3		1		Cotula(2008); Deininger(2013); McMicheal(2012); Tscharnke(2012); BMEL(2014)		See above.
		Land Grabbing	-1	2.1, 2.3	2		2		3		1		Cotula(2008); Deininger(2013); McMicheal(2012); Tscharnke(2012); BMEL(2014)		See above.
		Land inequality (soil quality)	-1	2.3	1		2		3		1		Cotula(2008);		See above.
		Loss of communal land	-1	2.3	1		1		2		1		Cotula(2008); Deininger(2013); McMicheal(2012); BMEL(2014)		See above.

		Dependencies on global markets	-1	2.1	1		2		3		3		Swinnen(2013); Cotula(2008); McMicheal(2012);		See above.
		Loss of regional food self-sufficiency	-1	2.1	1		1		2		2		Cotula(2008); McMicheal(2012);		Switching from cultivating crops for food to crops for industrial use within the bioeconomy, can lead to a loss of food self-sufficiency in a region. If functioning food markets and food trade with neighboring regions and countries are in place this may not be a problem. However, if a food crisis occurs the region has no opportunity to protect their population with policies and is dependent on the policies of other regions (e.g. (no)export ban).
		Patents and genetic resources not shared equitable	-2	2.5	1		1		3		3		Moschini (1997); Blakeney(2010); OECD(2009); EU(2012); BMEL(2014)		Patents are considered as a key incentive for private investments into biotechnology. As the bioeconomy is based on biotechnology, patents and intellectual property rights will play a crucial role, and it is rather unlikely that patents and genetic resources will be shared equitable.
		Use of "idle" land	-1	2.3	1		1		3		3		Cotulla(2008); Smolker(2008); Tilman(2009); OECD(2009); EU(2012); BMEL(2014)		Marginal land often provides important "hidden" services for the environment and local population. It can provide amongst others firewood, game and important ecosystem services. A core approach of the bioeconomy is to select and develop crops which can be grown efficiently and on a large scale on marginal land with low soil quality. As a result the local population would lose access to this land and its services.

		Soil overuse	-2	2.4	1	2	3	1	Juerges(2016); Chapell(2011); Banward(2011); BMEL(2014);	Soils are already severely threatened by ongoing land-use and degradation processes. The increased demand for agricultural and forest products through the bioeconomy would put further pressure on soils. A sustainable bioeconomy aims to employ soil management techniques as well as soil governance structures that maintain the long-term soil quality.
		Reduction of Biodiversity	-2	2.5	1	2	3	1	Sheppard(2011); Lewandowski(2015); Danielsen(2008); Landis(2008); BMEL(2014)	Monocultures and large scale industrial agriculture reduce biodiversity. A sustainable bioeconomy must also consider alternative agricultural management practices that maintain biodiversity, such as agroecological approaches.
		Score negative effects				-2.09	-3.64	-2.09		
		Score negative effects * (-1)				2.09	3.64	2.09		
	Effect Score					-0.09	0.86	2.41		
SDG 3	Positive	Development of new drugs	1	3.3	1	1	2	2	GBS (2015); OECD(2009); BMEL(2014)	Health care is a key bioeconomy sector. Increased investment into life science and health biotechnology research enable the development of new drugs and therapies.
		Reduce Air Pollution	1	3.9	1	1	2	2	OECD(2009); BMEL(2014)	Air pollution from industrial applications and burning fossil fuels causes serious health issues. As this has already been recognized and measures for the reduction of air pollution are slowly implemented, the BE and SBE scenario assumes stronger improvements through clean industry technologies and the use of alternative fuels.
		Score positive effects				1	2	2		

	Negative	Farmer health pestizide pollution	-1	3.9	1	2	3	1	Alavanja(2004); Kamel (2004); McCauley (2006);	The contact with herbicides and pesticides can have sever negative health effects for farmers. The BE scenario assumes stronger use of biotech crops that require the intensive application of chemical inputs. A SBE scenario needs to strongly reduce the toxicity and the use of such inputs.
		Negative health effects from nitrate polluted water consumption	-1	3.9	1	2	3	1	Rojas (2015); Wongsanit (2015); Jamaludin(2013);	Water sheds and ground water near regions with intensive industrial agriculture are heavily polluted with nitrate. A strong nitrate concentration in the drinking water has shown to cause negative health effects for humans. While the BE scenario assumes even an increase, a SBE must decrease nitrate pollution.
		Score negative effects				-2	-3	-1		
		Score negative effects * (-1)				2	3	1		
	Effect Score					-1	-1	1		
SDG 6	Positive	Productivity and efficiency increases of farm managment techniques	1	6.3, 6.4, 6.6	3	1	3	3	Deininger(2013); OECD(2009); EU(2012); BMEL(2014)	This is one of the main measures to achieve a bioeconomy.
		Sustainable and efficient production and use of natural resources	2	6.3, 6.4, 6.6	3	0	1	3	OECD(2009); EU(2012); BMEL(2014)	The bioeconomy aims to establish an efficient production and use of natural resources. This will be made sustainable in the sustainable bioeconomy.
						0.5	2.5	4.5		
	Negative	Groundwater depletion / Increased water usage	-2	6.4, 6.6	2	3	3	1	Gheewala(2011); Moraes(2011); Rosegrant(2013); Raghu(2011); BMEL(2014)	Groundwater depletion is already a pressing issue. A sustainable bioeconomy needs to address and mitigate this problem.

		Water pollution	-2	6.3	1	2	2	1	Gheewala(2011); Moraes(2011); Rosegrant(2013); Robertson(2009); BMEL(2014)	Water pollution is to a large extent caused by agricultural activities. A sustainable bioeconomy needs to address and mitigate this problem.
		Limited access to water	-1	6.1	1	2	3	1	Moraes(2011); BMEL(2014)	In some areas of the world small-holders and the deprived rural population have limited access to water. Higher water consumption by agricultural activities in a bioeconomy will foster this issue. A sustainable bioeconomy must not allow the rural population to be disadvantaged compared to agricultural companies in terms of access to water.
		Score negative effects				-4	-4.33	-1.67		
		Score negative effects * (-1)				4	4.33	1.67		
	Effect Score					-3.5	-1.83	2.83		
SDG 7	Positive	Increased use of biofuels and bioenergy	2	7.2	1	1	3	3	OECD(2009); EU(2012); BMEL(2014)	The bioeconomy is based on an increased use of biofuels and bioenergy.
		Investments into energy efficiency	2	7.3	1	1	3	3	OECD(2009); EU(2012); BMEL(2014)	Strong investment activities in the bioeconomy.
	Effect Score					2	6	6		
SDG 8	Positive	Opportunities for value added production	2	8.2	1	1	2	2	Cotula(2008); Deininger(2013); OECD(2009); EU(2012); BMEL(2014)	See above.

		Investments into technologies	1	8.2	1	1	3	3	OECD(2009); EU(2012); BMEL(2014)	Strong investment activities in the bioeconomy.
		Decoupeling economic growth from environmental degradation	2	8.4	1	0	1	3	OECD(2009); EU(2012); BMEL(2014)	It is assumed that with a sustainable bioeconomy this goal will be reached faster than with an unstainable bioeconomy.
		Score positive effects				1	3	4.33		
	Negative	Input intensive agriculture with low labor share	-1	8.5	1	1	3	3	Cotula(2008); Deininger(2013); McMicheal(2012); OECD(2009)	See above.
		Not decoupeling economic growth from environmental degradation	-2	8.4	1	2	0	0	Stern (2004); Grossman (1995); OECD(2009); EU(2012); BMEL(2014)	In the BAU scenario economic growth, at least in developing and transitional countries, will further lead to resource depletion and environmental degradation.
		Score negative effects				-2.5	-1.5	-1.5		
		Score negative effects * (-1)				2.5	1.5	1.5		
	Effect Score					-1.5	1.5	2.83		
SDG 9	Positive	Sustainable and efficient production and use of natural resources	1	9.4	1	0	1	3	OECD(2009); EU(2012); BMEL(2014)	See above.
		Investment into more climate friendly production technologies	1	9.4	1	0	3	3	OECD(2009); EU(2012); BMEL(2014)	Strong investment activities in the bioeconomy.

		Opportunities for value added production	1	9.2	1	1	2	2	Cotula(2008); Deininger(2013); OECD(2009); EU(2012); BMEL(2014)	See above.
		Investments into scientific research	1	9.5	1	1	3	3	OECD(2009); EU(2012); BMEL(2014)	Strong investment activities in the bioeconomy.
	Effect Score					0.5	2.25	2.75		
SDG 12	Positive	More environment friendly resource and waste management.	1	12.1, 12.3, 12.5	3	0	1	2	OECD(2009); EU(2012); BMEL(2014)	It is assumed that the SBE stronger emphasizes an environmental friendly resource use than the BE. As an example, the BE relies on high input agriculture which is not really environmental friendly under current circumstances.
		Sustainable and efficient production and use of natural resources	1	12.1, 12.2, 12.4	3	0	1	3	OECD(2009); EU(2012); BMEL(2014)	See above.
		Reduction of waste	2	12.5	1	1	2	2	OECD(2009); EU(2012); BMEL(2014)	Through cascade use and the use of waste for energy and industrial production, the bioeconomy will reduce waste.
		Investment into more climate friendly production technologies	1	12.1	1	1	3	3	OECD(2009); EU(2012); BMEL(2014)	Strong investment activities in the bioeconomy.
		Promote more climate friendly consumption habits	1	12.1	1	0	2	2	OECD(2009); EU(2012); BMEL(2014)	During the transition towards a bioeconomy, social acceptance of bio-based products must be achieved which is complementary to promoting more climate friendly consumption habits.
		Score positive effects				0.6	2.2	2.8		

	Negative	Unsustainable use of natural resources	-1	12.1, 12.2	1	2	2	0	Hoekstra (2014); Galli(2012); Giljum(2011); EU(2012); BMEL(2014)	Only the sustainable bioeconomy would aim to use natural resources sustainable.
		Score negative effects				-2	-2	0		
		Score negative effects * (-1)				2	2	0		
	Effect Score					-1.4	0.2	2.8		
SDG 13	Positive	Climate resistant crops / climate resilience	1	13.1	1	1	2	2	Varshney(2011); OECD(2009);	See above.
		Lower GHG emissions from reduced use of fossil fuels	2	COP	1	1	2	2	OECD(2009); EU(2012); BMEL(2014)	While already under the BAU a reduction of fossil fuels is propagated, e.g. Biofuel quotas, this will be stronger emphasized in both bioeconomy scenarios.
		Score positive effects				1.5	3	3		
	Negative	GHG emission from land-use change	-2	COP	1	2	3	1	Searchinger(2008); Kim(2009); Fargione(2008); Danielsen(2008); EU(2012); BMEL(2014)	Land-use change, in particular for oil crops, has shown to be a major source for GHG emissions. Since under the BE scenario the demand for biomass increases, it is assumed that further land conversion takes place. A sustainable bioeconomy must assure that land conversion does not emit further GHGs and that sensitive areas, such as peat lands, are protected and not converted.
		Score negative effects				-4	-6	-2		
		Score negative effects * (-1)				4	6	2		
	Effect Score					-2.5	-3	1		
SDG 14	Positive	Substitute capture fishing by aquaculture	1	14.4	1	1	2	2	OECD(2009); EU(2012); BMEL(2014)	The bioeconomy aims to reduce pressure on wild fish by strongly investments into better aquaculture technologies.
		Score positive effects				1	2	2		

	Negative	Nutrients run-off into coastal areas	-2	14.1	1	2	3	1	Howarth(2008); Beman(2005); Robertson(2009); BMEL(2014)	Without sustainability guidelines and measures, increased production will lead to increased nutrient run-off. Therefore, the BE scenario would be worse than the BAU scenario.
		Score negative effects				-4	-6	-2		
		Score negative effects * (-1)				4	6	2		
	Effect Score					-3	-4	0		
SDG 15	Positive	Stop of deforestation, land and soil degradation, desertification	2	15.1, 15.2, 15.3	3	0	0	2	OECD(2009); EU(2012); BMEL(2014)	The bioeconomy concepts recognize trees as a highly valuable biomass resource, in particular for lignin-cellulosic applications like biofuels. The bioeconomy criteria to only use sustainable managed forests, promotes the afforestation for commercial use in some region as well as allows for the deforestation in other regions. Similar, the goal of the bioeconomy is to use bio-based raw materials without compromising ecosystems, SDG 15 emphasizes that ecosystems need to be restored. The sustainable bioeconomy employs agricultural measures to stop deforestation, land and soil degradation and desertification.
		Reduce degradation of natural habitats and ecosystems	2	15.1, 15.5	2	0	0	2	Raghu(2011); OECD(2009); EU(2012); BMEL(2014)	The aim of a sustainable bioeconomy is to maintain natural habitats and ecosystems.
		Score positive effects				0	0	4		

		Land expansion	-2	15.1, 15.2, 15.3, 15.5	4		2		3		2		Cotula(2008); Deininger(2013); Lewandowski(2015); Hertel(2013); EU(2012); BMEL(2014)		The increasing demand for agricultural products is already making land expansion more and more attractive. An unsustainable bioeconomy would further increase land pressure. The sustainable bioeconomy would need to protect sensible ecosystems and avoid further land expansions.
	Negative	Land degradation	-2	15.1, 15.2, 15.3, 15.5	4		2		3		0		Juerges(2016); Chapell(2012); Banward(2011); BMEL(2014)		A sustainable bioeconomy should be based on sustainable land management including measurements against long term land degradation.
		Potential distribution of invasive plants	-2	15.8	1		2		3		3		Ferdinands(2011); Sheppard(2011); Raghu(2011); OECD(2009); BMEL(2014)		The investments into biotechnology-based crops would foster the application of those. Thus, the distribution of potential invasive plants would be higher for the bioeconomy scenarios than for the BAU scenario
		Score negative effects					-4		-6		-3.33				
		Score negative effects * (-1)					4		6		3.33				
	Effect Score						-4		-6		0.67				

A.2.2.2 Search Words

Table A2: Search words for the literature search

Bioeconomy +	productivity land use rural development sustainable sustainable development goals health water
Biofuels +	land grab farm income contract farming
Agriculture +	environment land degradation
Health +	pesticides nitrate water
Unsustainable resource use	
Biofortification	

A.2.3 Sensitivity Analysis

Table A3: Definition of evaluation methods

Method	*Base*	*Approach 2*	*Median*	*Sensitivity A*	*Sensitivity B*
Definition	Base method as defined in full text.	Approach 2 as defined in full text	Difference to base method: Instead of means, the median is taken.	Difference to base method: Base value can only vary between -1 and 1.	Difference to base method: Scenario value can only vary between 0 and 2.

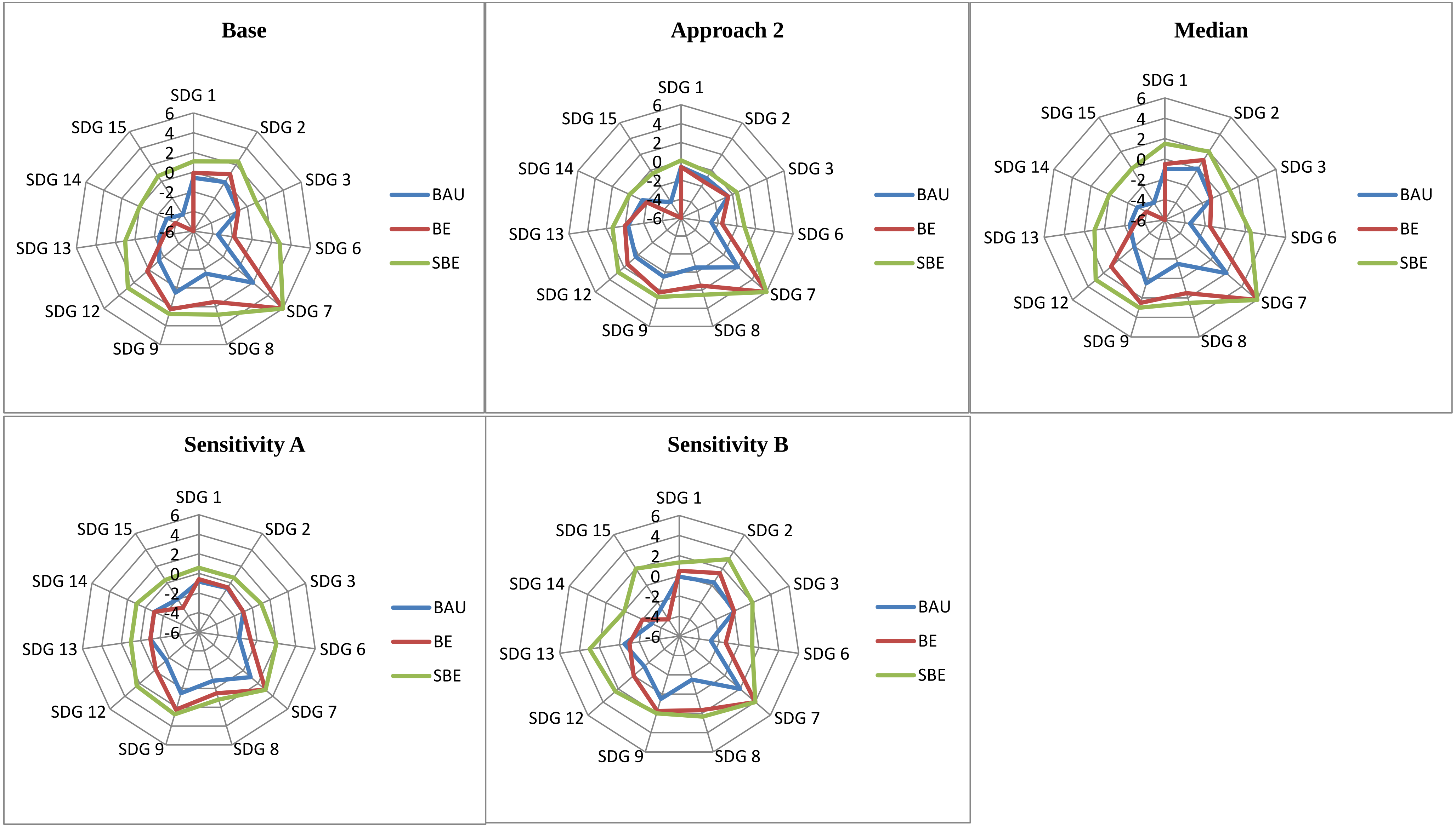

Figure A9: Results of the different evaluation methods by SDG.

3 Yet another reform of EU biofuel policies: Impacts of the latest reform of the European Union's Renewable Energy Directive

Ruth Delzeit[1,2], Tobias Heimann[1], Franziska Schünemann[3], and Mareike Söder[4]

[1] Kiel Institute for the World Economy

[2] University of Basel

[3] University of Hohenheim

[4] Thünen Institute Braunschweig

Abstract

The latest Renewable Energy Directive (RED II) by the European Union (EU) provides an updated framework for the use of renewable energy in the EU transport sector until 2030. We employ the computable general equilibrium (CGE) model DART-BIO for a scenario-based policy analysis and evaluate different possible futures of biofuel use within the specification of the RED II. Our results show that conventional biofuels will not become cost competitive to oil-based fuels. Moreover, we demonstrate the impact of the RED II specifications on the global production of food and feed crops. A further focus of this paper lies on the palm oil phase out as feedstock for biofuels in the EU, to halt deforestation and land-use change in tropical countries. We find that this phase-out has only a relatively small impact on global palm fruit production. Moreover, this study shows that the regulation acts as a technical barrier to trade, discriminating palm oil producing countries in favour of European rapeseed producers.

3.1 Introduction

Global biofuel production has experienced strong growth over the last decade (IEA, 2013; IEA, 2017), which was largely driven by climate mitigation policies especially in the European Union (EU). After promoting the use of biofuels with high mandates defined by the Renewable Energy Directive that came into force in 2009 (RED I), the EU has recast the directive for the period 2020-2030 (RED II) to correct for apparent trade-offs with respect to food security and biodiversity because of direct and indirect land-use change. The new legislation limits the amount of biofuels and bioliquids produced from cereal and other starch-rich crops, sugars, and oilseeds counting towards the mandate and promotes the use of non-food crops for biofuel production. Moreover, the directive categorizes palm-oil based biodiesel as biofuels with a high risk of causing indirect land-use change (ILUC) and thus bans them from the EU biofuel market from 2022 onwards. While biofuels have likely contributed to the surge in food prices in 2007, the role of biofuel production for ILUC and deforestation remains controversial (Arima et al., 2011; Broch et al., 2013; Klein Goldewijk et al., 2017; Zilberman 2017).

Concerns about potential negative effects of biofuel policies were already raised by Rosegrant (2008) who estimated an increase in global demand for crop land. Since then various studies employed computable general equilibrium (CGE) and partial equilibrium (PE) models to estimate the global economic effects of biofuel mandates in general (e.g Hertel, 2011; Laborde, 2011; Zhang, 2013; Valin, 2015) and the RED I in particular (e.g. Laborde & Valin, 2012; Calzadilla et al., 2016). Even though results of these studies were inconclusive, in 2015 the EU introduced a cap on food and feed crop-based biofuels of 7% to mitigate negative effects from land use change such as increased greenhouse gas emissions and loss of biodiversity (European Union, 2015).

More recently, with the RED II the European Commission further addresses the concern of potentially negative effects and aims at creating a renewable fuel mix in the transport sector, based on biofuels but also renewable energy produced for electric or hydrogen vehicles (European Union, 2018). Therefore, two major future scenarios are plausible. On the one hand, the integration of electric and hydrogen vehicles into the transportation portfolio may follow a rather slow development, forcing the EU countries to exploit their maximum biofuel limits to meet the 14% renewable energy target. On the other hand, technological leaps and large investments into infrastructure could accelerate the distribution of electric and hydrogen vehicles, crowding out relative expensive biofuels. However, while hydrogen and electricity are transport fuels that are not explicitly modelled in this evaluation, our paper is the first to analyze the impacts of the respective biofuel demand on agricultural markets for both possible future scenarios.

In addition, we are the first to assess the implications from the high ILUC-risk classification explicitly modelling palm oil. The high ILUC regulation effectively results in a ban on palm oil biodiesel within the EU. A crop is treated as high ILUC-risk if the annual expansion rate since 2008 was higher than 1%, and more than 10% of its annual expansion took place on land with high carbon stocks (hcs), such as forests and wetlands, which is defined under Article 29.4 of Directive (EU) 2018/2001 (European Union, 2019). The only crop being affected by this rule is palm fruit. While European farmers, biofuel producers and environmental associations welcome the policy (Copa/Cogeca, 2018; EJF, 2019; NABU, 2019), palm fruit-producing countries criticize the regulation as discrimination to protect European oilseed producers (MITI, 2019; WTO, 2019; CPOPC, 2020). Especially Malaysia and Indonesia that supply about 85% of global palm oil production (FAO, 2020) are strongly opposing the high ILUC-risk regulation, which is currently subject to World Trade Organisation (WTO) disputes (WTO, 2019).

The regulation also appears controversial because other crops are not considered as high ILUC-risky, even though Brazilian soybean exports to Europe heavily contributed to deforestation (Rajão et al., 2020). The share of expansion into land with high-carbon stock (Xhcs) is calculated by using the sum of percentage shares of total average annual expansion into different carbon rich areas since 2008, by weighting the expansion into wetland areas with the factor 2.6. The weighted sum is then divided by a productivity factor, indicating the energy yield per hectare (Annex to European Union, 2018). The resulting share of expansion into land with high-carbon stock is much higher for palm fruit (42%) than for soybean (8%). However, the absolute annual expansion of production areas since 2008 is 4.5 times higher for soybean compared to palm fruit (ibid.). As a consequence, when multiplying the absolute annual expansion area with Xhcs, the resulting absolut expansion into land with high-carbon stock of palm fruit and soybean are quite close in size. It needs to be noted that the assumed energy yield per hectar is 2.5 times higher for palm fruit cultivation compared to soybean production (ibid.).

The aim of our study is thus twofold. First, we quantify the impacts of the RED II on global land use and agricultural production in general, and secondly, we analyze if the current high

ILUC-risk classification only acts as a technical barrier to trade (TBT) or also as an effective measure for the urgently required protection of valuable forest and wetlands. Therefore, we analyze changes in crop prices, production, trade, and land use under different specifications of the RED II compared to a reference scenario with no biofuel policies. In section two the RED II policy and related literature are discussed. Section three provides a detailed description of the characteristics of the DART-BIO model as well as an elaboration of the scenario assumptions. In section four the results are presented, providing an overview of the impacts of the biofuel policies on agricultural markets. Section five concludes and discusses the results.

3.2 Background on the renewable energy directive RED II: policy and literature review

3.2.1 From RED I to RED II

The RED I was launched in 2009 and mandates that at least 20% of all energy usage in the EU must be met from renewable sources by 2020. The directive also includes a specific quota for the transport sector, in which at least 10% of each Member State's transport energy needs should originate from renewables (European Union, 2009). To ensure net savings in greenhouse gas emissions compared to fossil resources, additional requirements were introduced for biofuels counted towards the 10%-quota to meet strong sustainability criteria with respect to feedstock production (ibid.). Further, certain biofuels such as those produced from used cooking oil and animal fat were double-counted towards the quota (ibid.).

Now, the RED II sets an ambitious EU target for 2030 of at least 32% of renewable energy in total energy consumption, with a sub-target of 14% renewable energy in the transport that can be met by biofuels, electricity, or hydrogen (European Union, 2018). The policy design of the RED II emphasizes that even in an era of expected fast progress in developing alternatives to fossil fuel-fed combustion engines, the EU still attributes a major role to biofuels in the transport sector in the next decade. In order to reduce emissions from biofuel production, the directive includes different regulations for biofuels depending on the feedstock and the risk to cause ILUC. Biofuels produced from food or feed crops are limited to up to one percentage point higher than their share in final energy consumption in road and rail transport in 2019 with a total maximum of 7% by 2030 (European Union, 2018). Furthermore, the RED II aims for a transition towards advanced biofuels that are produced from feedstocks such as algae and straw, by requiring minimum targets of biofuels and biogas produced from these feedstocks of

0.2% in 2022, 1% in 2025 and, increasing up to at least 3.5% by 2030 (ibid.). Biodiesel made from Used cooking oil (UCO) (so called Used Cooking Oil Methyl Ester (UCOME) is not listed as advanced biofuel anymore. Part B of Annex IX includes used cooking oil and animal fats which are double counted towards the target but with no specific minimum targets, but limited to a share of 1.7% on total transport fuels (European Union 2018).

3.2.2 Previous analyses of the RED

In the literature, only a few economy-wide studies specifically address the impact of the RED II or the restriction in palm oil-based biofuels. Philippidis et al. (2018) make use of the MAGNET model to run a scenario-based analysis on reform proposals of the RED II, including a reduction of palm oil-based biodiesel. According to their model the reduction results in lower biodiesel and higher bioethanol production in the EU, as well as less vegetable oil imports from Asia and more production of oilseeds in the EU, while global oilseed production increases. To model the palm oil-based biodiesel reduction they reduce all vegetable oil imports of the EU from Asia according to the import share of palm oil, by imposing an endogenous tariff. For identifying market feedback effects, this mechanism bears three shortcomings. First, as also acknowledged by the authors, palm oil imports may be reduced too much since only about half of them are used in the biofuel industry. Second, since they model one aggregated oilseed sector and do not reduce palm oil imports only, it is likely that the EU continues to import the same import share of palm oil from Asia as before. Third, it remains unclear how it is assured that biodiesel imports into the EU are not based on palm oil. In addition, given the aggregated oilseed sectors, the authors are unable to track feedback effects on palm fruit production as well as substitution effects in other bio-industrial sectors. Thus, the question remains whether a ban on biodiesel based on palm oil leads to lower palm oil demand, providing less incentive to convert land into palm fruit plantations, or whether palm oil consumption is just shifted to other uses. In this study, we employ the unique characteristics of the DART-BIO model to analyse such market-based feedback effects and evaluate the effectiveness of the palm oil phase-out policy. Further, by implementing an explicit palm oil-based biodiesel sector we are able to avoid the three shortcomings mentioned above. In another study, Philippidis et al. (2019) use the RED II with a 7% quota on biofuels as a policy baseline in a model-based analysis. They compare this baseline to a high technology and a no-quota scenario to measure impacts on the EU's macroeconomic performance. One of their main conclusions is that the EU biofuel industry cannot survive without the political mandates.

3.3 Method and Data

3.3.1 The DART-BIO model and data sources

As examined in the literature review, computable general equilibrium (CGE) models have often been used to study the impacts of biofuels policies. This is because they are powerful tools when it comes to tracing policy effects on product and factor markets, as they encompass the complete circular flow of income in an economy through production and consumption linkages. In addition, global CGE models capture trade flows in the world economy and can thus depict feedback effects of highly integrated agricultural markets on land use in various regions. For our analysis of the RED II, we employ an updated version of the Dynamic Applied Regional Trade (DART-BIO) model, a multi-sectoral, multi-regional recursive dynamic CGE model of the world economy with a detailed representation of the biofuel industry and global land use (Springer, 1998; Klepper & Peterson, 2006; Calzadilla et al., 2016, Delzeit et al., 2018a). Table A5 in the appendix shows our regional aggregation featuring 21 regions with a focus on big global biofuel producers such as the US, Brazil, and the EU. Similarly, our sectoral disaggregation with 48 sectors, as shown in Table A6, considers the different stages of biofuel production in detail with the major biofuel feedstock crops, biofuels, and by-products. Hydrogen and electricity are not yet included as transport fuels in the DART Model.

The DART-BIO model is based on the GTAP9 database (Aguiar et al., 2016). Following Calzadilla et al. (2016), the model includes bioethanol production from sugar cane/beet, wheat, maize, and other grains; and biodiesel production from palm oil, soybean oil, rapeseed oil, and other oilseed oils. DART-BIO explicitly accounts for the by-products generated during the production process of different vegetable oils and biofuels. Dried distillers grains with solubles (DDGS) are by-products of the production of bioethanol from grains and oilseed meals/cakes are by-products of different vegetable oil industries. Thus, unlike the standard GTAP database, we differentiate between production activities and commodities, which allows us to model joint production in the bioethanol and vegetable oil industry. Calzadilla et al. (2016) and Delzeit et al. (2018b) find that differentiating different vegetable oils and their different shares of co-produced meals result in smaller price changes compared to models without these differentiations.

In this updated version, in addition to the biofuels in Calzadilla et al. (2016), biodiesel production from used cooking oil (UCOME), and cellulosic bioethanol production from straw (ETHC) is added. As the first CGE model, DART-BIO can make use of an explicit UCO sector for biofuel production when analysing biofuel policies. These two technologies have been identified to be the most important advanced and waste-based biofuel technologies in a stakeholder process (Delzeit et al., 2021a). Moreover, we include a dedicated palm oil-based biodiesel sector to be able to implement the palm oil biodiesel phase-out unambiguously. The new sectors are split from aggregated sectors in the original GTAP9 database using splitting weights calculated from data sources such as COMTRADE, FAOSTAT, and F.O. Licht. Details on the construction of the DART-BIO database as well as assumptions regarding production technologies are available in Delzeit et al. (2021b).

The economy in each region is modelled as a competitive economy with flexible prices and market clearing conditions. The economic structure of DART-BIO is fully specified for each region and covers production, investment, and final consumption by a representative consumer and the government. Private consumption is maximized according to a Stone-Geary utility function (Stone 1954), while multi-nested constant elasticity of substitution (CES) functions determine substitution between production factors and energy in the production sectors. Other intermediate inputs enter the production of commodities subject to fixed input-output relations. Apart from capital and labour, land is disaggregated into 18 different land types according to the length of the growing period and climatic zone. Thus, we include not only land-use heterogeneity in agriculture and forestry, but these agro-ecological zones (AEZ) also cover land heterogeneity in each region (Lee et al., 2005; Baldos, 2017). Within each region, capital and labour are mobile but constant elasticity of transformation (CET) functions govern land mobility between and within agriculture and forestry.

Trade between regions happens under the Armington assumption of imperfect substitution between imported and domestically produced commodities. The numeraire region is the United States. Global trade is balanced with a flexible current account; all other regions' current account balances are fixed. Investment in each region is determined by fixed private marginal propensities to save, but fast-growing regions' saving rates converge to those of industrial countries. The model is recursive-dynamic and is solved for a sequence of static annual equilibria for periods from 2011 until 2030. Over this period, we calibrate the model to match regional GDP growth projections of the OECD (2018a) via adjustments of labor productivity and update key parameters between the model runs. The capital stock available for the next period is updated with the current period's investments and depreciation, while labour supply changes according to regional workforce and population growth projections OECD (2018b).

3.3.2 Definition of scenarios

To capture the potential impact of the RED2 on agricultural and energy markets, we define different scenarios until 2030 that consider the possible developments in the renewable energy market. As already mentioned above, the use of hydrogen and electricity in the transport sector is explicitly modelled in this study. Table 2 gives an overview of these scenarios that are described in detail below. Within the scenarios, the different mandates are implemented via a binding quota on Armington consumption. Practically, this quota is implemented as a negative endogenous tax on consumption.

Table 2: Scenarios

Name	Biofuel policies		
	Feed-and food-based biofuels	**Palm oil-based biodiesel**	**UCOME**
REF	No biofuel policies from 2019 onwards	No restriction	No restriction
RED2max	Maximum of 7% of total consumption in transport sector	Consumption share in total transport sector reduced to 0% between 2022 and 2030	Maximum of 1.7% of total consumption in transport sector
RED2corr	Maximum of 7% of total consumption in transport sector and minimum of 2018 biofuel consumption shares	Consumption share in total transport sector reduced to 0% between 2022 and 2030	Maximum of 1.7% of total consumption in transport sector
RED2eq	7% of total consumption in transport sector are reached until 2030	Consumption share in total transport sector reduced to 0% between 2022 and 2030	Maximum of 1.7% of total consumption in transport sector
RED2eqPL	7% of total consumption in transport sector are reached until 2030	No restriction	Maximum of 1.7% of total consumption in transport sector

Reference scenario (REF)

The reference scenario reflects trends in the global economy based on the economic and population growth projections mentioned above from 2011 until 2030 (OECD 2019). In addition, the reference scenario is calibrated to mirror empirical biofuel consumption and input shares of different vegetable oils in biodiesel until 2018 according to Eurostat (2020) for the EU and the USDA Global Agricultural Information Network (GAIN) reports (GAIN 2010, 2012, 2017a-j, 2018a-b) for most of the other regions. After 2018, there are no biofuel policies in place. Essentially until 2018, all scenarios are the same as the reference scenario and differ only in the implementation of the RED II in the EU from 2019 onwards.

RED2 max scenario (RED2max)

The RED2 max scenario is a literal implementation of the new EU legislation with respect to biofuels. The RED II mandates that not more than 7% of the road transport fuel is allowed to come from food- or feed-based biofuel sources. In addition, the consumption share of biodiesel from UCO is limited to 1.7% of total transport fuel consumption. Finally, since the RED II stipulates that the share of biodiesel from palm oil is classified as “high-iluc risk” its share in road transport is gradually reduced to 0 from 2023 until 2030. This means that the RED II does not define a minimum target for conventional and advanced biofuels, but only maximum shares. Therefore, these mandates are implemented as maximum allowable consumption shares that constrain each region’s biofuel consumption, differentiated for the respective biofuel type. The absolute allowable numbers, of course, differ depending on each region’s transport sector size. This scenario thus allows producers complete flexibility in terms of minimum production of conventional biofuels and could lead to a contraction of the food- and feed-based biofuel industry. As a consequence, 14% of renewable energy in transport would need to be met by electricity or hydrogen.

RED2 corridor scenario (RED2corr)

Given that the production capacities of conventional biofuels and UCO-based biodiesel in the EU already exist and were economically feasible under the RED I, EU biofuel producers likely continue to use their production facilities after 2019, even if the RED II sets no minimum targets. Therefore, we define a *RED2 corridor* scenario that preserves existing production capacities for fuels from food and feed crops as well as UCO and thus sets a minimum target. Here we assume that consumption shares of biofuels in total transport fuels are at least as high as their 2018 levels (see the first column of Table A7) from 2019 to 2030. The maximum shares of 7% for feed- and food crop-based biofuels, 1.7% for UCO biodiesel, and the gradual reduction of palm oil biodiesel according to the RED II remain in place in this scenario. Hence, biofuel consumption shares can develop within a corridor pathway with an upper bound (7% of biofuels based on food or feed crops, 1.7% of UCOME on total transport fuels, gradual reduction of palm oil biodiesel to 0) and a lower bound (2018 consumption shares for conventional and UCO-based biofuels).

RED2 equal7 scenario (RED2eq)

To investigate the possibility that the 14% share of renewables in total transport fuel consumption until 2030 cannot be met without a sufficiently large amount of biofuels, in the *RED2 equal7_*scenario (*RED2eq*) we assume that member states meet the 14% renewable energy in transport target with the maximum allowable share of biofuels according to the RED II. This means that the share of feed- and food-based biofuels are gradually increased to 7% (having the restriction on palm oil-based biodiesel in place) and the share of UCO-based biodiesel to 1.7% until 2030.

RED 2 equal7 no restriction scenario (RED2eqPL)

Finally, the restriction on palm oil has been widely criticized by the major palm oil producers Indonesia and Malaysia as a technical barrier to trade to protect the European biodiesel industry. The EU has claimed the ban on palm oil biodiesel is necessary to avoid deforestation and indirect land-use change. The latter argument implies that the restriction of palm oil-based biodiesel in the EU should lead to lower palm oil production to avoid additional land-use change. To investigate whether the EU's argument is true or whether the palm oil restriction is only an TBT in disguise, we run a scenario where we implement the same assumptions as in *RED2eq7*, but release the restriction on biodiesel from palm oil. This means that the maximum share of conventional biodiesel of 7% is still met until 2030, but that palm oil biodiesel can contribute to meet the share by replacing other types of biodiesel. While the other scenarios are compared to the reference scenario, we will compare the *RED2eqPL* scenario to the *RED2eq* scenario to address the impact of the palm oil restriction explicitly.

3.4 Results

The RED II is likely to have strong impacts on biofuel markets within the EU, but also affects biofuel, energy, and agricultural markets as well as land use change globally through bilateral trade. We start by analyzing the impacts of the RED II as defined in the different scenarios compared to the reference scenario within the EU and continue by analyzing global effects. This section concentrates on biofuel and agricultural commodity markets, while the results for global energy markets can be found in appendix part A.

3.4.1 RED II impacts on EU biofuel markets

As defined in the scenario setting above, all scenarios are calibrated to reach the 2018 biofuel consumption values. After 2018 the different scenario settings become effective, which leads to strongly diverging developments in biofuel consumption among the scenarios as shown in Figure 10. An exemption are the results of the *RED2max* scenario, which are the same as of *REF* in 2030 as there is no minimum quota in both scenarios. Therefore, we refrain from discussing the *RED2max* scenario in our analysis. Simply implementing an upper limit of 7% with no requirements for minimum values as in the *RED2max* scenario causes an enormous contraction of the biofuel industry. Biofuel consumption in this scenario is identical to the *REF* scenario without any regulation and converges to about 10 billion USD from 2019 onwards. This is because without a minimum quota, biofuels are not competitive vis-à-vis fossil fuels. The lack of competitiveness of biofuels also affects biofuel consumption values in the *RED2corr* scenario, where consumption values from 2019 to 2030 stay close to the 2018 number of about 40 billion USD, the lower bound of biofuel consumption in this scenario. Thus, without minimum quotas set by policy makers biofuel consumption in the EU would be much lower. In both the *RED2eq* and the *RED2eqPL* scenarios, on the other hand, biofuel consumption continues to grow until 2030 to reach the defined quota of 7% share in the transport sector at 65 billion USD. Note that the small kink in 2023 in the RED2eq scenario is caused by the onset of the palm oil ban.

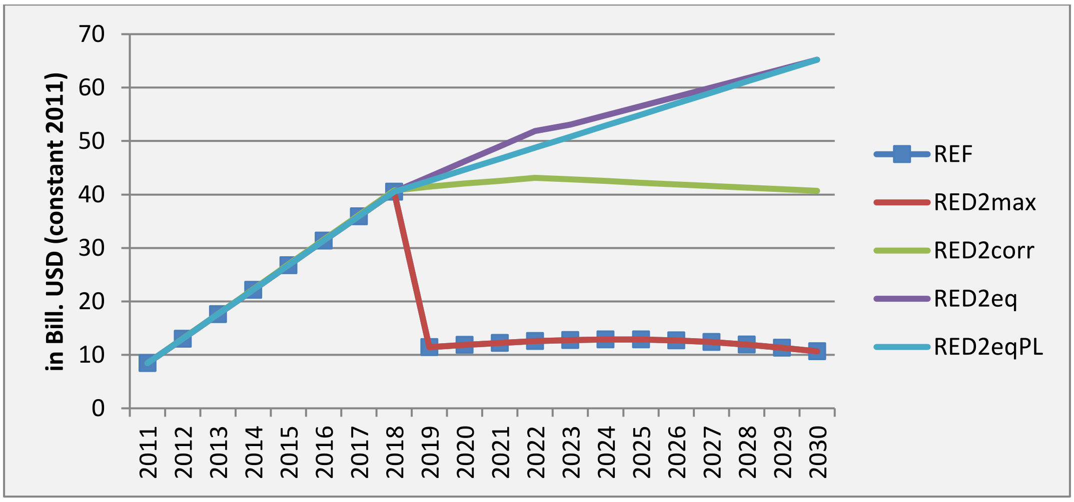

Figure 10: Annual total biofuel consumption in the EU in the different scenarios

To illustrate the impact of the palm oil restriction in more detail, Figure 11 shows the input shares of different vegetables oils and UCO in biodiesel production under the *RED2eq* and *RED2eqPL* scenarios in the EU in 2030. The palm oil restriction leads to an increased input of all other vegetable oils into biodiesel production, while rapeseed oil is the main beneficiary of the restriction with an increased input share of 9 percentage points. This finding already indicates a preferential treatment of EU-domestically produced vegetable oil over imports, given that the EU is the largest global producer of rapeseed. The share of UCOME in total transport fuel consumption, does not differ between the two scenarios, since the restriction of 1.7% on the consumption share is binding under both scenarios. A detailed description of the scenario specific shares of different biofuels in total transport fuels consumption in different EU regions, can be found in the appendix in Table A7.

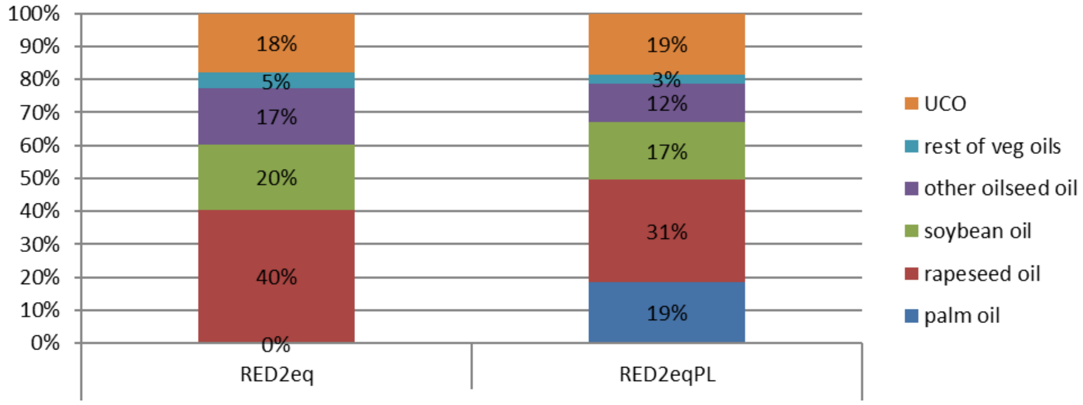

Figure 11: Input shares in biodiesel production in the EU in 2030

The potential benefit of the RED II policy for EU biofuel producers also becomes apparent when looking at the 2030 EU biofuel prices and production in Table 3. In general, the major share of biofuels consumed in the EU is also produced in the EU, while soybean oil and palm oil are mainly imported and then processed (see next section). Meeting demand for bioethanol under the *RED2corr* scenario causes an increase in prices by 18% and in production by 131% (compared to the *REF* scenario in 2030 (first row of Table 3). In the *RED2eq* where biofuels reach the 7% quota, bioethanol prices increase by 30% and production by 334%.

Similarly, compared to *REF*, total biodiesel production is 399% higher with the 2018 consumption share quota under the *RED2corr* scenario, while production is 663% higher under the *RED2eq* scenario. Prices of BDIE_OTH rise by 16.8 (*RED2corr*) and 22.9% (*RED2eq*), while for UCOME with the limitation of 1.8% on total transport fuel the price increase is smaller under both scenarios (1.1 and 1.5%). Due to the ban on imports of palm oil-based biodiesel under the *RED2eq* scenario compared to the *RED2eqPL* scenario, EU's biodiesel production is 0.8% lower and prices 2.5% higher with the palm-oil phase-out.

Table 3: Changes in prices and production of biofuels in the EU in 2030 compared to REF Scenario.

	Production (in Bill USD) REF 2030	Δ EU prices in %			Δ EU production in %		
		RED2corr vs REF	RED2eq vs REF	RED2eqPL vs RED2eq*	RED2corr vs REF	RED2eq vs REF	RED2eqPL vs RED2eq*
Bioethanol	4.19	18.0	30.3	0.3	131	334	-0.1
Biodiesel SUM	5.99				399	663	-0.8
Biodiesel Other	4.41	16.8	22.9	2.5	411	733	33.7
UCOME	1.58	1.1	1.5	0	367	470	0.3
Palm-oil Biodiesel	0.004	0.1	0.2	-0.2	85	73	-99.9

* Compares the RED2eq and RED2eqPL scenarios and shows the effect of the palm-oil phase-out for the EU biodiesel mandate.

Imports from regions outside the EU increase under all scenarios compared to the *REF* scenario as shown in Table 4 below. In the case of BETH, imports originate mainly from Brazil and reach 0.56 billion USD under the *RED2eq* and *RED2eqPL* scenarios, which is more than 5 times the amount of imports in the *REF*. At the same time, ethanol imports from the USA are only 2 times higher under *RED2eq* and *RED2eqPL*. Thus, the palm oil phase-out has no substantial effect on production and imports of bioethanol, but much more so on biodiesel trade. Biodiesel from soybeans is imported from the USA and reaches 0.65 billion USD under the *RED2eq* Scenario. These trade flows are slightly reduced to 0.57 billion when releasing the restriction on biodiesel based on palm-oil under the *RED2eqPL* scenario. At the same time, imports of BDIE_PLM from MAI show an enormous increase from 0 in *RED2eq* to 1.02 bill USD in the *RED2eqPL* scenario. Thus, imported palm-based biodiesel mainly displaces locally produced biodiesel, which indicates that predominantly domestic producers of biodiesel within the EU benefit from the palm oil phase-out. Whether this is also the case for domestic vegetable oil and oilseed producers will be discussed in the following section that looks at the implications for agricultural commodity markets.

Table 4: EU net imports in billion USD in 2030 under different scenarios by trading partner

		REF	RED2corr	RED2eq	RED2eqPL
Bioethanol	BRA	0.10	0.35	0.56	0.55
	USA	0.05	0.10	0.13	0.13
Biodiesel	USA	0.13	0.51	0.65	0.57
Palm-oil Biodiesel	MAI	0.00	0.00	0.00	1.02
UCOME	USA	0.02	0.06	0.06	0.06

3.4.2 RED II impacts on EU agricultural commodity markets

As already mentioned above, instead of importing ready-to-use biodiesel, the EU typically imports the vegetable oils to process biodiesel domestically. Figure 12 shows exports and imports of different vegetable oils from, to, and within the EU. While when summing up net trade of EU member states with non-EU members (denoted as “EU” in Figure 12) the EU is a net exporter of rapeseed oil under the *REF* Scenario, it becomes a net importer under all other biofuel scenarios, although rapeseed oil is predominantly traded within the EU (see single regions in Figure 12). This is mainly driven by DEU who turns into the largest net importer under all biofuel quota scenarios and starts to import rapeseed oil mainly from the European regions CEU and MEE. In contrast, soybean oil is mostly imported from non-EU regions, and all EU regions are net importers of soybean oil under all scenarios. Net imports of rapeseed and soybean oil into the EU are largest under the *RED2eq* scenario, where demand is high due to the 7% quota and palm oil is not available due to the palm oil biodiesel ban.

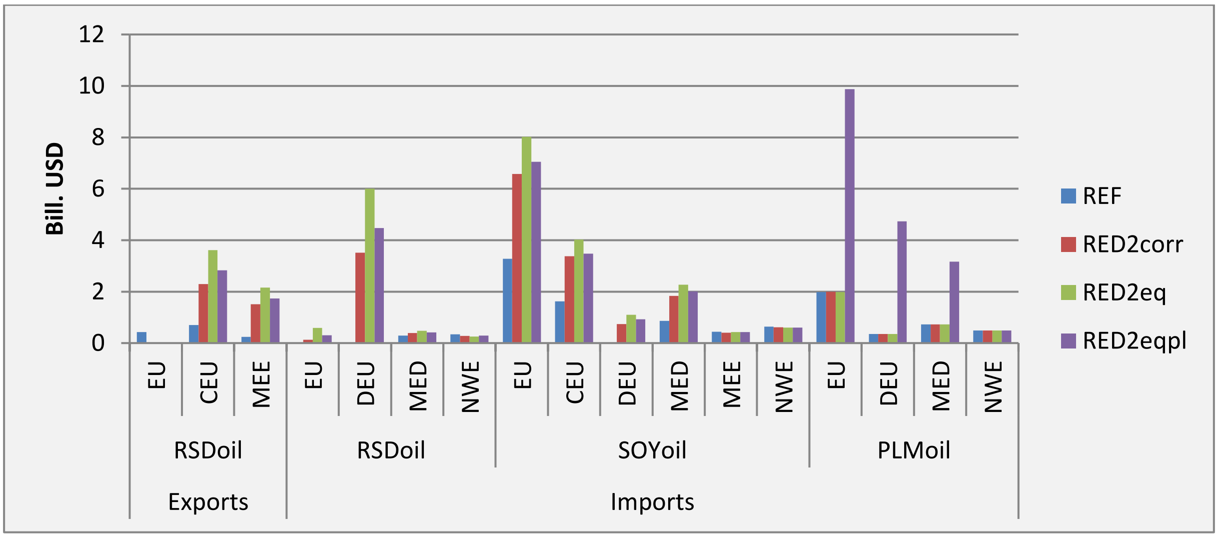

Figure 12: Net trade of EU with the sum non-EU regions (denoted “EU”), and net trade of EU regions with the sum of EU and non-EU regions. RSDoil = Rapseed Oil, SOYoil = Soybean oil, PLMoil = Palm oil.

In the *RED2eqPL* scenario without the restriction, rapeseed oil and soybean oil imports into the EU, predominantly into DEU and MED, are partly replaced by palm oil. In fact, palm oil imports are 5 times larger compared to when the restriction is in place. Considering palm oil, the EU is a net importer from non-EU regions, mainly from MAI. Comparing the *RED2eqPL* and *RED2eq* scenarios, the palm oil restriction under *RED2eq* leads to lower net imports of palm oil into the EU. In particular to DEU and MED, who would use the most palm oil-based biodiesel in the *RED2eqPL* scenario. While in the scenario with the palm oil restriction (*RED2eq*), nearly 79% of palm oil enters the food processing sector in the EU in 2030, without the palm oil restriction, 76% of palm oil is used in the production process of biodiesel. However, the impacts of the palm oil policy on the EU's food processing sector are negligible, since palm oil only contributes 0.1% to total inputs in the food processing sector.

Even though the EU becomes a net importer of rapeseed oil in all scenarios, the EU simultaneously expands production of rapeseed oil to meet the high domestic demand compared to the REF scenario, as shown in the first row of Table 5 (RED2corr 105%, RED2eq 187%). The EU soybean oil production rises less drastically compared to rapeseed oil, by 21-29%. Through the higher demand for vegetable oils, their prices in the EU increase strongly, namely for rapeseed oil by 17.3% in the RED2corr scenario and by 25% in the RED2eq scenario and for soybean oil accordingly by 30.3% and 43.0%. As a result of the higher production, prices of meals, which are co-products of vegetable oil production, fall by up to 43% compared to the REF scenario.

Table 5: Changes in production and prices of selected vegetable oils and meals in the EU.

	Production (bills. USD) REF 2030	Δ EU production			Δ EU prices		
		RED2corr vs REF	RED2eq vs REF	RED2eqPL vs RED2eq*	RED2corr vs REF	RED2eq vs REF	RED2eqPL vs RED2eq*
Rapeseed oil	6.79	105.0%	187.3%	22.4%.	17.3%	25.0%	3.1%
Soybean oil	3.41	20.6%	29.1%	5.0%.	30.3%	43.0%	6.0%
Rapeseed meal	2.05	101.8%	182.0%	22.1%.	-31.9%	-43.3%	-11.3%
Soybean meal	4.97	19.4%	27.5%	4.8%.	-11.4%	-15.9%	-3.9%

* Compares the RED2eq and RED2eqPL scenarios and shows the effect of the palm-oil phase-out for the EU biodiesel mandate.

Part of these increases are due to the restriction on palm-based biodiesel in the RED II. The phase-out is responsible for an increase of rapeseed oil production in the EU by 22.4% (last column of Table 5). EU imports of rapeseed oil and soybean oil are also larger in *RED2eq* scenario than in the *RED2eqPL* scenario as demonstrated in Figure 12. Furthermore, the phase-out of palm oil-based biodiesel also has an impact on soybean and rapeseed oil and their meal prices. In the EU soybean oil is 6% more expensive, and its meal, which is a main feedstock in livestock production, about 4% cheaper compared to a situation without the phase-out.

These effects are also apparent when looking at crop markets in Table 6. In general, production of crops used for biofuel production (wheat, maize, rapeseed, sugar cane and beet) increases at the expense of the other crops (Table 6). Mirroring the different biofuel targets under the RED II scenarios, the strongest increase in crop production occurs under the *RED2eq* scenario (third column), the lowest under the *RED2corr* scenario (second column). Rapeseed production, for example, rises by 25.4% under the *RED2corr* scenario while it increases by 45.2% under the *RED2eq* scenario. This strong increase is caused by the high input share of rapeseed oil into biodiesel production (see Figure 11).

This is also due to the palm oil phase-out which leads to an increase in rapeseed production by 9.7% in the EU when comparing the REDeqpl and the REDeq scenario (fourth column), corresponding to an increase of 14% when comparing REDeqpl to REF. Thus, not only domestic EU biofuel producers benefit from the phase-out, but also domestic rapeseed producers. Interestingly, soybean production within the EU decreases slightly in the *RED2eq* scenario compared to the REF scenario, but this is compensated for by cheaper imports such that consumption does not change (Figure 12).

Table 6: Changes in production and prices of agricultural commodities in the EU.

	Production (bills. USD) REF 2030	Δ EU production			Δ EU prices		
		RED2corr vs REF	RED2eq vs REF	RED2eqPL vs RED2eq*	RED2corr vs REF	RED2eq vs REF	RED2eqPL vs RED2eq*
Paddy rice	1.87	-0.3%	-0.7%	-0.2%	0.1%	0.2%	-0.2%
Wheat	68.10	-0.6%	-0.2%	-1.0%	1.3%	3.0%	0.1%
Maize	23.59	1.5%	8.9%	-0.9%	1.4%	3.4%	0.0%
Other grains	25.43	-2.0%	-2.9%	-0.9%	1.5%	3.4%	0.0%
Rapeseed	18.94	25.4%	45.2%	9.7%	1.6%	3.6%	0.2%
Soybeans	1.67	0.6%	-0.8%	-0.2%	1.9%	4.3%	0.0%
Other oil seeds	22.24	2.4%	5.0%	1.7%	1.2%	3.0%	0.0%
Sugar cane/beet	7.66	6.6%	12.4%	0.1%	8.5%	18.3%	0.0%
Other crops	279.66	-1.3%	-2.8%	-0.5%	1.1%	2.7%	0.0%
DDGS maize	0.61	100.5%	313.7%	-0.2%	-34.3%	-51.4%	-0.5%
DDGS wheat	0.47	114.5%	271.2%	-0.5%	-31.7%	-54.1%	-0.4%
Processed Food	775.92	0.0%	-0.3%	-0.1%	0.3%	0.6%	0.0%
Processed Meat	1376.00	0.1%	0.1%	0.0%	-0.2%	-0.1%	-0.1%

* Compares the RED2eq and RED2eqPL scenarios and shows the effect of the palm-oil phase-out for the EU biodiesel mandate.

Since the bioethanol market in the EU is small compared to the biodiesel market, impacts on crops used for bioethanol production are smaller compared to those used for biodiesel production. Because bioethanol in the EU is mainly produced from maize, maize production rises by 8.9% in the *RED2eq* scenario, while the production of other grains with low shares in bioethanol production declines. In all scenarios, crop prices increase due to the high demand and competition for land.

The biofuel policies have only small effects on production and prices of processed meat and food. This is because the two sectors are very large in value terms. However, we can observe the expected signs of the effects. The prices for meat decrease and the production increases given the lower prices of biofuel processing by-products that are used as livestock feed, i.e. oil seed meals (Table 5) and DDGS (Table 6). Conversely, the prices of other processed food increases and production decreases slightly given the higher crop prices in all scenarios.

3.4.3 RED II impacts on global agricultural commodity markets and land use

While we find that the RED II biofuel policy causes significant rearrangements in crop production patterns within the EU, the spill-overs to areas outside the EU are smaller and mainly pertain to rapeseed and soybean feedstock and oils. Table 7 shows changes in global crop and biofuel production and prices.

Table 7: Changes in production and prices on global markets in 2030

	Production (bills. USD) REF 2030	Δ global production			Δ global prices		
		RED2corr vs REF	RED2eq vs REF	RED2eqPL vs RED2eq	RED2corr vs REF	RED2eq vs REF	RED2eqPL vs RED2eq
Paddy rice	362.85	0.0%	-0.1%	0.0%	0.0%	0.1%	-0.2%
Wheat	309.77	0.0%	0.2%	-0.1%	0.5%	1.2%	0.1%
Maize	322.64	-0.1%	0.3%	-0.1%	0.4%	0.9%	0.0%
Other grains	123.15	-0.6%	-0.9%	-0.2%	0.5%	1.2%	0.0%
Palm fruit	57.20	0.0%	0.0%	-2.4%	0.3%	0.5%	-5.8%
Rapeseed	60.30	8.5%	15.2%	3.8%	0.8%	1.9%	0.2%
Soybeans	190.87	0.9%	1.4%	0.2%	0.6%	1.2%	0.0%
Other oil seeds	120.46	0.7%	1.4%	0.4%	0.5%	1.1%	0.0%
Sugar cane/beet	123.29	0.5%	1.1%	0.0%	0.9%	2.0%	0.0%
Other crops	2171.14	0.0%	-0.1%	0.0%	0.4%	0.9%	0.0%
DDGS wheat	0.09	110.0%	260.6%	-0.5%	-33.7%	-50.9%	-0.5%
DDGS maize	2.87	20.5%	65.5%	-0.2%	-11.0%	-28.6%	-0.4%
DDGS oth grains	0.37	111.8%	283.6%	-0.2%	-33.5%	-51.6%	-0.4%
Palm oil	40.85	0.8%	0.2%	-38.2%	0.2%	0.4%	-1.3%
VOLN	643.04	0.0%	0.1%	0.1%	0.4%	0.7%	-0.3%
Bioethanol	15.08	33.4%	85.2%	0.0%	7.9%	17.8%	0.3%
Biodiesel	8.80	175.4%	315.7%	28.4%	14.4%	20.8%	2.5%
Processed Food	6504.8	0.0%	-0.1%	0.0%	0.2%	0.3%	0.0%

* Compares the RED2eq and RED2eqPL scenarios and shows the effect of the palm-oil phase-out for the EU biodiesel mandate.

Under the *RED2eq* scenario, there is a strong increase in global rapeseed production by 15.2%, which is almost double the increase in the *RED2corr* scenario (8.5%). Global soybean production on the other hand increases only by 1.4% in *RED2eq* and 0.9% in *RED2corr* compared to *REF*. The impacts on global grain markets are less pronounced because only 2-4% of the global maize and 0.8-1.5% of wheat production enter bioethanol process chains.

Global land-use changes mirror changes in production as shown in Figure 13. Area changes for grains are relatively small in all scenarios except for "other grains" which is mainly due to the output reduction in the EU. Oilseeds on the other hand increase their global area substantially, dominated by rapeseed. Under the *RED2eq* scenario, the area planted with rapeseed increases by more than 11%. Almost 3% of this area increase is caused by the palm oil phase-out alone, whereas palm oil area is reduced by about 1.5%. The implications of this particular land-use change are discussed in more detail in the next section.

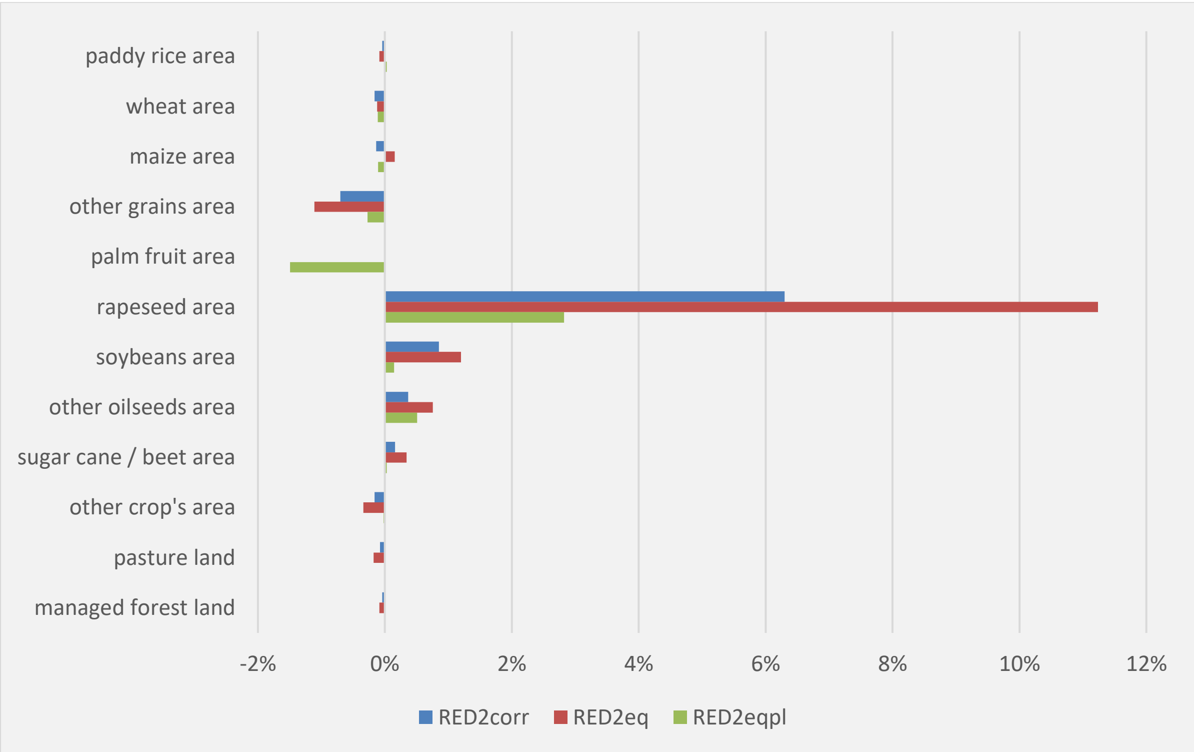

Figure 13: Changes in land-use area compared to the REF scenario in 2030 in percent. RED2eqPL compares the RED2eq and RED2eqPL scenarios and shows the effect of the palm-oil phase-out for the EU biodiesel mandate.

3.4.4 Implications of the palm oil phase-out

Globally, the major palm fruit-producing regions are MAI (56% of global production under *REF* in 2030) and AFR (35% of global production). Both are also the largest producers of palm oil, as palm fruit itself is rarely exported but rather processed domestically and then traded internationally as palm oil. Due to the palm oil phase-out, palm oil production in MAI decreases by 7%. Smaller producers, such as AFR and LAM, also reduce their output leading to a decline in global production of 38% (third column of Table 7). Therefore, the palm oil restriction causes global palm fruit production to drop by 2.4% and its price to decline by 5.8% (third and last column of Table 7). Due to the underlying data structure a share of palm fruit and palm oil enters the accumulative sector “processed vegetable oils” (VOLN), which is again consumed by various sectors, but not by biofuel processing. This explains the differences in the changes of palm fruit and palm oil production.

Since the main argument for the palm oil biodiesel phase-out is to reduce the pressure for deforestation in tropical countries, a closer look on land use changes is essential. Figure 14 displays the land use reactions of oilseed crops under the palm oil phase-out. While palm fruit land is reduced by 340,000 ha, rapeseed and soybean area expands by 969,000 ha and 213,000 ha, respectively. Thus, the expansion of rapeseed and soybean area consumes more than 3 times the area spared by reduced palm fruit production. A major share of the soybean area expansion takes place in Brazil.

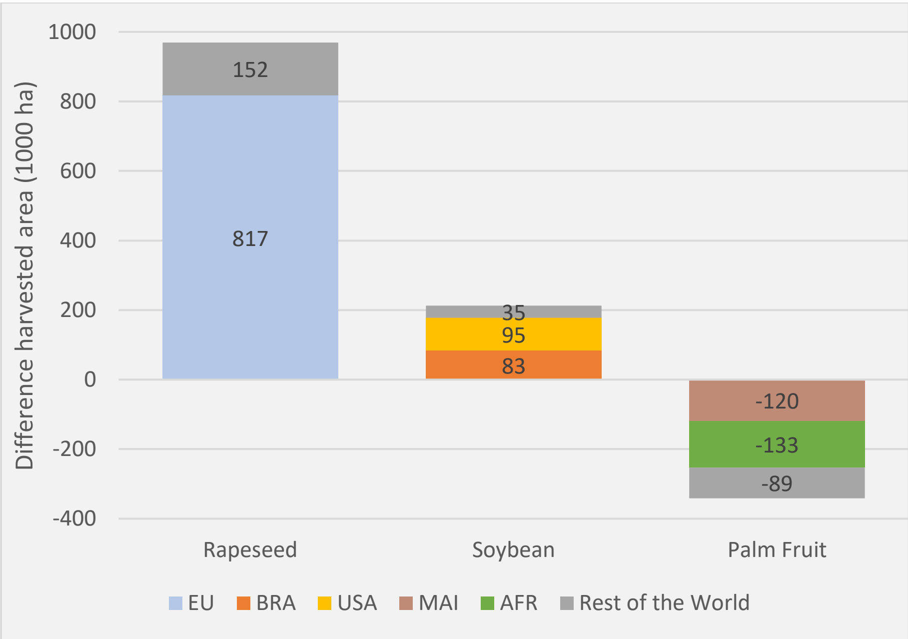

Figure 14: Change of harvested area under palm oil biodiesel phase-out for selected oilseeds.

The relatively small land-use effects are especially apparent when looking at the major global palm fruit producer MAI. In 2018, 10% of global palm fruit output is used for biodiesel production which is mainly consumed in the EU. While the palm oil biodiesel phase-out in the EU leads to a global reduction in palm fruit land by 1.9% in 2030, land used for palm fruit in MAI is only reduced by 1.1%. One reason why the effect on palm fruit production in MAI is lower compared to the global average is a cost advantage of palm fruit production compared to

AFR and LAM. As the price for palm fruit drops due to the palm oil phase-out, the production in those two regions reacts stronger (AFR: -2.8%, LAM: -8.2%).

Figure 15 shows production and export data for MAI for *RED2eq* and *RED2eqpl*. By scenario definition, in the *RED2eq* scenario the production of palm oil-based biodiesel as well as a stop in palm and vegetable oil exports to the EU is stopped almost completely. It should be noted that while we model EU biofuel quotas, we do not include biofuel quotas in other regions such as in MAI. Thus, the reduction in palm oil biodiesel production in this region is likely to be overestimated. Moreover, to evaluate the implications of the phase-out on palm fruit production, we need to consider the palm oil and "rest of vegetable oil" (VOLN) sector jointly to comply with the above-mentioned characteristics of the underlying data structure. Figure 15 shows that with the demand for palm oil in the EU going to zero, exports of palm and vegetable oils to CHN and IND increase as a result of lower global market prices for palm fruit and palm oil in the *RED2eq* scenario. While we observe an overall decrease in palm oil production in MAI, VOLN production increases, resulting in only a minor change in actual palm fruit production.

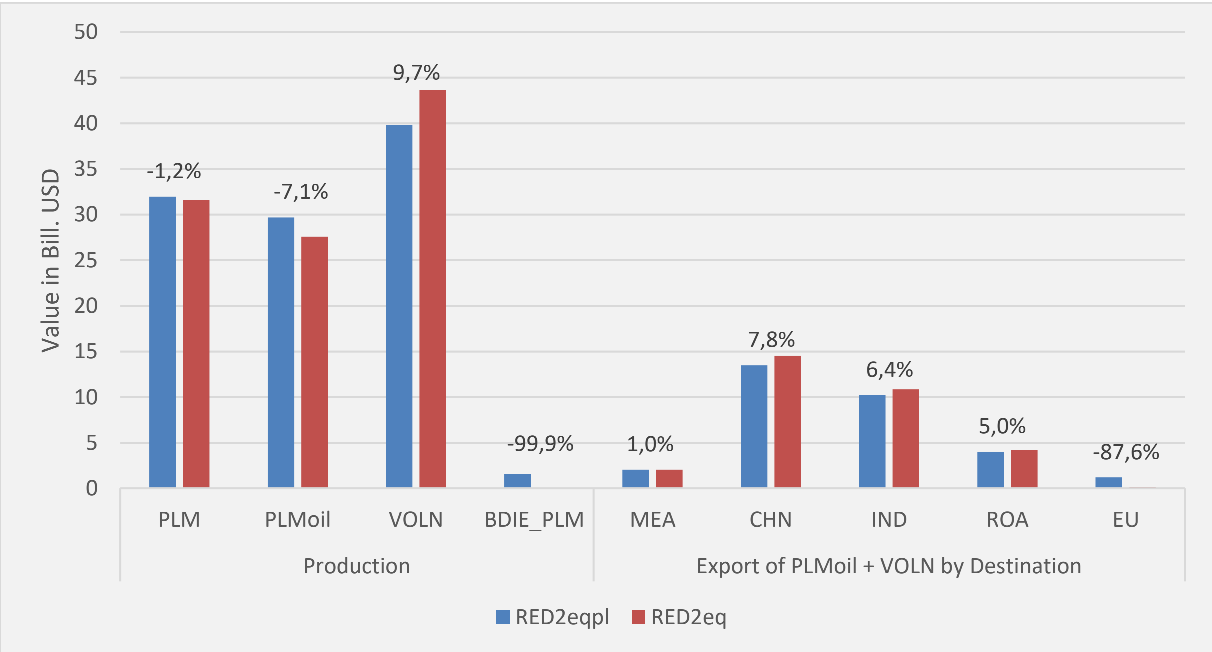

Figure 15: Production of selected commodities and exports of palm and vegetable oils in MAI 2030. Percentage values indicate change due to palm oil phase-out. PLM = Palm fruit, PLMoil = Palm oil, VOLN = Other vegetable oils, BDIE_PLM = Palm oil Biodiesel; MEA = Middle East and North Africa, CHN = China, IND = India, ROA = Rest of Asia.

3.5 Discussion and Conclusion

This study analyzes the recast of the EU's Renewable Energy Directive II that has introduced restrictions for biofuel feedstock from food and feed crops as well as a phase-out of feedstock from land with high carbon value, mainly pertaining to palm fruit. Despite these restrictions, the RED II sets mandates for biofuels in the EU transport sector that are likely to have impacts on global agricultural markets and land use.

Our findings lead to several conclusions. First, we find that given current fossil fuel prices, biofuels are not cost-competitive compared to fossil oil-based fuels, which is in line with results from Philipidis et al. (2019). Without policies such as the RED II, biofuel consumption in the EU would return to a negligible level. Secondly, the increasing demand for biofuels is to a large extent satisfied by rapeseed-based biodiesel, which is especially driven by the phase-out of palm oil-based biodiesel that causes imports of palm oil and palm oil-based biodiesel to the EU to decline. This is compensated for by higher production quantities of EU-based rapeseed and rapeseed oil, and to a certain degree by an increase of imported soybean oil. EU farmers can be considered to be beneficiaries of this policy since they generate additional revenues due to expanding the production of rapeseed while simultaneously obtaining higher prices. In turn, they produce less grains and other annual crops. Nevertheless, impacts on global grain markets remain small and prices increase by a maximum of 1% depending on the scenario.

Furthermore, our results show how crucial it is to differentiate between different oilseed crops and vegetable oils when analyzing biofuel policies. Phillipidis et al. (2018), who also specifically addresses the palm oil phase-out, do not find considerable impacts on the EU's crop markets, as they do not consider feedback and substitution effects between vegetable oils on domestic and global markets. Our results show that the phase-out of palm oil as biofuel feedstock changes the use of different vegetable oil types. More rapeseed oil and soybean oil are used for biofuels, and palm oil is increasingly used by non-biofuel sectors such as the chemical and food industry within the EU, but also in non-EU regions such as China and India. A shortcoming of our model is that we cannot consider different qualities and hence prices of certified and un-certified palm oil (or palm oil-based biodiesel). Cultivating certified palm oil for the EU biofuel market requires additional investments which are usually compensated for by a price mark up. Other markets and sectors do not require certification, and only niche markets pay a premium for certified palm oil. It is highly questionable if farmers of certified palm oil can compensate their costs of investment once the palm oil phase-out is in place. Thus, the implications for palm fruit farmers who used to sell to the EU biofuel market might be underestimated, and social and ecological efforts to reach the certification standard could be reversed.

Our findings also support the claim of palm oil-producing countries that the palm oil phase acts as a technical barrier to trade. We find that the phase-out of palm oil as a biofuel feedstock in the EU has only a relatively small impact on global palm fruit production, while EU farmers are the primary beneficiaries. The motivation by the EU for the phase-out is the protection of high carbon stock (hcs) land by reducing the expansion of palm fruit production. Nevertheless, besides an expansion in rapeseed production, our results show an expansion of soybean production in Brazil. There is a considerable probability that a share of this expansion might actually take place in hcs land, but now in South America instead of South-East Asia.

Therefore, a key factor for accessing the effectiveness of the policy is the biofuel productivity of oilseed crops in terms of land use. As shown above, our model results indicate that due to the palm oil phase-out, more than three times of the area saved by reduced palm fruit cultivation is needed for additional soybean and rapeseed production to meet the demand for biofuels. These findings lie in between the range of results of other studies. Debenath (2019) states that the biofuel yield for palm fruit is 4.45 mt/ha while it is 1 mt/ha for rapeseed and 0.36 mt/ha for soybean. In contrast, in their report for the European Commission, Valin et al. (2015) assume 1.7 times higher biofuel yield per ha for palm fruit compared to rapeseed, and 5 times higher yield compared to soybean. For the RED II calculation of land expansion into *hcs*-land, as described in the introduction, the European Commission chooses a productivity factor of 2.5 for palm fruit and 1 for rapeseed and soybean (European Union 2019). Compared to the scientific studies, especially the productivity factor for soybean is selected very generously. Moreover, given the absolute historic expansion of soybean production areas into *hcs* land in South America, like the Amazon Forest but also the Cerrado or the Chaco Forest, it is questionable whether the shift in biodiesel production from palm oil to soybean oil substantially reduces global emissions from land use change. The relatively lower share of expansion into *hcs* land of soybean compared to palm fruit production might be overcompensated by the higher amount of land required for producing the same amount of biodiesel. Consequently, it raises concerns if it is justified to have a palm oil biodiesel phase-out, but not a soybean oil biodiesel phase-out.

The results of this study point to the following recommendations. Besides palm fruit production for biofuels, policies should ensure the responsible production of any crop in sensitive and so-called high ILUC risk, regions. Focusing only on one crop in a single sector, either with binding sustainability criteria or a ban of utilization leads to substitution effects and waters down the effectiveness of the policy. As elaborated on above, the palm oil phase-out jeopardizes the efforts for sustainable palm fruit production, without bringing forest restoration or a halt of deforestation in tropical areas. Tropical forests might benefit more from enhanced binding sustainability criteria and certification schemes for the use of all vegetable oils in every sector and industry.

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A.3 Appendix

A.3.1 Global and EU Energy Market

The EU's biofuel policy has an impact on global energy markets. The substitution of fossil fuels in the transport sector by biofuels causes prices of unprocessed fuels (coal, crude oil, gas) as well as processed crude oil (refined oil, motor gasoline, transport diesel) to fall by up to 0.4%. This effect is higher under the RED2eq Scenario compared to the RED2corr Scenario, given the higher share of biofuels on total transport fuels under the RED2eq Scenario.

Since in the EU the main type of biofuels is biodiesel the global production of transport diesel declines by 0.6% while the global production of motor gasoline falls by 0.3%. Together with refined oil, they are produced from crude oil, such that with falling demand for crude oil being processed to transport diesel or gasoline, the production of refined oil increases by 0.1%.

Table A4: Change in global average prices, production, and net imports of fossil fuels in 2030 compared to REF

	Δ global prices		Δ global production		Δ EU net imports	
	RED2corr	RED2eq	RED2corr	RED2eq	RED2corr	RED2eq
coal	-0.1%	-0.2%	0.0%	0.0%	-0.5%	-0.7%
crude oil	-0.2%	-0.4%	-0.1%	-0.2%	-1.1%	-2.0%
gas	-0.1%	-0.2%	0.0%	0.0%	-0.1%	-0.1%
refined oil	-0.2%	-0.3%	0.1%	0.1%	-3.5%	-6.4%
motor gasoline	-0.2%	-0.3%	-0.1%	-0.3%	1.3%	1.9%
transport diesel	-0.2%	-0.4%	-0.4%	-0.6%	-3.6%	-5.7%

The EU is a net importer of all fossil fuels except motor gasoline. With the substitution of fossil fuels with biofuels, net imports of transport diesel are reduced by 3.6% under the RED2corr Scenario and 5.7% under the RED2eq Scenario, while negative imports (meaning net exports) of motor gasoline rise by 1.3% and 1.9% respectively. Similarly, crude oil exports are reduced, and via substitution effects amongst the other unprocessed fossil fuel sectors, also imports of coal and gas decline to a smaller degree (0.1 to 0.7%).

A.3.2 Additional Tables and Figures

Table A5: Regions in DART-BIO

Central and South America		**Europe**	
BRA	Brazil	FSU	Rest of former Soviet Union
PAC	Paraguay, Argentina, Uruguay, Chile	CEU	Central European Union with Belgium, France, Luxembourg, Netherlands
LAM	Rest of Latin America	DEU	Germany
		MED	Mediterranean with Cyprus, Greece, Italy, Malta, Portugal, Spain
Middle East and Northern Africa		MEE	Eastern European Union with Austria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia, Slovenia, Romania, Bulgaria, Croatia
MEA	Middle East and Northern Africa	NWE	North-Western European Union with Denmark, Finland, Ireland, Sweden, United Kingdom
AFR	Sub-Saharan Africa	RNE	Rest of Northern Europe: Switzerland, Norway, Lichtenstein, Iceland
Asia		**Northern America**	
CHN	China, Hong Kong	CAN	Canada
IND	India	USA	United States of America
EAS	Eastern Asia with Japan, South Korea, Taiwan, Singapore		
MAI	Malaysia, Indonesia	**Oceania**	
ROA	Rest of Asia	ANC	Australia, New Zealand, Rest of Oceania
RUS	Russia		

Table A6: Sectors in DART-BIO

Agricultural related products (29)		**Energy products (15)**	
<u>Crops</u>		COL	Coal
PDR	Paddy rice	CRU	Oil
WHT	Wheat	GAS	Gas
MZE	*Maize*	*MGAS*	*Motor gasoline*
GRON	Other cereal grains	*MDIE*	*Motor diesel*
PLM	*Oil Palm fruit*	OIL	Petroleum and coal products
RSD	*Rapeseed*	ELY	Electricity
SOY	*Soybean*	*ETHW**	*Bioethanol from wheat*
OSDN	Other oil seeds	*ETHM**	*Bioethanol from maize*
C_B	Sugar cane and sugar beet	*ETHG**	*Bioethanol from other grains*
AGR	Rest of crops	*ETHS*	*Bioethanol from sugar cane*
		ETHC	*Cellulosic Bioethanol from straw*
<u>Processed agricultural products</u>			
VOLN	Other vegetable oils	<u>Biofuels</u>	
SGR	Sugar	*BETH*	*Bioethanol*
FOD	Rest of food	*BDIE_PLM*	*Biodiese made from palm oill*
		BDIE_OTH	*Biodiesel made from other vegetable oils*
		UCOME	*Used Cooking Oil Methyl Ester*
*PLMoil**	*Palm oil*		
*RSDoil**	*Rapeseed oil*	**Non-energy products (3)**	
*SOYoil**	*Soybean oil*	CRPN	Other chemical rubber plastic products
*OSDNoil**	*Oil from other oil seeds*	ETS	Paper, minerals, and metals
*SOYmeal**	*Soybean meal*	OTH	Other goods and services
*OSDNmeal**	*Meal from other oil seeds*		
*PLMmeal**	*Palm meal*	**Forest and forest products (2)**	
*RSDmeal**	*Rapeseed meal*	FRS	Forestry
*DDGSw**	*DDGS from wheat*	FRI	Forest related industry
*DDGSm**	*DDGS from maize*		
*DDGSg**	*DDGS from other cereal grains*		
UCO	*Used cooking oil*		
STRAW	*Starches, straw*		
<u>Meat and dairy products</u>			
OLVS	Outdoor livestock and related animal products (cattle and other grazing animals, raw milk and wool)		
ILVS	Indoor livestock (swine, poultry and other animal products from indoor livestock)		
PCM	Processed animal products		

Note: New products are in cursive. All goods are produced by an analogous industry, except were indicated by an asterisk (*), which indicates jointly produced goods. Bioethanol and DDGS are jointly produced by the bioethanol industry (3 types of industries), and oilseeds oil and meal are jointly produced by the vegetable oil industry (4 types of industries).

Table A7: Shares of different biofuels in total transport fuels consumption in different EU regions in percent

		REF 2018	REF 2030	RED2max 2030	RED2corr 2030	RED2eq 2030	RED2eqPL 2030
BETH	**CEU**	6.1%	2.4%	2.4%	6.1%	7.0%	7.0%
	DEU	4.3%	2.6%	2.6%	4.3%	7.0%	7.0%
	MED	1.2%	0.8%	0.8%	1.2%	7.0%	7.0%
	MEE	3.8%	1.4%	1.4%	3.8%	7.0%	7.0%
	NWE	3.7%	1.1%	1.1%	3.7%	7.0%	7.0%
BDIE_OTH	**CEU**	3.6%	1.4%	1.4%	5.1%	7.0%	5.3%
	DEU	3.3%	0.3%	0.3%	4.2%	7.0%	5.3%
	MED	3.0%	0.8%	0.8%	4.5%	7.0%	5.2%
	MEE	2.9%	2.1%	2.1%	3.6%	7.0%	5.3%
	NWE	3.4%	0.2%	0.2%	4.1%	7.0%	5.3%
BDIE_PLM	**CEU**	1.5%	0.0%	0.0%	0.0%	0.0%	1.8%
	DEU	1.2%	0.0%	0.0%	0.0%	0.0%	1.8%
	MED	1.9%	0.0%	0.0%	0.0%	0.0%	1.7%
	MEE	0.9%	0.0%	0.0%	0.0%	0.0%	1.8%
	NWE	0.9%	0.0%	0.0%	0.0%	0.0%	1.8%
UCOME	**CEU**	1.7%	0.2%	0.2%	1.7%	1.7%	1.7%
	DEU	0.9%	0.1%	0.1%	1.2%	1.7%	1.7%
	MED	0.8%	0.2%	0.2%	1.2%	1.7%	1.7%
	MEE	1.0%	0.6%	0.6%	1.3%	1.7%	1.7%
	NWE	1.5%	0.7%	0.7%	1.7%	1.7%	1.7%
BDIE_SUM	**CEU**	6.8%	1.6%	1.6%	6.8%	8.7%	8.7%
	DEU	5.4%	0.4%	0.4%	5.4%	8.7%	8.7%
	MED	5.7%	1.0%	1.0%	5.7%	8.7%	8.7%
	MEE	4.9%	2.7%	2.7%	4.9%	8.7%	8.7%
	NWE	5.8%	0.9%	0.9%	5.8%	8.7%	8.7%

Note: The share of bioethanol (BETH) shows its share in the sum of gasoline and bioethanol; the shares of biodiesel types show their share in the sum of fossil diesel and all biodiesel types. BDIE_SUM is the sum of all three biodiesel types (BDIE_OTH, BDIE_PLM and UCOME).

4 Land for Fish: A scenario-based CGE analysis of the effects of aquaculture production on agricultural markets.

Tobias Heimann[1] and Ruth Delzeit[1,2]

[1] Kiel Institute for the World Economy

[2] University of Basel

Abstract

Aquaculture fish production is a fast-growing food sector and increasingly relying on plant-based protein fodder to substitute fishmeal utilization. This study employs a global Computable General Equilibrium (CGE) model to quantify the effects of plant-based fodder consumption by the aquaculture sector on agricultural markets and land use. We conduct a scenario analysis simulating, first, the fish sector developments expected by FAO; second, a rebuilding of sustainable wild fish stocks to achieve SDG 14; and third, a stronger expansion in aquaculture production with varying fishmeal supply. The results show direct effects of aquaculture production and limited fishmeal supply on agricultural production, land use, and food prices. Substituting fishmeal with plant-based feed when rebuilding sustainable fish stocks has lower effects on agricultural markets than growth in aquaculture production comparable to the first decade of this century. In addition, expanding aquaculture production increases prices for capture fish via fishmeal demand. Finally, rebuilding sustainable fish stocks to achieve SDG 14 has significant adverse effects on welfare and food prices in marine fish dependent regions in the southern hemisphere. The results of this study illustrate the interconnectedness of SDG 14 (*Life under Water*), SDG 15 (*Life on Land*) and SDG 2 (*No Hunger*).

4.1 Introduction

Fish plays a crucial role in the human food basket as a rich source of proteins and vital nutrients (Troell, et al., 2014). The global consumption of fish has strongly risen in the last decades (FAO, 2018). However, the sustainability of current fish production is debatable. Even with regional quotas in place, many wild fish species are fished at an unsustainable intensive level, bringing global capture fishing to its natural limits (World Bank, 2017). While the fishing volumes for wild fish have stagnated, the increasing demand for fish is met by the fast expansion of aquaculture fish production (FAO, 2020). In the last two decades, aquaculture fish production has expanded stronger than any grain or livestock production (Troell, et al., 2014). Most of this growth comes from fed-fish species, such as finfish and crustacea (FAO, 2018), which still rely on wild catch fishmeal as fodder input (Froehlich, et al., 2018a; FAO, 2020). Froehlich et al. (2018a) advocate that if the relevance of fishmeal as fodder is not reduced, fishmeal demand by aquaculture production growth will push forage fish capture above its ecological limits, jeopardizing the sustainability of aquaculture fish production for wild fish stocks. In the last years, fish farmers have already started reducing fishmeal use and substituting it with plant-based protein fodder (FAO, 2018). However, this change is not rooted in sustainability concerns. Tacon & Metian (2015) argue that this can be seen as a reaction to high prices for fishmeal due to increasing demand and decreasing supply of forage. They add that as this trend will continue, the fish sector requires alternative fodder commodities for the future.

Even when considering plant-based feed, the sustainability of aquaculture production remains uncertain. The production factor land is already under great pressure, as it is required for food production for humans and terrestrial animals, biomass provision for material and energy usage, ecosystem service provision, greenhouse gases (GHG) mitigation and capture. Consequently, various questions emerge: How severe is the additional pressure on crop production and land if fishmeal is substituted by plant-based fodder? Which regions are most affected by the plant-based fodder demand of aquaculture fish production? How do global markets react if ambitioned quotas limit wild catch so that global fish stocks may be rebuilt to sustainable levels within 15-20 years? What are the implications for welfare and food prices in developing regions? And finally, is aquaculture production a sustainable alternative for capture fisheries?

This study highlights the interdependencies and trade-offs for achieving sustainable development, as reflected by the UN Sustainable Development Goals (SDG), more precisely SDG 14 (*Life under Water*), SDG 15 (*Life on Land*) and SDG 2 (*No Hunger*). Rebuilding sustainable fish stocks is stated by SDG Target 14.4. However, reducing capture fisheries can foster the demand for other animal protein sources, whose production might affect land use and land-use change, thus negatively affecting the achievement of SDG 15. Furthermore, increasing demand for agricultural products can lead to higher prices. In addition, not only reduced availability of capture fish but also changes in crop production and increased prices for food and feed crops can have adverse effects on food security, and hence, the achievement of SDG 2. In turn, increasing aquaculture production to produce more food (SDG 2) can have adverse effects on marine ecosystems through fishmeal demand (SDG 14) and on terrestrial ecosystems by increased demand for fodder crops (SDG 15). Our results spotlight these trade-offs to make them visible for policymakers, so that sustainable policy design can assess and consider such trade-offs while reaching for the achievement of the SDGs.

Here, we employ a version of the Dynamic Applied Regional Trade (DART) model, namely DART-BIOFISH, to analyze feedback effects from increasing aquaculture fish consumption on capture fishery production and plant-based fodder demand. DART is a global computable general equilibrium (CGE) model. An essential attribute of DART-BIOFISH is the explicit modelling of biofuels and their by-products (e.g. oilseed meal) used in the livestock industry, which allows for a detailed characterization of the fodder composition for livestock and aquaculture, as well as the evaluation of feedback effects on land use. Land-use change through land conversion from mangroves or other land types into ponds cannot be analyzed.

In section two, we provide an overview of the resource economic linkages of capture and aquaculture fisheries. Section three describes the model and the implementation of the explicit fish sector, as well as the scenario design. The results are described in section four, followed by a discussion and conclusions in section five.

4.2 Literature review

The main focus of this study is to use an applied model to simulate resource economic linkages between capture fisheries, aquaculture production, and fodder supply, and analyze their implication on agricultural markets. Several studies already highlight the resource economic mechanics between capture and aquaculture fisheries. While Anderson (1985) was the first to derive a formal model capturing the competition of capture and aquaculture fisheries on a common market, later studies also integrated interaction caused by fishmeal and oil consumption in the aquaculture industry (Mullon, et al., 2009; Merino, et al., 2010; Regnier & Schubert, 2017; Bergland, et al., 2019). Most fishmeal production comes from small pelagic forage fish species that play a crucial role in the natural marine food chain (Tacon & Metian, 2009). Naylor et al. (2000) elaborate on the ecological links between aquaculture and capture fisheries, arguing that an extensive and unsustainable expansion of aquaculture farming can pose significant threats for both fishing industries due to ecological overexploitation. Mullon et al. (2009) provide an explicit model of the global fishmeal and fish oil market, which Merino et al. (2010 & 2012) employed to analyze feedback effects from aquaculture production on fishmeal production and prices. These studies support the remarks by Naylor et al. (2000), who advocate for smart fishery governance to protect the ecosystem, meet societal needs and emphasize the relevance of alternative plant-based protein sources for fish fodder. A crucial factor to analyze such feedback effects is the "Fish In - Fish Out" (FIFO) ratio that determines the efficiency of aquaculture in terms of fishmeal consumption (Merino, et al., 2012).

Regnier and Schubert (2017) employ a Lotka-Volterra type model to assess the implications of aquaculture farming on biological resources and consumer utility. Here, a key parameter is the technological efficiency which indicates how much fish is required for aquaculture production and thus reflects the FIFO ratio. This ratio can be reduced by either technological progress, which means increasing feeding efficiency and the substitution of fishmeal by plant-based feed, or shifting the production to less carnivorous species (Regnier & Schubert, 2017). In fact, the aquaculture industry implemented significant innovations in feed composition and feeding efficiency in recent years, leading to a reduction of the FIFO ratio (Kobayashi, et al., 2015; FAO, 2020). In our research, the FIFO depends on the input prices of the respective fodder items and their elasticity of substitution; thus, this fishmeal efficiency parameter is price-driven.

The results of our paper and the study of Regnier and Schubert (2017) demonstrate how evidence from analytical and applied models can be combined to deliver a more holistic picture of the implicit effects of economic activities. While Regnier and Schubert (2017) conduct a detailed theoretical analysis of the effects of aquaculture production on the marine ecology, we concentrate on the key aspect of fishmeal efficiency improvements and their implications on agricultural markets and land use.

So far, the land use of aquaculture fish production has been a neglected topic in CGE-based food market analysis. Kobayashi et al. (2015) employ the partial equilibrium model IMPACT from the International Food Policy Research Institute (IFPRI) to conduct scenario-based projections on capture and aquaculture fish production until 2030. However, they do not evaluate feedback effects on land-use change and agricultural markets. Froehlich et al. (2018b) use a static agricultural sector model to estimate feed and land-use linkages considering aquaculture in 2050. They conclude that even if one-third of the global protein demand of humans is met by fish, the impact on land use compared to livestock is relatively low due to the high feed efficiency of aquatic species. Nevertheless, Tacon and Metian (2015) state that while aquaculture consumes only a small fraction of terrestrial compound feed on a global scale, this fraction can be much higher on regional markets due to the regional concentration of aquaculture production. According to the FAO (2020), Asia accounts for 89% of aquaculture production, with China alone being responsible for 68% of global production in 2018. With the DART-BIOFISH model, we are able to identify which regions are most affected by feedback effects through agricultural markets.

4.3 Method

4.3.1 The DART model

The DART model is a multi-sectoral, multi-regional recursive dynamic CGE model of the world economy (Springer 1998). It is based on recent data from the Global Trade Analysis Project (GTAP), covering multiple sectors and regions (Aguiar, et al., 2016). The economy in each region is modelled as a competitive economy with flexible prices and market clearing conditions. DART-BIO is the land-use version of the DART model and shares the same core characteristics. However, DART-BIO focuses on the heterogeneity of land, the complex production process chains of biofuels, and therefore includes several activities/commodities not present in the original GTAP database.

The DART-BIO model is calibrated based on the GTAP 9 database (Aguiar et al., 2016), representing the global economy in 2011 and covering 57 sectors and 140 regions. To incorporate biofuels and their by-products into the DART-BIO model, several sectors are split and added to the standard GTAP 9 database, as explained in detail in Delzeit et al. (2021). The DART-BIO model includes conventional bioethanol production from sugar cane/beet, wheat, maize, and other grains; and conventional biodiesel production from palm oil, soybean oil, rapeseed oil, and other oilseed oils. It further includes the production of by-products generated during the production process of biofuels, like dried distillers grains with solubles (DDGS) of bioethanol production from grains and oilseed and meal/cakes of the vegetable oil industry (see Delzeit et al. (2021) for details). Figure A10 in the appendix shows the implemented production pathways for biodiesel and the co-production of feed for the livestock and aquaculture industry.

In order to account for land heterogeneity, the DART-BIO model incorporates the agro-ecological zone (AEZ) database (Lee, et al., 2005; Baldos, 2017). Thus, we use 18 GTAP-AEZs, covering six different lengths of growing periods spread over three different climatic zones. Within each AEZ and region, the land is allocated to different uses (i.e. cropland, pasture, and forest) via a constant elasticity of transformation (CET) structure (for details, see Delzeit et al., 2021).

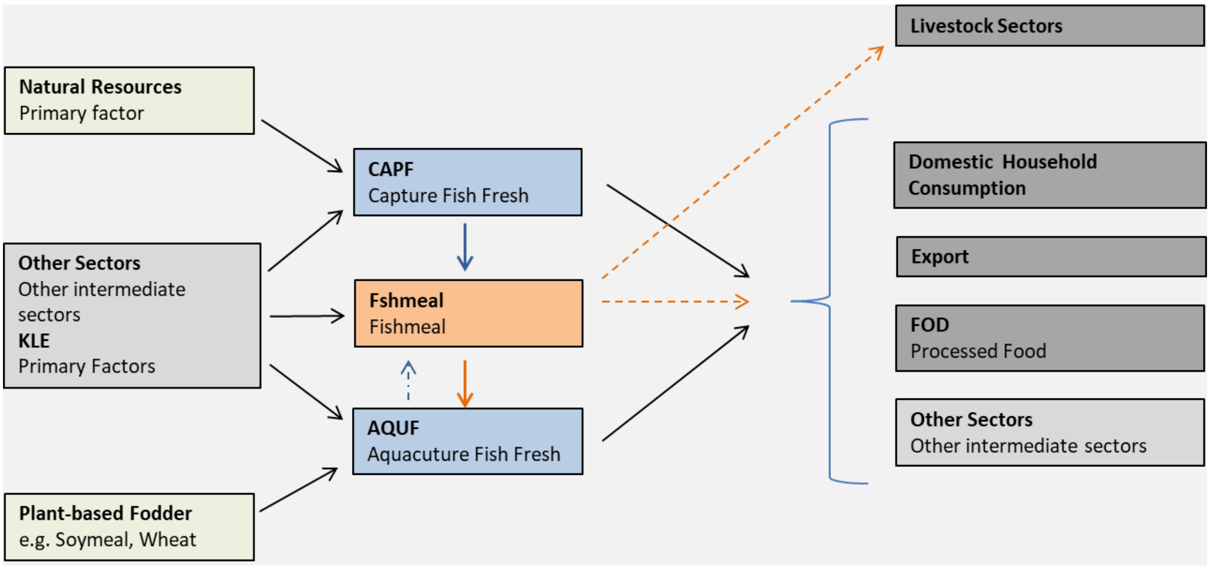

Figure 16: Fish sectors in the DART-BIOFISH model

In addition to the DART-BIO sectors, three fish sectors (capture fisheries, aquaculture production, fishmeal production) are added for creating the database for the new version called DART-BIOFISH. In this version, we can account for interdependencies of capture fisheries and aquaculture production via consumption preferences for fish products and substitution possibilities for fishmeal and plant-based fodder in aquaculture fish production. Figure 16 provides an overview of the linkages between the respective sectors. The two sectors for processed capture and aquaculture fish are aggregated to the general food sector to reduce the number of sectors in the model. The fishmeal sector also captures fish oil production but is referred to as fishmeal within this paper. Furthermore, the appendix holds a detailed description of the construction of the DART-BIOFISH database. We devoted special attention to the construction of realistic feed shares in the aquaculture industry. The fodder composition is based on Pahlow et al. (2015), who provide species-specific estimates on 88% of all global commercial feed-fed fish. The aquaculture sector in the DART-BIOFISH model only consists of species with known fodder composition. Compared to the FAO data on aquaculture production (FAO, 2020), this translates to 80% of total fed fish aquaculture.

A complete list of sectors can be found in the appendix, as well as the regional aggregation, which differentiates the leading biofuel producing and consuming countries in line with the focus of the model on analyzing dynamic effects of bioenergy and land-use policies.

4.3.2 Fish Sector Specifications

As described in Calzadilla et al. (2016), the production of goods and services in the DART model follows a nested production structure with constant elasticities of substitution (CES). When modelling aquaculture fish production, we need to define a specific nested production structure of this sector (Figure 17). For protein feed like fishmeal or oilseed crop meal, we use a substitution elasticity of 2, which is the same as for feed in livestock production. This value is chosen because it can be assumed that the feed items are imperfect substitutes and thus that the elasticity should be larger than 1. Since there is no empirical data for these elasticities, we test the sensitivity in a sensibility analysis (see section 4). Considering the nesting of protein and non-protein feed, we decided on no substitution. On the one hand, there are no reliable estimations on substitution elasticities between those two food categories, as they may be very fish-specific. On the other hand, fish needs a certain protein intake to grow and develop. Thus, we assume that the share of protein feed must remain constant over time while we allow for substitution within the source of protein. In the sectors for processed food (FOD) and services (SERV; e.g. restaurants), we allow for an imperfect substitution of meat and fish products. Research has shown that fish consumption is related to market developments of meat products, in particular poultry and pig meat (Troell, et al., 2014; FAO, 2018), which are reflected by the sector *"Indoor Livestock"* (ILVS) in our model. Therefore, we also select a substitution elasticity of 2 for animal products in the production structure of FOD and SERV.

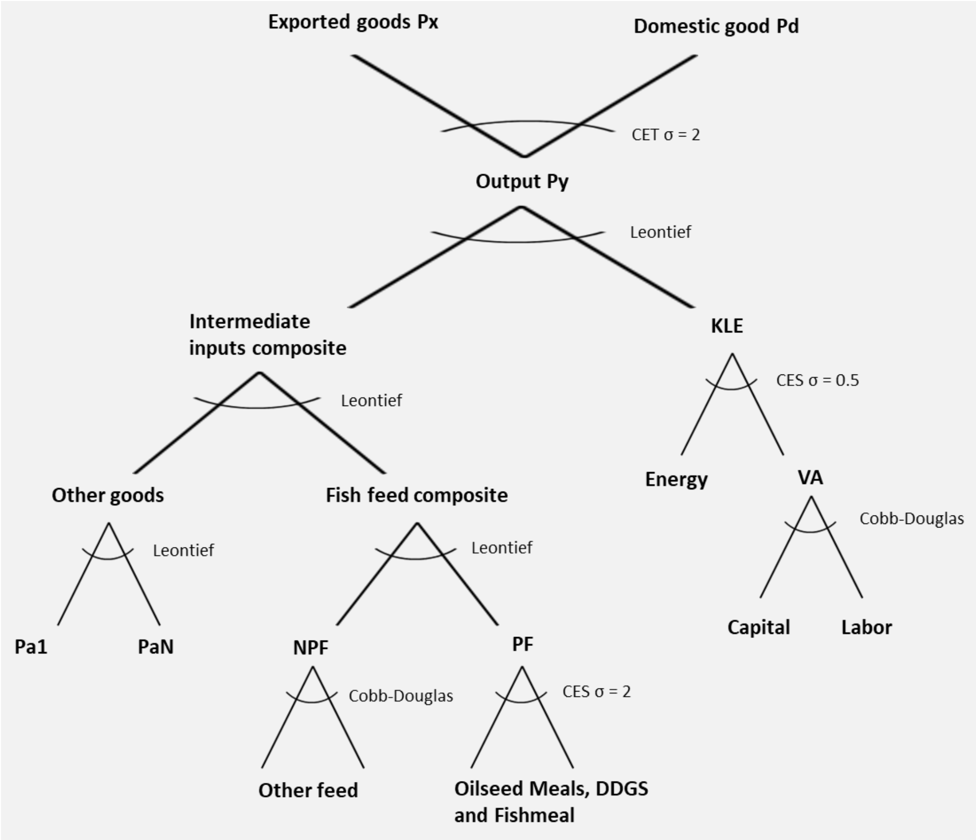

Figure 17: Nesting of aquaculture production in DART-BIOFISH

On the demand side of the model, consumer preferences follow the linear expenditure systems (LES) implemented in DART. Since we cannot differentiate between fish species and catch origin, we assume identical income elasticities for aquaculture and capture fish as provided by GTAP for the initial fish sector.

4.3.3 Scenarios

To evaluate the interdependencies of capture fisheries, aquaculture, and crop production, a scenario analysis is employed. Table 8 provides an overview of the quantification. While the model runs from 2011 to 2030, the analysis only concentrates on the period of 2018 to 2030. The years 2011 to 2018 are used to calibrate the fish production shares of 2018, as explained in the appendix. In this period, the model is identical for all scenarios.

The *Baseline* follows the FAO estimations from the 2020 version of "*The State of World Fisheries and Aquaculture*" report. For the *SDG14* scenario, we assume ambitious total allowable catch (TAC) quotas to rebuild sustainable fish stocks until 2030 such that the target 14.4 of the SDGs is achieved. The quantification for rebuilding sustainable marine fish stocks reflects the moderate path of the World Bank Report *"The Sunken Billions Revisited"* (World Bank, 2017).

The share of fish protein in the human diet increases with rising per capita incomes (FAO, 2020). Hence, not only population growth leads to more fish consumption, but also economic growth. However, production factors like insufficient transport infrastructure and disease control, but also governance and regulatory constraints hinder the growth of aquaculture production (Troell, et al., 2014; Gentry, et al., 2017; OECD/FAO, 2017). We assess the impact of overcoming these barriers to growth by two additional scenarios: *FGrow* and *LimFishm*. In both scenarios, we model stronger growth for the aquaculture sector. We decided to assume a doubled annual growth rate of the FAO projection for aquaculture production because this approximately reflects the historical growth rate of the aquaculture sector in the first decade of this century (FAO, 2020). In addition, in the *LimFishm* scenario, fishmeal becomes scarce so that the global production quantities remain on the same level as in the FAO projection. This scenario accounts for the projection that with increasing demand, an increase in fishmeal production from fodder fish is not expected due to regulations to protect fish stocks as well as high costs and required effort for enlarging catch activities driven by shrinking fish stocks (FAO, 2020).

Considering the dynamics of the model, total factor productivity (TFP) is calibrated according to the GDP estimation of the OECD (OECD 2018a), and population growth is taken from the OECD (OECD 2018b). The average global agricultural productivity growth is at 1.2%, which is in line with the estimations of the FAO/OECD Agricultural Outlook (FAO/OECD, 2020). These dynamics are identical for all scenarios.

Table 8: Scenario Quantification

Scenario / ***Sector***	**FAO Projection (Baseline)**	**Achieve SDG 14 (SDG14)**	**Fast Growth (FGrow)**	**Limited Fishmeal Supply (LimFishm)**
Capture Fisheries	Region-specific FAO projection	Reduction by 5% p.a. from 2018 – 2023, then constant	Region-specific FAO projection	Region-specific FAO projection
Aquaculture Production	Region-specific FAO projection	Region-specific FAO projection	Double growth rate of region-specific FAO projection	Double growth rate of region-specific FAO projection
Fishmeal Production	Global production constant from 2018 - 2030	Endogenous	Endogenous	Global production constant from 2018 - 2030

4.4 Results

4.4.1 Global Perspective

Global Markets

The first section of the results provides an overview of the scenario effects on global agricultural markets. Figure 18 displays the *Baseline* development of fish production and the most relevant fish feed sectors over time. By scenario design, capture fisheries and fishmeal production stay nearly constant, while global aquaculture production increases by 2.4% p.a.. This leads to strongly increasing fishmeal prices, with a faster increase in capture fish prices than prices for aquaculture fish. In the *Baseline* scenario, soybean meal production expands most, with moderately rising prices scoring about half the price level of fishmeal.

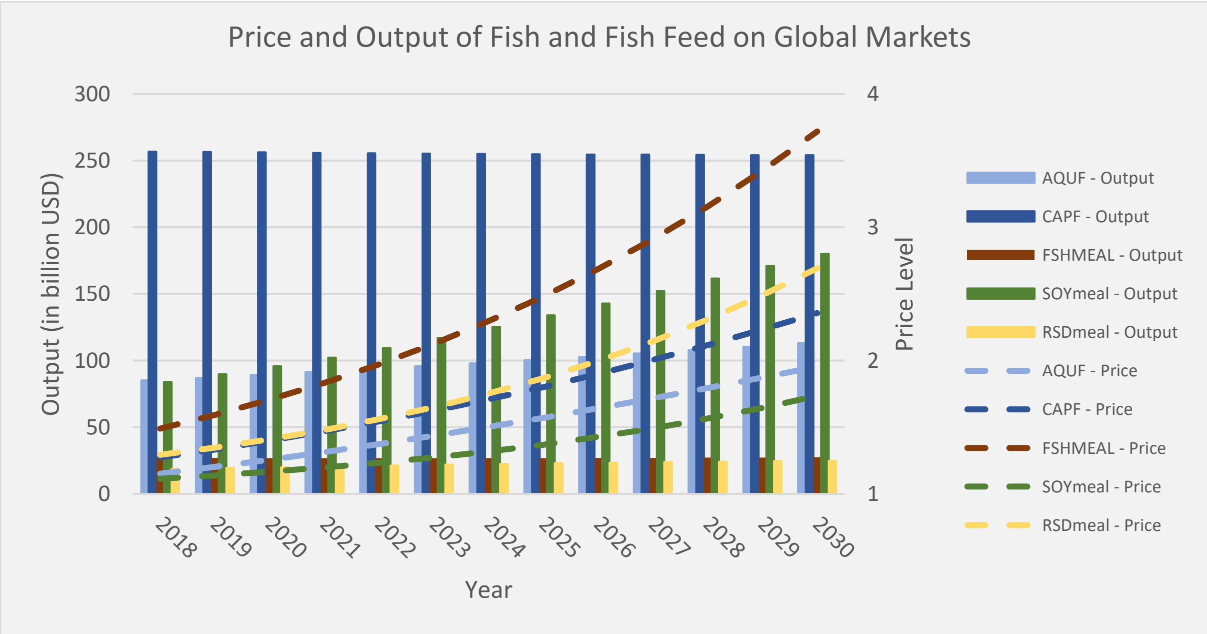

Figure 18: Baseline development of global production and prices for fish and main fish feed 2018-2030.

Table 9 shows the differences in the scenario results compared to the *Baseline* scenario, for the year 2030. Rebuilding sustainable fish stocks in scenario *SDG14* results in 21.8% lower wild fish catches and causes a price spike of 37.6%. This substantial price jump must be kept in mind when analyzing the effects of the *SDG14* scenario on food security, especially in coastal regions. Furthermore, we see a reduction of 17.6% in fishmeal production. The reaction of the fishmeal sector is mirrored by the oilseed meal sectors, which show a moderate price effect but a larger expansion in production by 4.8% to 12.5%. Interestingly, we observe a strong joined reaction of fishmeal and oilseed meal sectors in scenario *FGrow*, in which aquaculture production is 32.9% higher than in the *Baseline*. In scenario *LimFishm*, fishmeal is much more expensive. As a result, the production and price of the oilseed meals are the highest of all scenarios. In all scenarios, we can observe feedback effects on crop production and prices, as shown in the upper third of Table 9.

Table 9: Global production and prices for agricultural commodities and feed. Differences to Baseline Scenario. Output in billion USD.

Sector	Baseline Output 2030	Output			Price		
		Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm
WHT	321.27	0.1%	0.3%	0.2%	0.8%	1.6%	2.1%
MZE	311.80	0.1%	-0.4%	-0.6%	0.9%	1.7%	2.5%
AGR	2311.08	-0.2%	-0.1%	-0.3%	0.7%	1.5%	2.0%
RSD	70.68	2.1%	4.5%	7.3%	1.3%	2.8%	4.1%
SOY	252.64	1.6%	2.5%	3.9%	1.3%	2.2%	3.1%
OSDN	130.56	0.7%	1.2%	2.0%	0.8%	1.5%	2.1%
OLVS	986.74	0.8%	-0.5%	-0.6%	1.4%	-0.5%	-0.3%
ILVS	1388.51	1.2%	-1.8%	-2.1%	0.6%	0.7%	1.1%
AQUF	113.14	1.6%	32.9%	32.9%	3.9%	-18.3%	-18.1%
CAPF	254.00	-21.8%	0.0%	0.0%	37.6%	2.7%	3.6%
FSHMEAL	27.58	-17.6%	22.8%	0.0%	27.8%	4.2%	31.1%
RSDmeal	24.89	7.3%	16.0%	26.2%	3.2%	8.1%	10.6%
SOYmeal	180.22	4.8%	7.4%	11.6%	1.4%	2.7%	3.8%
OSDNmeal	16.24	12.5%	25.2%	34.4%	2.1%	4.2%	8.2%

Considering the livestock and fish sectors, two observations need to be pointed out. First, changes in the fish sector have implications on the livestock sector, particularly for indoor livestock (ILVS) like poultry and pig meat. A reduction in capture fisheries increases, and expanding aquaculture production decreases the production of livestock. Therefore, in all scenarios, the price for indoor livestock rises, in scenario *SDG14* due to higher demand for meat, and in *FGrow* and *LimFishm* because of higher feed prices. Second, expanding aquaculture production leads to higher prices for capture fish. The negative price effect from substituting wild catch fish with aquaculture fish in consumer diets is overcompensated by the higher demand for fishmeal, which causes higher prices of fishmeal and capture fish. As a result, aquaculture production does not relieve but rather intensify pressure on wild fish stocks in our model.

It needs to be emphasized that aquaculture production is implemented in the model via a production quota, which absorbs the price effect of aquaculture production between scenario *FGrow* and *LimFishm*. While the price does not change significantly, the endogenous quota in scenario *LimFishm* is 10% higher than in *FGrow*, and can be interpreted as augmented price change for aquaculture fish. In addition, in scenario *SDG14*, the aquaculture production quota is not binding for the region "*Rest of Asia*" (ROA). Therefore, we have a 1.6% higher production than intended. The underlying reason is that outdoor livestock (OLVS) and capture fish get very expensive in that region. In this scenario and region, aquaculture fish becomes, in relative terms, so cheap that it substitutes a large share of OLVS and CAPF consumption. A higher substitution elasticity in the intermediate production of food (FOD) would let the other even cheaper animal product sectors (ILVS, PCM) substitute a larger share of what is now covered by aquaculture fish and thus keep the quota binding. However, implementing a customized elasticity for one region would lead to inconsistencies in the scenario design. Furthermore, it is also an interesting result that in case of achieving SDG 14 the FAO aquaculture production estimate for ROA is simulated to be too low by our model.

Furthermore, due to oilseed oil and meal being co-products from one production process, we see higher oilseed oil production and lower oilseed oil prices, as displayed in Table 10. The lower prices for oilseed oil are passed through to biodiesel production. In scenario *LimFishm*, high aquaculture production combined with low fishmeal production leads to an increase of over 20% in biodiesel production. However, in this study, biofuel consumption is not calibrated to any climate or biofuel policy, and thus much lower than in reality. Nevertheless, the results demonstrate how the DART-BIO model works and that biofuel and the animal feed industry are connected.

Table 10: Global production and prices for vegetable oils and biodiesel. Differences to Baseline Scenario. Output in billion USD.

Sector	Baseline Output 2030	Output			Price		
		Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm
RSDoil	22.93	2.9%	5.9%	9.7%	-4.8%	-12.0%	-16.5%
SOYoil	75.79	3.9%	6.6%	10.3%	-3.8%	-5.9%	-9.2%
OSDNoil	20.74	4.5%	8.1%	10.7%	-3.0%	-5.2%	-7.2%
BDIE	22.96	8.4%	18.2%	23.4%	-1.9%	-3.6%	-4.6%

Fish Feed Composition

Figure 19 displays the initial global aggregated aquaculture fish sector composition in 2018 and the shares of the composition in 2030. Already in the *Baseline*, there is a clear substitution of fishmeal by soybean meal. The share of rapeseed meal stays constant, while other oilseed meals (OSDN) and other feedstuff show slightly higher shares. We can observe the expected reactions caused by the developments of prices as mentioned before. When fishmeal becomes increasingly expensive, it mainly gets substituted by soybean meal.

At the regional level, the most significant substitution of fishmeal by soybean meal can be observed in the region *"Rest of Northern Europe"* (RNE), which includes Norway. The share of fishmeal falls from 52% in 2018 to 31.3% in the *Baseline*, and 21.6% for scenario *LimFishm*, in 2030. Therefore, the soybean meal share increases from 8% in 2018 to 36% in the *Baseline*, and 52% in *LimFishm*, in 2030. The shares for scenarios *SDG14* and *FGrow* are in between the numbers of *Baseline* and *LimFishm*. Also, in *"Rest of Asia"* (ROA), the share of fishmeal is reduced from 7% in 2018 to 2.6% and 2% in *Baseline* and *LimFishm* in 2030, respectively. Here, the variation between the scenarios is small, as the fishmeal share is already very low in the *Baseline*. In China, we see a moderate reduction of the fishmeal share from 25% in 2018 to 18% in the *Baseline* and 13% in *LimFishm*. The weaker reduction of the fishmeal share compared to RNE is rooted in lower fishmeal and high soybean meal prices in China. Thus, the incentive to substitute fishmeal is higher in RNE.

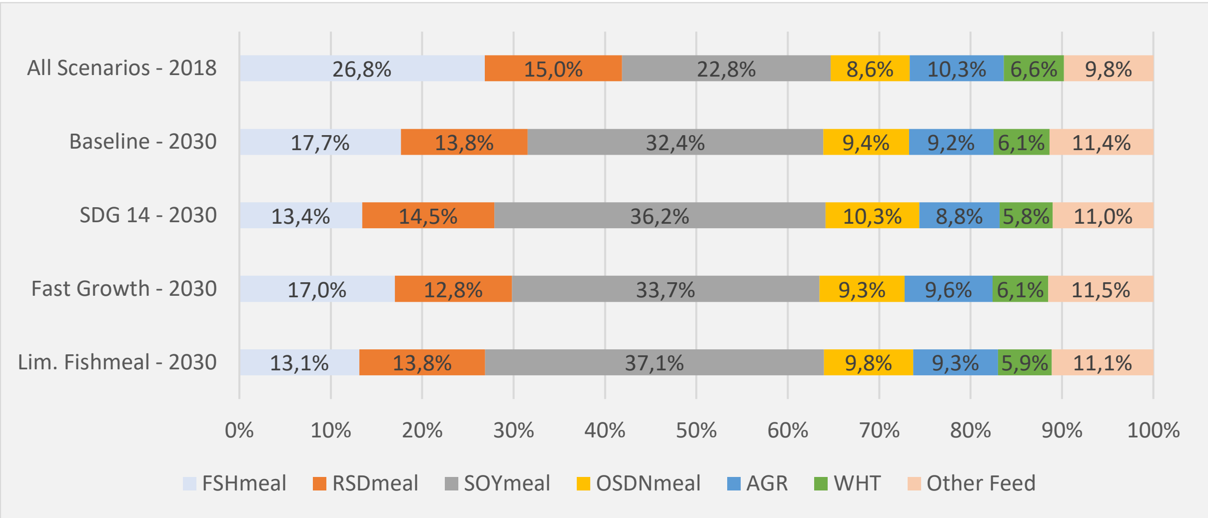

Figure 19: Fish Feed Composition Shares in 2018 and 2030, Global Aggregate.

Global Fish Trade

China is not only the biggest producer but also the biggest net importer of captured fish and aquaculture. In the case of aquaculture, the second-biggest importer is the EU. Figure 20 shows the net trade for aquaculture fish. Interestingly, China has fewer net imports in scenario *SDG14* than in the *Baseline*, while ROA and the EU increase their net imports. A reason for this is the relative prices for animal products in the respective region. While aquaculture production is constant and capture fisheries reduced, it is cheaper to substitute the capture fish reduction by importing aquaculture fish for EU and ROA. In contrast, for China it is more beneficial to decrease net aquaculture imports due to increased prices, and substitute capture and aquaculture fisheries with indoor livestock and processed meat.

However, in scenario *FGrow* and *LimFishm,* net imports rise by about 38% in China and 64% in the EU, whereas LAM and ROA switch from net importers in the *Baseline* to net exporters in the other scenarios. Especially ROA improves its trade balance by expanding aquaculture by twice the expected growth rate. In RNE, we can observe a drop in net exports between scenario *FGrow* and *LimFishm*. The aquaculture production in no other region has a share of fishmeal usage as high as in RNE. When reducing the availability of fishmeal, this region is hit particularly hard by increasing cost, making their product less competitive on global markets, thus leading to fewer exports and more domestic consumption.

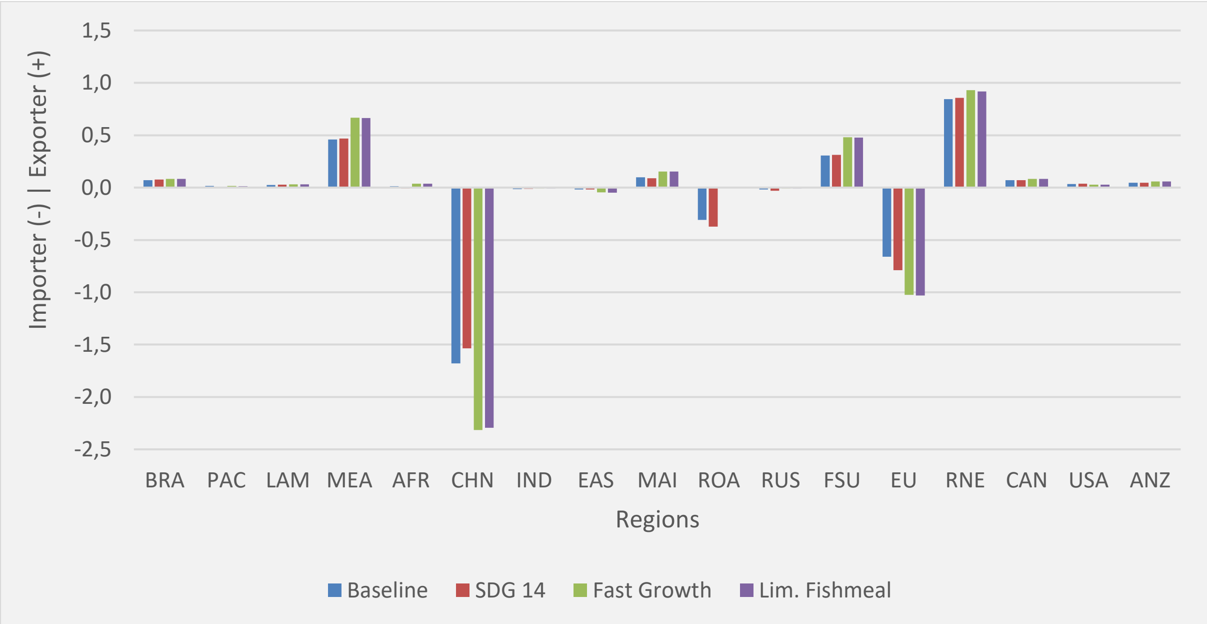

Figure 20: Net Trade of Aquaculture Fish in 2030, including trade within region. In billion USD.

For capture fisheries, China and the EU are the largest net importers, while several regions are net exporters on comparably high levels. The net trade for capture fisheries is displayed in Figure A11 in the appendix. Figure A12 in the appendix shows net trade for soy and rapeseed. China is the leading importer of both crops, with import quantities increasing further in each scenario and subsequent soy exports increasing from Brazil and the USA.

4.4.2 Regional Perspective

Regional Markets

The regional distribution of aquaculture and capture fisheries in the *Baseline* is demonstrated in Figure 21. China is the largest producer of both aquaculture and capture fisheries, followed by ROA. It needs to be emphasized that aquaculture production only covers commercial feed fed fish. In Asia, particularly in China, small-scale filter fish cultivation has a long tradition (FAO, 2020), and the production shares considering total aquaculture would be much higher for these regions.

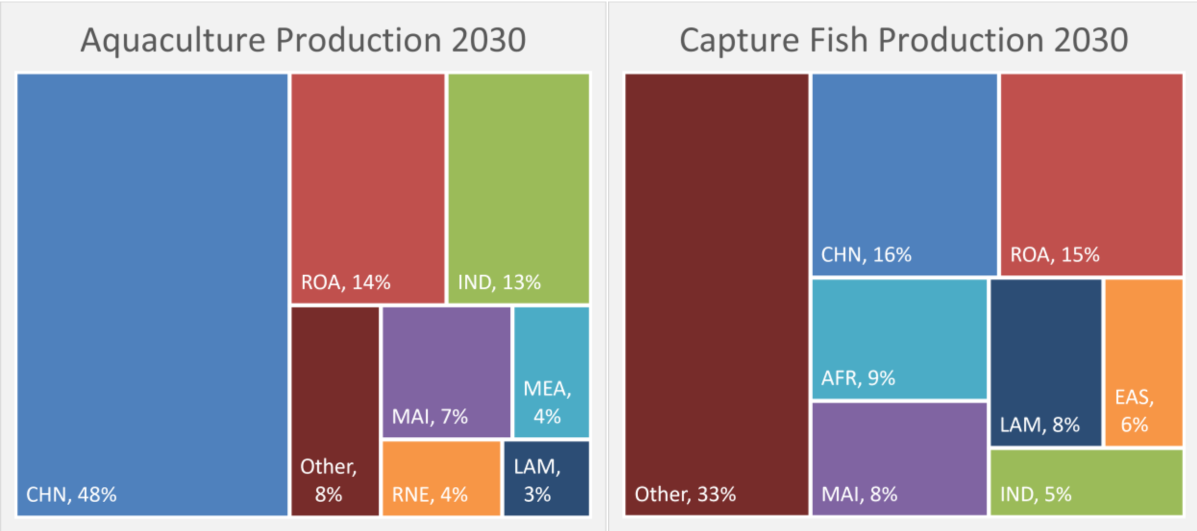

Figure 21: Aquaculture and capture fisheries production shares by region in 2030.

Table 11 shows the scenario results on oilseed production in the major production regions. The most substantial relative feedback effects take place in the regions with the largest aquaculture sector. Especially China is expanding its oilseed crop and oilseed meal production. However, in absolute terms, the most considerable expansion of production happens for soy in Brazil. Soy production is already prominent in this country, and in scenario *FGrow* and *LimFishm*, soy production increases by 2.2% and 3.4%, respectively, compared to the *Baseline*.

Table 11: Changes in Regional Production of Oilseeds in Selected Regions.

Diff. to Baseline	Sector	Region							
		BRA	LAM	AFR	CHN	ROA	EU	CAN	USA
Δ SDG14	RSD	0.2%		1.0%	6.7%	0.2%	-0.1%	2.7%	0.1%
	SOY	1.5%	1.4%	3.5%	3.0%	11.6%	2.5%	2.7%	2.1%
	OSDN	0.1%	0.4%	0.3%	1.7%	2.0%	0.8%	0.0%	0.3%
Δ FGrow	RSD	-0.2%		2.9%	14.2%	0.7%	0.0%	5.4%	-0.1%
	SOY	2.2%	2.1%	3.8%	3.3%	22.0%	2.7%	1.8%	2.9%
	OSDN	-0.9%	1.2%	0.9%	3.0%	5.6%	1.8%	-1.7%	0.2%
Δ LimFishm	RSD	0.1%		4.8%	23.6%	1.3%	-0.1%	9.0%	0.2%
	SOY	3.4%	3.6%	6.8%	5.8%	26.1%	5.1%	2.5%	4.7%
	OSDN	-1.0%	1.2%	1.7%	5.4%	6.9%	2.4%	-2.6%	0.6%

The reduction of capture fish in scenario *SDG14* and the expansion of oilseed crop production in *FGrow* and *LimFishm* directly affect the prices of staple crops and the food sector. Figure 22 summarizes the scenario-based price differences for food, meat and staple crops in 2030. The decreased availability of fish in scenario *SDG14* leads to significantly higher prices in the food sector in Sub-Saharan Africa (AFR) and the southern part of Latin America (PAC). In addition, the prices for processed meat, a substitute for fish, increase in several regions. In contrast, the expansion of aquaculture production in scenario *FGrow* and *LimFishm* leads to small positive and even negative price effects in the food and processed meat sectors. Therefore, we observe larger price increases for the staple crops wheat, maize, and paddy rice. The different reactions of the sectors are mainly rooted in two reasons: On the one hand, besides being substituted by cultivating oilseed crops, wheat and maize are also used as fish fodder and thus, demand and price increase when expanding aquaculture production. On the other hand, a large share of the aquaculture production goes into the food sector, where it substitutes more expensive capture fish and outdoor livestock. Staple crops, therefore, are to a much larger share directly consumed. Hence, increasing aquaculture production can lead to lower prices in the food sector, particularly in regions like India, MAI and ROA, where outdoor livestock is very expensive, but also lead to higher local prices for the staple crops.

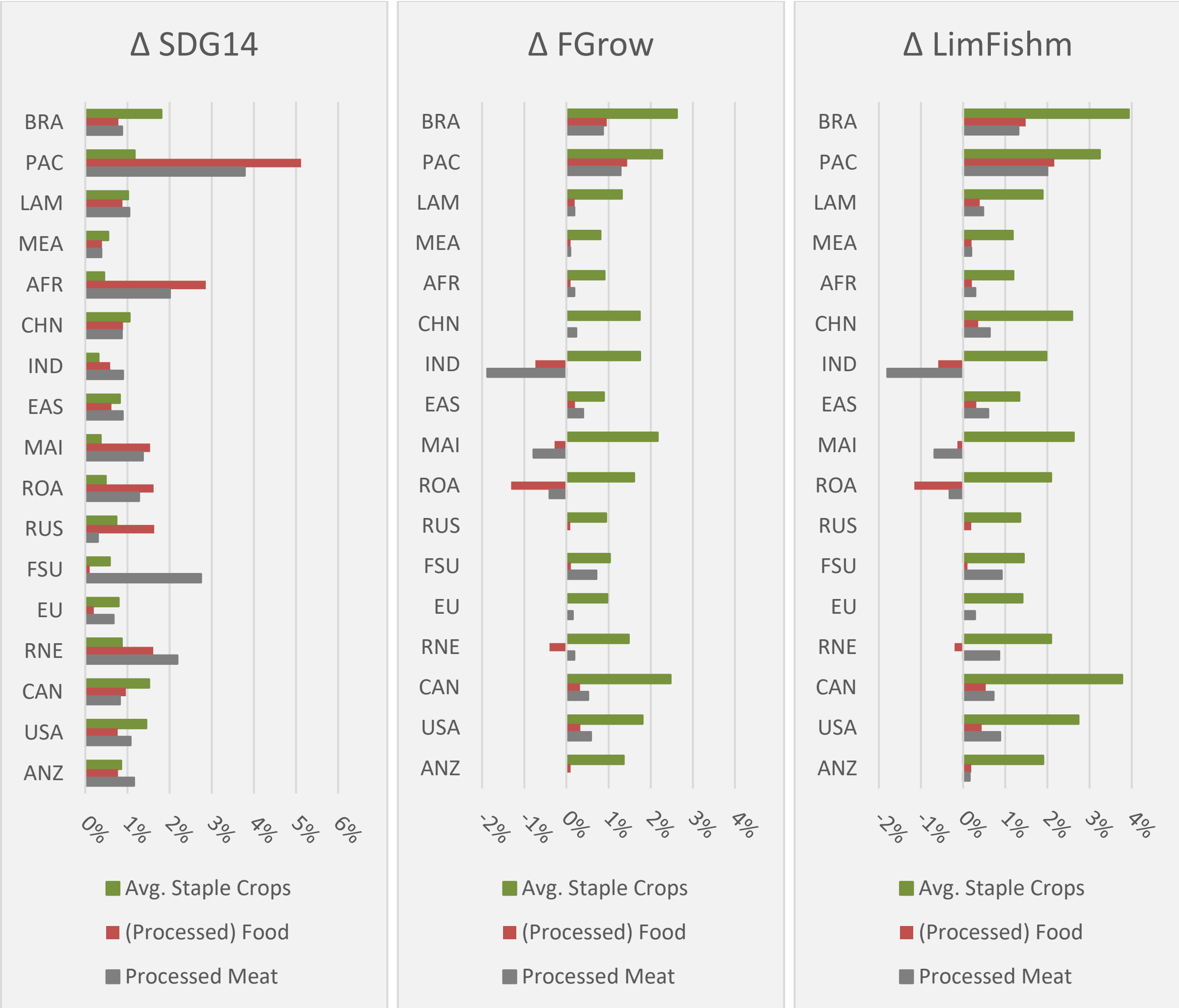

Figure 22: Regional Price Changes of Food Sectors. Change compared to Baseline in 2030. Staple Crops: Maize, Wheat, Paddy Rice.

Land Use

The reactions of regional and global agricultural markets, of course, have feedback effects on land use. Table 12 displays major changes in land use for the most affected regions. The effects are in line with the results on crop production. Increased production of aquaculture fish and increased prices for fishmeal lead to an expansion of cropland for oilseed crops, particularly for soybean in the Americas and India, and rapeseed in the Asian regions. Reducing capture fisheries to rebuild sustainable wild fish stocks already causes a 6.6% expansion of rapeseed production area in China, compared to the *Baseline*. Setting twice the expected growth rate for aquaculture production while keeping fishmeal production constant leads to a 2.7% (BRA) and 4.4% (USA) increase in soybean cultivation area, and 23.4% (CHN) increase in area used for rapeseed production. The land expansion in these sectors mainly goes at the expense of cultivating AGR, a collective sector for various crops, including cash crops like coffee and cotton, but also vegetables and fruits.

Table 12: Scenario-based differences in land use in 2030. Percentage difference to Baseline.

Region	Crop / Land Use	Area Baseline 2030 (in 1000 ha)	Δ SDG14	Δ FGrow	Δ LimFishm
BRA	SOY	44833	1.2%	1.8%	2.7%
	C_B	7814	-0.4%	-0.6%	-0.9%
	AGR	11160	-1.2%	-1.6%	-2.5%
	Pasture	174717	-0.1%	-0.5%	-0.7%
PAC	SOY	32524	0.3%	1.8%	2.4%
	AGR	9179	-1.0%	-1.7%	-2.4%
	Pasture	140668	1.8%	-0.2%	-0.3%
CHN	RSD	6903	6.6%	14.1%	23.4%
	SOY	3657	3.0%	3.2%	5.7%
	OSDN	6022	1.6%	2.9%	5.3%
	AGR	59942	-0.5%	-0.8%	-1.3%
	Pasture	376264	0.1%	-0.7%	-0.9%
USA	SOY	54524	1.9%	2.7%	4.4%
	AGR	48502	-1.3%	-1.0%	-1.8%
	WHT	14496	-2.3%	-1.6%	-2.8%
	MZE	26116	0.5%	-1.0%	-1.5%
ROA	OSDN	11641	2.0%	5.6%	6.9%
	AGR	28348	-0.2%	-0.3%	-0.4%
IND	WHT	36969	-0.2%	1.4%	1.3%
	RSD	6069	-0.1%	1.4%	1.4%
	SOY	8314	0.1%	2.4%	2.5%
	Pasture	9185	0.1%	-0.8%	-0.9%

The effects on wheat, maize, and pasture land are ambiguous across regions and scenarios. While we see an expansion of pasture land in the *SDG14* scenario, driven by the reduced supply of capture fish that leads to a higher demand for outdoor livestock, the use of pasture land shrinks in *FGrow* and *LimFishm*. This results from the increased supply of aquaculture fish that substitutes more expensive outdoor livestock but is also driven by increased prices and demand for cropland for fish feed production. In the USA, the area for maize decreases when aquaculture production increases. Also here, the substitution of capture fisheries with other animal products, for which maize is an essential fodder item, plays a crucial role in scenario *SDG14*. Notably, when comparing *SDG14* to the Baseline in general, we observe an effect from replacing the reduced fishmeal in aquaculture production (replacement effect) on the one hand, but also a substitution effect from increased consumption of other livestock products (substitution effect).

For wheat, we see opposing developments in the USA and India. Comparing *SDG14* and *FGrow* shows that wheat and AGR in the USA are the only items with stronger adverse effects on reducing capture fisheries than expanding aquaculture production. This might be the result of a strong combination of replacement and substitution effect in that region, as explained above. Also, we have a unique reaction for wheat in India, as the expansion in *LimFishm* is lower than in *FGrow*. This is caused by small adjustments in the food sector. In contrast to wheat, fishmeal does not play a significant role in the fish fodder composition for India. Consequently, we do not see significant effects on the land-use change in scenario *SDG14* and between *FGrow* and *LimFishm*.

4.4.3 Welfare Effects

A major advantage of CGE models, compared to partial equilibrium and other sectoral models, is that they can reflect economy-wide feedback and welfare effects. Table 13 displays the changes in the real gross domestic product (GDP), aggregated income of the representative agent (AI), and consumer price index (CPI) compared to the *Baseline*. If AI is reduced less than CPI, or AI increases stronger than CPI, we have a positive welfare effect from an intervention, which is also reflected in a positive change in GDP.

In general, we can see that the scenarios change GDP by less than 1%. An exception is the *SDG14* scenario in ROA, caused by reactions of their relatively big fishing industry. Sub-Saharan Africa and Asian regions are most affected by the reduction of capture fish, each experiencing loss in income and rising consumer prices.

Brazil, Canada, the USA and Oceania profit from each scenario. These regions supply feed for livestock and aquaculture. While they profit from higher demand for livestock and reduced fishmeal availability in the *SDG14* scenario, they benefit from increased aquaculture production in the two other scenarios. Southern America (PAC) shows particularly interesting results, as in this region capture fish production plays an important role, but also soybean production for animal feed. Under *SDG14,* the losses from reduced capture fishery are higher than the profits from increased feed production. Therefore, in scenarios *FGrow* and *LimFishm,* the expanded soybean production lead to welfare gains.

The results from the *SDG14* scenario demonstrate why economic welfare indicators from CGE models may not be the best welfare measure for resource policies. Producers and consumers of capture fish lose in terms of welfare. Only regions that profit stronger from the increased price and production of capture fish substitutes and fish feed experience a positive effect. However, we cannot account for changes in health and value of an ecosystem like the ocean, as it is not captured in our model. Moreover, rebuilding sustainable fish stocks provides long-term profits, which are not reflected in the GDP of 2030. Thus, while the measurable welfare effect is negative, the unobserved intertemporal real welfare effect could be positive.

Table 13: Welfare Effects. Change compared to Baseline in 2030.

Region	Real GDP			Aggregated Income			Consumer Price Index		
	Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm
BRA	0.14%	0.22%	0.33%	0.56%	0.75%	1.11%	0.42%	0.52%	0.76%
PAC	-0.19%	0.36%	0.44%	-0.11%	0.94%	1.15%	0.19%	0.56%	0.70%
LAM	0.00%	0.02%	0.00%	0.11%	0.00%	-0.04%	0.14%	-0.02%	-0.04%
MEA	-0.17%	-0.08%	-0.12%	-0.22%	-0.23%	-0.34%	0.02%	-0.12%	-0.18%
AFR	-0.49%	0.06%	0.06%	-0.05%	0.20%	0.24%	0.76%	0.15%	0.20%
CHN	-0.43%	-0.48%	-0.74%	-0.51%	-0.92%	-1.37%	0.02%	-0.36%	-0.51%
IND	-0.43%	-0.56%	-0.61%	-0.15%	-1.19%	-1.30%	0.36%	-0.59%	-0.63%
EAS	-0.07%	-0.03%	-0.05%	-0.16%	-0.20%	-0.31%	-0.06%	-0.17%	-0.25%
MAI	-0.48%	-0.26%	-0.32%	-0.08%	-0.60%	-0.73%	0.56%	-0.29%	-0.36%
ROA	-1.24%	-0.17%	-0.28%	-0.66%	-0.52%	-0.71%	0.82%	-0.37%	-0.43%
RUS	-0.15%	-0.06%	-0.09%	-0.29%	-0.25%	-0.37%	-0.04%	-0.16%	-0.23%
FSU	-0.13%	0.01%	0.01%	-0.20%	-0.03%	-0.08%	-0.01%	-0.03%	-0.07%
EU	-0.01%	0.02%	0.03%	-0.05%	-0.09%	-0.15%	-0.03%	-0.12%	-0.18%
RNE	-0.12%	-0.10%	-0.42%	-0.19%	-0.28%	-0.79%	-0.01%	-0.17%	-0.31%
CAN	0.04%	0.13%	0.19%	0.06%	0.14%	0.20%	0.05%	0.01%	0.02%
USA	0.01%	0.05%	0.08%	0.00%	0.00%	0.00%	-0.01%	-0.05%	-0.07%
ANZ	0.03%	0.06%	0.09%	0.01%	-0.03%	-0.07%	-0.01%	-0.10%	-0.16%

Considering the *FGrow* and *LimFishm* scenario, the adverse welfare effects in major aquaculture production regions, particularly Asia, seem unexpected at first. By expanding aquaculture production, one could expect increasing aggregated income from a higher activity level, decreasing prices through increased supply, and thus, a higher GDP. However, while CPI decreases, AI decreases stronger, leading to a lower GDP compared to the *Baseline*. This is rooted in two reasons. First, doubling the aquaculture growth rate is introduced as a production shock and is not productivity- or demand-driven. As we shift the supply curve while the demand curve stays constant, increasing production leads to decreasing prices. Moreover, this causes reduced demand and prices for aquaculture substitutes, thus reducing income for their producers, while their costs increase due to higher feed prices from increased feed demand of the aquaculture sector. Second, we observe a small pass-through effect. While aquaculture production mainly consists of imported feed, capital and labour, the substitutes need a larger share of other sectors for their production, i.e. energy and services. As a result, the demand for those sectors decreases slightly. Since these are very large sectors, already minor changes can have small effects on GDP. In a nutshell, aquaculture producing regions suffer from the production shock due to decreasing product prices and increasing feed prices, and the losses for the producer (income) trump the gains for consumers (price reduction). Regions producing aquaculture feed and regions importing aquaculture products benefit.

For the *LimFishm* scenario, these effects are fortified, as fishmeal gets scarce and expensive, leading to higher production costs and more feed imports from plant-based feed producing regions. Especially in China and Northern Europe, we observe a negative effect on GDP by this shock. Therefore, Southern America strongly profits. Here as well, potential positive welfare effects from reduced pressure on marine ecosystems by limiting the use of fishmeal compared to the *FGrow* scenario are not reflected by our economic welfare indicators.

4.4.4 Sensitivity Analysis

The sensitivity analysis concentrates on the elasticity of substitution for protein feed in the aquaculture production function. As explained in the section above, we decided to use an elasticity of 2 for our evaluation. However, as this decision may impact the results, we conducted a sensitivity analysis by running each scenario with half (σ=1) and double (σ=4) elasticity of substitution for protein fish feed. In addition, we split the fishmeal and oilseed meal nest and assume $\sigma^{os}=2$ for the elasticity within the oilseed meals and $\sigma^{fm}=1$ for the elasticity between oilseed meals and fishmeal. A low elasticity assumes a slow technological development considering the substitutability of fishmeal in fish feed, while a high elasticity assumes a fast technological development.

The results show the expected reactions of the model. Figure A13 in the appendix provides the new shares of fish fodder composition in 2030 for each scenario conditional on the elasticity of substitution. The variation of fodder composition between the scenarios is very similar across the different elasticities. With the low elasticity, the share of fishmeal is reduced from 23% (*Baseline*) to 19% (*LimFishm*), and in case of a high substitution elasticity from 11% (*Baseline*) to 7% (*LimFishm).* Thus, the changes in fishmeal shares are relatively robust across scenarios, while we see large differences comparing the elasticities within a scenario. In the model with the high elasticity, the share of fishmeal in the fodder composition is already 5.5% lower in 2018, and throughout all scenarios, 12% lower in 2030, compared to the model with the low elasticity. The model with the split nesting delivers similar results as the model with the low elasticity, but we can observe a higher substitution between soybean meal and rapeseed meal. Conclusively, the aggregated oilseed meals are now cheaper than in the low elasticity model, which causes a slightly increased consumption of total oilseed meals and lower fishmeal usage.

The sensitivity analysis results for global production and prices are presented in the appendix (Table A11 and Table A12). Sectors that are not directly affected by aquaculture and capture fish production do not show any considerable variation caused by the different elasticities. For the fish and fish feed sectors, the low elasticity leads to higher prices for fish products and lower prices for their substitutes. Consistently, applying the higher substitution elasticity has the opposite effect. Moreover, the differences in prices and production in the scenarios compared to the respective *Baseline* indicate the expected outcomes. With a high substitution elasticity, quantity effects are larger and price effects are smaller for the fish sectors and relatively expensive feed, like rapeseed meal. For relatively cheap feed, like soybean meal, the opposite is the case. The quantity and price changes of the model with the split nesting lie between the model with low elasticity and the standard model with $\sigma=2$. The only exception is the production quantity of rapeseed and rapeseed meal. While it substitutes fishmeal in the standard model, it is substituted by soybean meal in the split nest model. In general, the results are closer to the standard model than to the low elasticity model, besides for livestock production.

4.5 Discussion and Conclusion

This study reveals the linkages of the marine and aquaculture fish sectors with agricultural markets. We have shown that expanding aquaculture production and reducing the share of fishmeal used in fish feed leads to increased production of oilseed crops. In the case of the most extreme *LimFishm* scenario, the additional cultivated soybean area equates to 1.2 times the area of the Netherlands. The land required for this production expansion is absorbed from maize, sugar, and various other crops. As a result, we also see rising prices for staple crops. Especially in the Americas and China, regional effects for land-use change and price reactions are observed.

A shortcoming of this model is that we do not control for consumers' preferences for fish species and allow fishmeal to be largely substituted in the regional specific fish fodder composition. As shown by the sensibility analysis, the feedback effects of aquaculture on land use depend on the technical substitutability of fishmeal. Soybean meal production is much cheaper and can be more easily expanded compared to fishmeal production. Thus, if technically feasible, it is profitable for fish farmers to abstain from using fishmeal as fodder. However, not all protein intake of fish can be substituted by plant-based feed, and especially fish oil, a co-product of fishmeal production (Mullon, et al., 2009), is difficult to replace (Naylor, et al., 2009). In addition, consumers prefer carnivorous fed fish species (FAO, 2020). Therefore, it is difficult for producers to change the production portfolio towards more herbivorous or filter fish species (Regnier & Schubert, 2017).

The future will show to which extent fodder formulations can be optimized to minimize the dependencies on fishmeal or if fish breeding techniques can lead to the cultivation of more herbivorous fed fish aquaculture that satisfies consumer preferences. In our model, expectations on the technical progress are reflected by the elasticity of substitution in the feed nest, which determines the reaction of producers towards changes in relative (input) price, which again ultimately impacts the resulting changes in production and prices of aquaculture. However, for the scenario comparison, the elasticities play only a minor role because the changes between the scenarios only show low variations when applying different elasticities. Thus, the results of the scenario analysis can be considered reasonable robust.

Questions considering the consequences of our scenarios for marine and terrestrial ecosystems are answered superficially by this study. As shown in the results section, aquaculture production causes land-use change for oilseed crop production. However, ecological effects from constructing fish and shrimp ponds (Ali, 2006; Tran, et al., 2015), water pollution, diseases, and intermixture of wild and farmed species are not part of this study but need to be considered for a holistic evaluation (Naylor, et al., 2000; Klinger & Naylor, 2012). Another crucial aspect for a holistic evaluation is the sustainable management of marine resources. On the one hand, in our model aquaculture production increases capture fish prices due to fishmeal demand. This confirms the misgivings stated by Froehlich et al. (2018a) that forage fish demand may push wild fish stocks beyond their ecological limits. On the other, we see adverse welfare effects from rebuilding sustainable fish stocks to achieve the SDG target 14.4 but cannot account for positive welfare effects from maintaining the marine ecosystem. This adds to the "Beyond GDP" debate, as it shows that common economic welfare indicators cannot capture all crucial assets for sustainable human welfare (Dasgupta, 2021). Including the value of ecosystems and biodiversity into economic models is one of the most pressing topics for interdisciplinary modelers.

While our model allows only limited derivation on the effects on ecosystems, we provide valuable insights on the impacts on agricultural markets and land use. Notably, the effects on agricultural markets are lower when reducing the capture fishing activities to rebuild sustainable wild fish stocks than when expanding aquaculture production at the same rate as in the first decade of this century. Thus, substituting the reduced capture fish in human diets has a lower impact than increasing aquaculture production, whose products substitute meat as well as vegetarian food. Furthermore, as already mentioned above, the expansion of the aquaculture industry is not restricted by a lack of demand but by production barriers that hinder a stronger growth (Gentry, et al., 2017). If the production barriers can be overcome, developments compared to our extreme scenarios *FGrow* and *LimFishm* could become realistic, leading to increased pressure on agricultural markets. In addition, in the *LimFishm* scenario, our results show a substantial increase in prices for fishmeal. The literature sees two different implications of high fishmeal prices on the fishing sector: a) if the high prices are driven by fish scarcity, more investments into fishing efforts and hence further depletion of already scarce wild fish stocks will take place, or b) in case the high prices are consequences from binding TACs, we observe resource inefficiencies due to overcapacities in the fishing sector (Mullon, et al., 2009) but in turn might be able to protect natural fish stocks (Regnier & Schubert, 2017; Bergland, 2019).

Regarding the impact on welfare, expanding aquaculture production has GDP reducing effects in our scenarios. In aquaculture producing regions, rising prices for feed and decreasing prices for aquaculture fish for producers overcompensate the gains for consumers from lower aquaculture prices. However, it needs to be noted that removing the barriers for aquaculture growth only allows the expansion of aquaculture production and does not improve cost efficiency. Therefore, only oilseed producing and net aquaculture importing regions profit from the aquaculture production expansion in terms of welfare.

Finally, the results of this study reveal the linkages and trade-offs between SDG 14 (*Life under Water*), SDG 15 (*Life on Land*), and SDG 2 (*No Hunger*). As results from the *SDG14* and *LimFishm* scenarios illustrate, policies to achieve SDG 14 can lead to land-use change, which causes trade-offs for achieving SDG 15. However, improving the availability of fish-based protein food to support SDG 2, as assumed in scenario *FGrow* and *LimFishm*, leads to implications for achieving SDG 15 and 14 via fodder production for aquaculture cultivation. Furthermore, we show that fishing policies and aquaculture production affect regional staple food and consumer prices. Especially achieving SDG Target 14.4 can harm the achievement of SDG 2, as it causes crop prices to increase, and therefore impede access to food, particularly in Sub-Saharan Africa and South-East Asia, where capture fish plays a crucial role for food security in coastal regions (FAO, 2020). However, rebuilding sustainable fish stocks leads, in the long term, to sustainable and higher catch levels than the unsustainable catch levels that are fished today (World Bank, 2017). Here, the time dimension needs to be considered, as the SDGs are targeted towards the year 2030. Rebuilding sustainable fish stocks will cause restraints in this period and conflict SDG 2 but provide benefits later on (World Bank, 2017). The findings of this study demonstrate that the regions whose food security depend on marine fishing activities need support in the transition period until sustainable fish stocks are achieved, as they are the ones who suffer most by introducing global TACs for reaching SDG 14.

Further research needs to be conducted to investigate how these trade-offs can be minimized. For instance, dietary patterns and the substitution of animal products in a human diet play a crucial role in analyzing food security effects. It is well known that meat production requires more feed than producing the same amount of aquaculture fish (Froehlich, et al., 2018b) and that energy-efficient feed conversion is an essential attribute in favour for aquaculture fish production (Merino, et al., 2012; Regnier & Schubert, 2017). Thus, if aquaculture fish consumption substitutes meat consumption, we may observe falling food prices. However, prices might increase if aquaculture fish consumption mainly replaces vegetarian diets. To analyze such assumptions and derive precise conclusions on food security and the potential role of aquaculture for achieving the SDGs, the food and meat sector needs to be modelled in more detail. An in-depth analysis of interactions between the meat and fish sectors, the consequences for food security, as well as the role of biofuel policies are topics for future research.

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A.4 Appendix

A.4.1 Additional Figures and Tables

Table A8: Regions in DART-BIOFISH

Central and South America		**Europe**	
BRA	Brazil	FSU	Rest of former Soviet Union
PAC	Paraguay, Argentina, Uruguay, Chile	CEU	Central European Union with Belgium, France, Luxembourg, Netherlands
LAM	Rest of Latin America	DEU	Germany
		MED	Mediterranean with Cyprus, Greece, Italy, Malta, Portugal, Spain
Middle East and Northern Africa		MEE	Eastern European Union with Austria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia, Slovenia, Romania, Bulgaria, Croatia
MEA	Middle East and Northern Africa	NWE	North-Western European Union with Denmark, Finland, Ireland, Sweden, United Kingdom
AFR	Sub-Saharan Africa	RNE	Rest of Northern Europe: Switzerland, Norway, Lichtenstein, Iceland
Asia		**Northern America**	
CHN	China, Hong Kong	CAN	Canada
IND	India	USA	United States of America
EAS	Eastern Asia with Japan, South Korea, Taiwan, Singapore		
MAI	Malaysia, Indonesia	**Oceania**	
ROA	Rest of Asia	ANC	Australia, New Zealand, Rest of Oceania
RUS	Russia		

Table A9: Sectors in DART-BIOFISH

Agricultural related products (28)	
Crops	
PDR	Paddy rice
WHT	Wheat
MZE*	Maize
PLM*	Oil Palm fruit
RSD*	Rapeseed
SOY*	Soy bean
OSDN	Other oil seeds
C_B	Sugar cane and sugar beet
AGR	Rest of crops
Processed agricultural products	
VOLN	Other vegetable oils
FOD	Rest of food
PLMoil*	Palm oil
RSDoil*	Rapeseed oil
SOYoil*	Soy bean oil
OSDNoil*	Oil from other oil seeds
SOYmeal*	Soy bean meal
OSDNmeal*	Meal from other oil seeds
PLMmeal*	Palm meal
RSDmeal*	Rapeseed meal
DDGSw*	DDGS from wheat
DDGSm*	DDGS from maize
DDGSg*	DDGS from other cereal grains
Meat, dairy and fish products	
OLVS	Outdoor livestock and related animal products (cattle and other grazing animals, raw milk and wool)
ILVS	Indoor livestock (swine, poultry and other animal products from indoor livestock)
PCM	Processed animal products
AQUF**	Aquaculture Fish Production
CAPF**	Capture Fish Production
Fshmeal**	Fishmeal

Energy products (14)	
COL	Coal
CRU	Oil
GAS	Gas
MGAS	Motor gasoline
MDIE	Motor diesel
OIL	Petroleum and coal products
ELY	Electricity
ETHW*	Bioethanol from wheat
ETHM*	Bioethanol from maize
ETHG*	Bioethanol from other grains
ETHS	Bioethanol from sugar cane
ETHL	Bioethanol from lignocellulosic biomass
Biofuels	
BETH	Bioethanol
BDIE	Biodiesel

Non-energy products (2)	
SERV	Services
OTH	Other goods

Forest and forest products (1)	
FRS	Forest

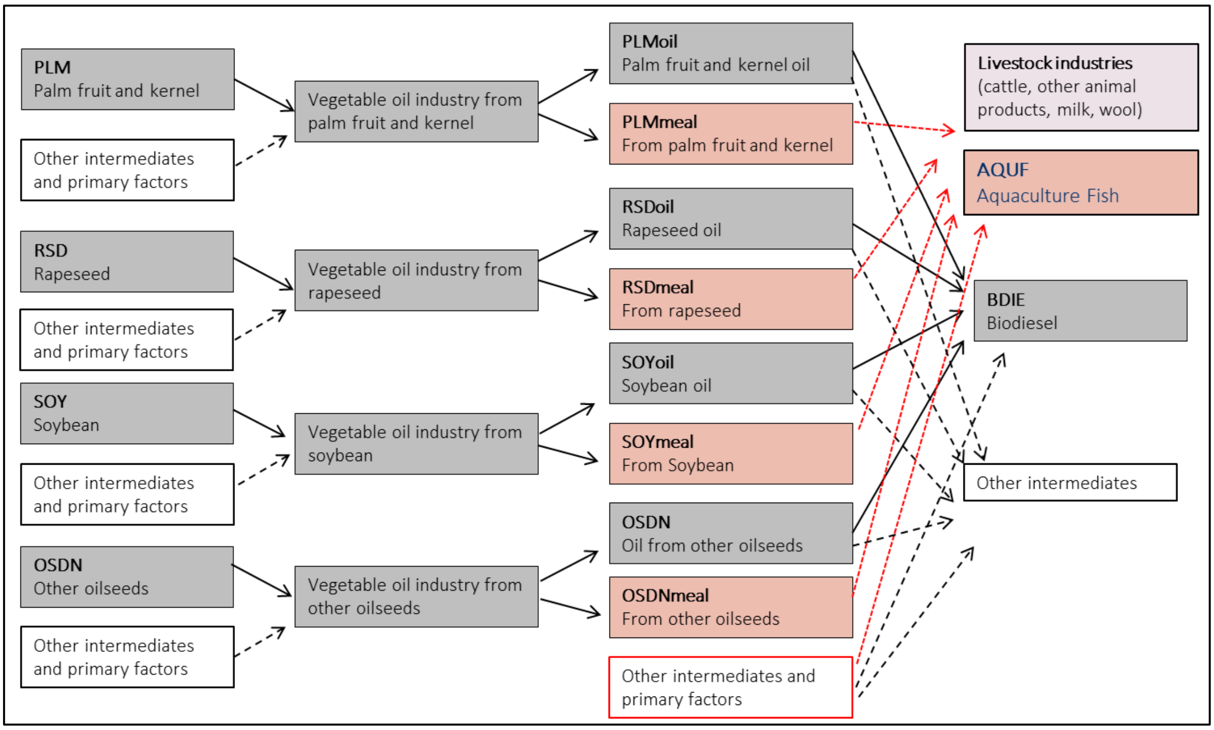

Figure A10: Oilseed oil and meal co-production in the DART-BIO model

Table A10: Global production and prices. Differences to Baseline Scenario.

Sector	Baseline Output 2030	Output			Price		
		Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm
PDR	359.24	-0.1%	-0.1%	-0.1%	0.4%	0.6%	0.8%
WHT	321.27	0.1%	0.3%	0.2%	0.8%	1.6%	2.1%
MZE	311.80	0.1%	-0.4%	-0.6%	0.9%	1.7%	2.5%
PLM	55.81	0.0%	-0.2%	-0.2%	0.8%	0.4%	0.8%
RSD	70.68	2.1%	4.5%	7.3%	1.3%	2.8%	4.1%
SOY	252.64	1.6%	2.5%	3.9%	1.3%	2.2%	3.1%
OSDN	130.56	0.7%	1.2%	2.0%	0.8%	1.5%	2.1%
C_B	118.46	-0.1%	-0.2%	-0.3%	0.3%	0.7%	0.9%
AGR	2311.08	-0.2%	-0.1%	-0.3%	0.7%	1.5%	2.0%
OLVS	986.74	0.8%	-0.5%	-0.6%	1.4%	-0.5%	-0.3%
ILVS	1388.51	1.2%	-1.8%	-2.1%	0.6%	0.7%	1.1%
PCM	1803.43	0.8%	-0.6%	-0.7%	1.0%	0.2%	0.4%
AQUF	113.14	1.6%	32.9%	32.9%	3.9%	-18.3%	-18.1%
CAPF	254.00	-21.8%	0.0%	0.0%	37.6%	2.7%	3.6%
FSHmeal	27.58	-17.6%	22.8%	0.0%	27.8%	4.2%	31.1%
PLMmeal	0.10	-0.4%	-0.3%	-0.5%	8.7%	17.1%	23.4%
RSDmeal	24.89	7.3%	16.0%	26.2%	3.2%	8.1%	10.6%
SOYmeal	180.22	4.8%	7.4%	11.6%	1.4%	2.7%	3.8%
OSDNmeal	16.24	12.5%	25.2%	34.4%	2.1%	4.2%	8.2%
DDGSw	0.55	-0.7%	-1.9%	-2.5%	2.0%	1.9%	2.8%
DDGSm	2.94	-0.9%	-2.9%	-4.2%	2.6%	2.7%	4.1%
DDGSg	0.11	-0.7%	-2.1%	-2.7%	2.0%	2.0%	2.9%
PLMoil	39.00	-0.2%	-0.2%	-0.3%	0.6%	0.2%	0.5%
RSDoil	22.93	2.9%	5.9%	9.7%	-4.8%	-12.0%	-16.5%
SOYoil	75.79	3.9%	6.6%	10.3%	-3.8%	-5.9%	-9.2%
OSDNoil	20.74	4.5%	8.1%	10.7%	-3.0%	-5.2%	-7.2%
VOLN	660.10	-0.2%	-0.6%	-0.8%	1.2%	0.9%	1.5%
BETH	19.08	-2.3%	-3.5%	-5.1%	0.1%	0.2%	0.4%
BDIE	22.96	8.4%	18.2%	23.4%	-1.9%	-3.6%	-4.6%
BDIE_PLM	0.09	-4.6%	-4.4%	-3.8%	0.2%	0.3%	0.1%
FOD	7912.91	-0.4%	-0.1%	-0.2%	0.8%	0.0%	0.1%

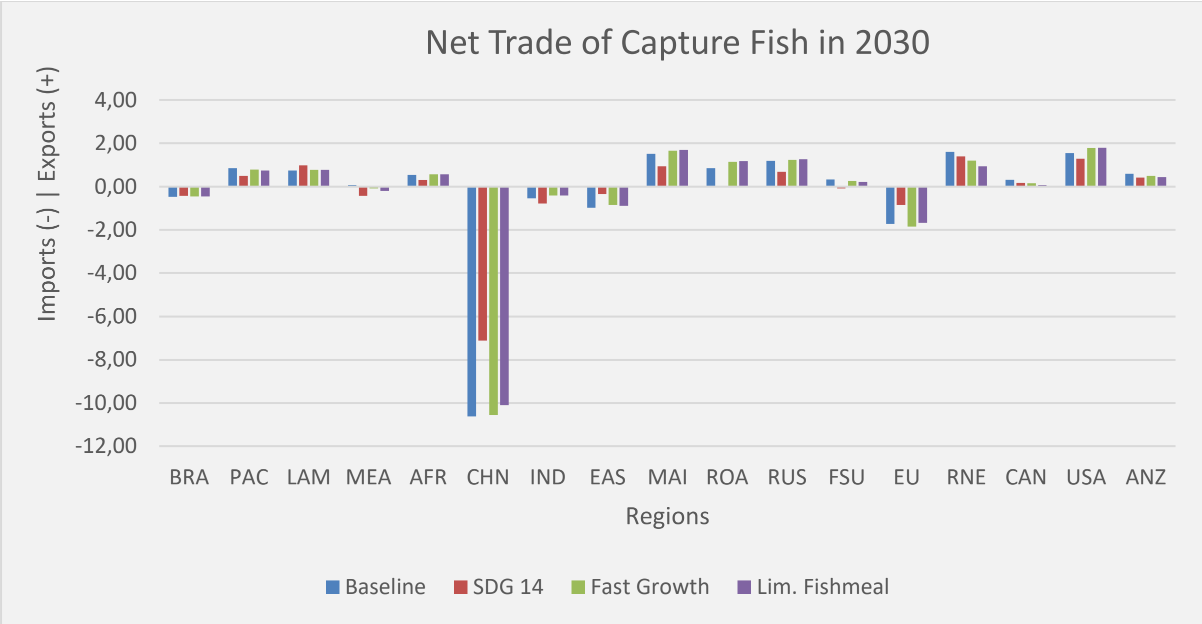

Figure A11: Net Trade of Capture Fish in 2030, in billion USD.

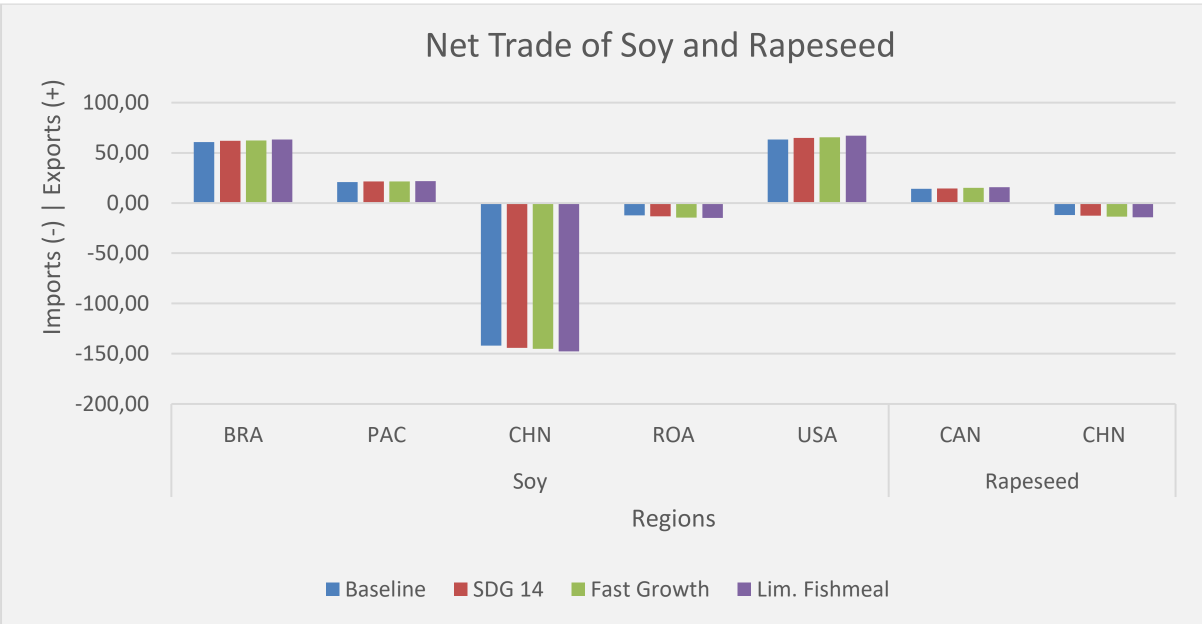

Figure A12: Net Trade of Soy and Rapeseed in 2030, in billion USD.

Table A11: Sensitivity Analysis: Global Production with Varying Elasticity of Substitution. Differences to Baseline in 2030. Note: σ=Elasticity within fishmeal and oilseed meal nest; For analysis with split fishmeal and oilseed meal nesting: σ^{fm} = Elasticity between fishmeal and oilseed meals nets, σ^{os} = Elasticity within oilseed meals nest.

Sector	Baseline Output 2030 (in bill. USD)			Output								
	σ = 1	σ^{fm} = 1; σ^{os} = 2	σ = 4	σ = 1			σ^{fm} = 1; σ^{os} = 2			σ = 4		
				Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm
PDR	359,20	359,29	359,31	-0,1%	-0,1%	-0,1%	-0,1%	-0,1%	-0,1%	0,0%	0,0%	-0,1%
WHT	321,20	321,68	321,47	0,1%	0,2%	0,2%	0,2%	0,3%	0,3%	0,1%	0,3%	0,3%
MZE	312,23	312,37	311,33	0,1%	-0,3%	-0,5%	0,1%	-0,3%	-0,5%	0,1%	-0,4%	-0,6%
PLM	55,82	55,82	55,80	0,0%	-0,2%	-0,2%	0,0%	-0,2%	-0,2%	0,0%	-0,2%	-0,2%
RSD	71,07	69,65	68,75	2,1%	5,6%	8,6%	1,7%	4,1%	6,6%	1,2%	2,5%	4,1%
SOY	249,07	250,88	257,79	1,2%	1,9%	2,9%	1,4%	2,4%	3,6%	1,8%	3,2%	4,9%
OSDN	131,34	130,13	129,81	0,7%	1,5%	2,5%	0,5%	1,1%	1,8%	0,4%	0,7%	0,9%
C_B	118,51	118,50	118,40	-0,1%	-0,2%	-0,2%	-0,1%	-0,2%	-0,2%	-0,1%	-0,2%	-0,3%
AGR	2311,70	2312,27	2310,69	-0,2%	-0,1%	-0,3%	-0,2%	-0,1%	-0,2%	-0,2%	-0,1%	-0,2%
OLVS	988,92	988,88	983,84	0,9%	-0,5%	-0,4%	0,9%	-0,5%	-0,4%	0,7%	-0,6%	-0,8%
ILVS	1394,78	1394,87	1381,12	1,5%	-1,7%	-1,7%	1,5%	-1,7%	-1,7%	1,1%	-1,9%	-2,3%
PCM	1807,87	1807,81	1798,07	1,0%	-0,5%	-0,5%	1,0%	-0,5%	-0,5%	0,8%	-0,7%	-0,9%
AQUF	113,14	113,14	113,52	0,4%	32,9%	32,9%	0,4%	32,9%	32,9%	2,3%	32,5%	32,5%
CAPF	254,00	254,00	254,00	-21,8%	0,0%	0,0%	-21,8%	0,0%	0,0%	-21,8%	0,0%	0,0%
FSHMEAL	33,75	33,29	19,36	-9,9%	24,2%	11,0%	-9,9%	24,2%	11,1%	-27,6%	21,9%	-13,5%
PLMmeal	0,10	0,10	0,10	-0,5%	-0,3%	-0,5%	-0,5%	-0,3%	-0,5%	-0,4%	-0,2%	-0,4%
RSDmeal	25,18	23,57	22,72	7,2%	19,0%	29,5%	6,1%	15,5%	24,5%	4,5%	10,3%	16,6%
SOYmeal	172,98	175,83	190,35	3,5%	5,9%	8,8%	3,8%	6,8%	10,2%	4,9%	8,8%	13,3%
OSDNmeal	15,92	15,29	16,98	10,2%	26,1%	36,4%	9,9%	25,1%	34,0%	10,8%	22,0%	26,5%
DDGSw	0,55	0,55	0,55	-0,6%	-1,9%	-2,5%	-0,6%	-1,8%	-2,3%	-0,6%	-1,8%	-2,2%
DDGSm	2,96	2,95	2,91	-0,6%	-2,7%	-3,7%	-0,6%	-2,8%	-3,8%	-0,9%	-3,1%	-4,3%
DDGSg	0,11	0,11	0,11	-0,6%	-2,0%	-2,6%	-0,6%	-1,9%	-2,5%	-0,7%	-2,0%	-2,6%
PLMoil	39,00	39,00	39,00	-0,2%	-0,2%	-0,3%	-0,2%	-0,2%	-0,3%	-0,1%	-0,2%	-0,2%
RSDoil	23,10	22,49	22,18	2,8%	7,6%	11,5%	2,3%	5,4%	8,6%	1,8%	3,3%	5,6%
SOYoil	72,95	74,19	79,93	2,7%	5,0%	7,3%	3,0%	6,0%	8,7%	4,4%	7,9%	12,2%
OSDNoil	20,17	20,36	21,58	3,2%	7,6%	10,2%	3,3%	7,8%	10,2%	4,4%	8,2%	9,8%
VOLN	660,90	660,78	659,14	-0,2%	-0,5%	-0,7%	-0,2%	-0,5%	-0,7%	-0,2%	-0,6%	-0,8%
BETH	19,23	19,20	18,90	-2,1%	-3,3%	-4,7%	-2,2%	-3,4%	-4,9%	-2,3%	-3,7%	-5,2%
BDIE	21,31	22,09	25,21	5,8%	16,9%	21,3%	6,1%	17,8%	22,1%	9,0%	18,6%	23,2%
BDIE_PLM	0,09	0,09	0,10	-5,1%	-4,6%	-4,5%	-5,1%	-4,5%	-4,2%	-4,0%	-4,0%	-3,0%
FOD	7908,93	7910,29	7919,38	-0,4%	-0,1%	-0,2%	-0,4%	-0,1%	-0,2%	-0,3%	0,0%	-0,1%

Table A12: Sensitivity Analysis: Global Prices with Varying Elasticity of Substitution. Differences to Baseline in 2030. Note: σ=Elasticity within fishmeal and oilseed meal nest; For analysis with split fishmeal and oilseed meal nesting: σ^{fm} = Elasticity between fishmeal and oilseed meals nets; σ^{os} = Elasticity within oilseed meals nest.

Sector	Baseline Prices 2030 (const. USD)			Prices								
	σ = 1	σ^{fm} = 1; σ^{os} = 2	σ = 4	σ = 1			σ^{fm} = 1; σ^{os} = 2			σ = 4		
				Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm	Δ SDG14	Δ FGrow	Δ LimFishm
PDR	3,26	3,26	3,26	0,4%	0,6%	0,9%	0,4%	0,6%	0,8%	0,4%	0,5%	0,6%
WHT	2,34	2,34	2,34	0,8%	1,7%	2,2%	0,73%	1,6%	2,1%	0,7%	1,5%	1,9%
MZE	2,63	2,62	2,63	0,8%	1,8%	2,5%	0,8%	1,7%	2,3%	0,8%	1,6%	2,1%
PLM	3,76	3,76	3,75	0,9%	0,5%	1,0%	0,8%	0,4%	0,9%	0,7%	0,3%	0,6%
RSD	2,82	2,80	2,79	1,2%	3,3%	4,6%	1,1%	2,7%	3,8%	1,0%	2,1%	2,9%
SOY	2,32	2,32	2,34	1,2%	2,0%	2,8%	1,2%	2,1%	3,0%	1,3%	2,3%	3,2%
OSDN	2,74	2,73	2,73	0,8%	1,7%	2,4%	0,7%	1,4%	2,0%	0,6%	1,1%	1,5%
C_B	2,31	2,31	2,31	0,3%	0,7%	0,9%	0,2%	0,6%	0,9%	0,3%	0,6%	0,8%
AGR	2,84	2,84	2,84	0,7%	1,5%	2,1%	0,6%	1,4%	1,9%	0,6%	1,4%	1,7%
OLVS	2,19	2,19	2,18	1,5%	-0,4%	0,0%	1,5%	-0,4%	-0,1%	1,3%	-0,6%	-0,5%
ILVS	1,17	1,17	1,17	0,6%	0,7%	1,1%	0,6%	0,6%	1,0%	0,6%	0,6%	0,9%
PCM	1,08	1,08	1,08	1,1%	0,2%	0,6%	1,1%	0,2%	0,5%	0,9%	0,1%	0,2%
AQUF	1,97	1,97	1,93	5,5%	-18,0%	-17,2%	5,5%	-18,0%	-17,3%	2,9%	-18,3%	-18,5%
CAPF	2,50	2,48	2,20	44,0%	5,5%	12,3%	43,9%	5,3%	12,0%	34,1%	0,4%	-1,5%
FSHMEAL	4,06	4,04	3,26	35,9%	7,2%	45,6%	35,9%	7,1%	45,4%	23,1%	2,1%	22,0%
PLMmeal	2,94	2,37	2,14	11,2%	35,0%	45,0%	7,1%	17,4%	22,4%	5,7%	9,8%	13,9%
RSDmeal	2,75	2,63	2,56	3,0%	9,7%	11,9%	3,1%	8,7%	11,2%	2,8%	6,8%	9,1%
SOYmeal	1,71	1,73	1,76	1,3%	2,4%	3,4%	1,3%	2,7%	3,8%	1,5%	3,0%	4,3%
OSDNmeal	2,01	1,76	1,55	2,3%	4,5%	8,1%	2,2%	4,3%	7,8%	1,1%	2,5%	4,9%
DDGSw	1,61	1,60	1,60	2,0%	1,9%	3,0%	2,0%	1,9%	2,9%	1,9%	1,7%	2,3%
DDGSm	2,86	2,86	2,89	2,4%	2,6%	4,0%	2,5%	2,6%	4,1%	2,4%	2,8%	4,0%
DDGSg	1,67	1,67	1,67	2,0%	2,1%	3,2%	1,9%	2,0%	3,0%	1,8%	1,8%	2,5%
PLMoil	2,28	2,28	2,28	0,6%	0,2%	0,6%	0,6%	0,2%	0,6%	0,5%	0,1%	0,3%
RSDoil	1,26	1,35	1,41	-4,7%	-15,0%	-19,3%	-4,2%	-12,0%	-16,1%	-3,3%	-8,1%	-11,6%
SOYoil	0,72	0,70	0,65	-2,8%	-4,7%	-7,0%	-3,1%	-5,6%	-8,2%	-4,1%	-7,1%	-10,6%
OSDNoil	0,94	0,96	0,97	-1,9%	-4,1%	-5,6%	-2,4%	-5,2%	-7,0%	-3,4%	-6,6%	-8,5%
VOLN	1,73	1,72	1,72	1,2%	0,9%	1,6%	1,2%	0,9%	1,6%	1,0%	0,8%	1,3%
BETH	1,08	1,08	1,08	0,1%	0,2%	0,3%	0,1%	0,2%	0,3%	0,1%	0,3%	0,4%
BDIE	0,88	0,88	0,85	-1,3%	-3,1%	-4,0%	-1,5%	-3,5%	-4,4%	-2,2%	-4,1%	-4,8%
BDIE_PLM	1,09	1,09	1,09	0,3%	0,3%	0,1%	0,3%	0,3%	0,1%	0,2%	0,3%	0,0%
FOD	1,17	1,17	1,17	0,9%	0,0%	0,3%	0,9%	0,0%	0,2%	0,7%	-0,1%	-0,1%

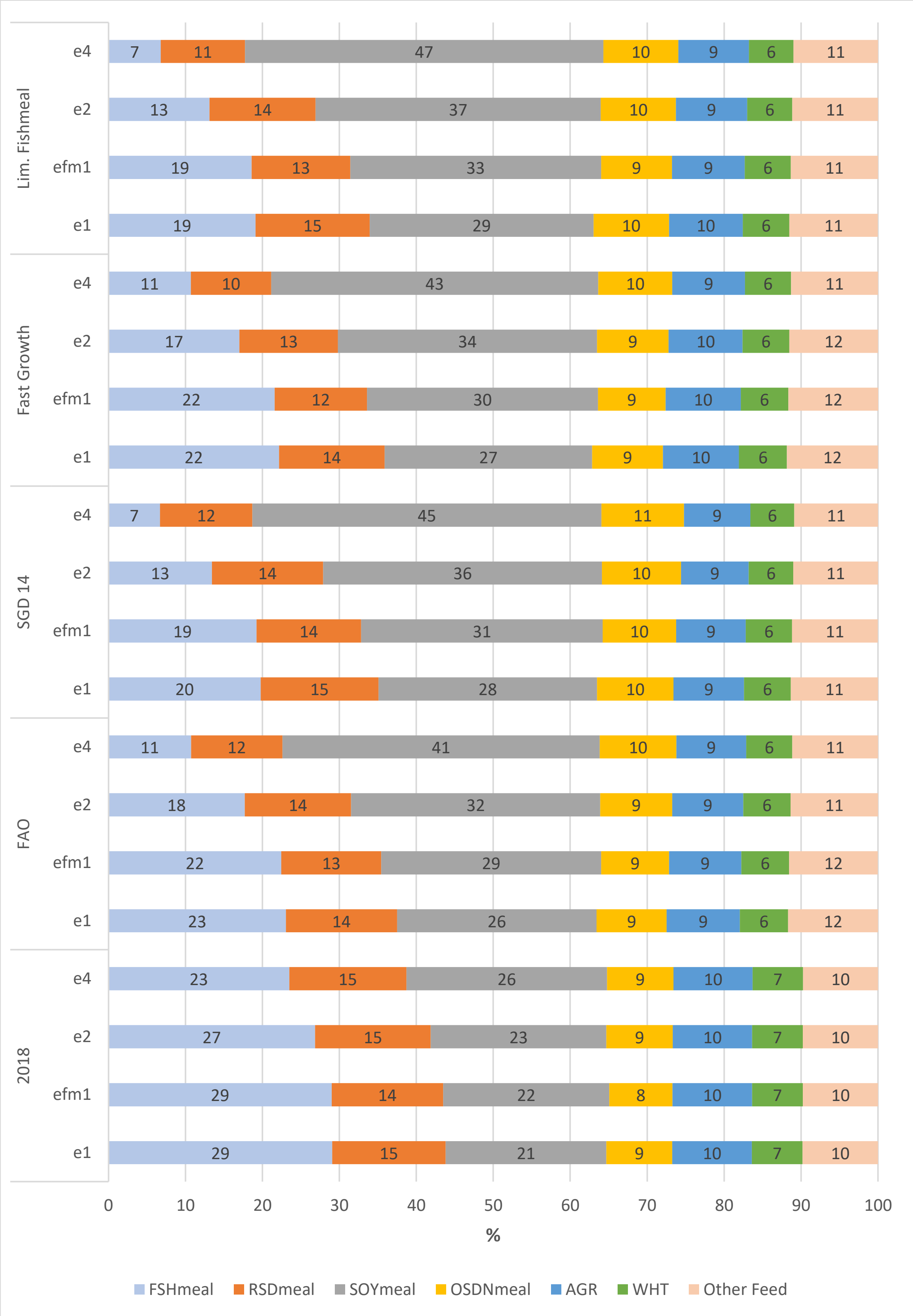

Figure A13: Results of the Sensitivity Analysis on Fish Feed Composition; Volume Shares in 2018 and 2030 in Percent. Note: e1: σ=1; e2: σ=2; e4: σ=4; efm1: Split nesting for fishmeal and oilseed meals: = Elasticity between fishmeal and oilseed meals nets σ^{fm};=1, Elasticity within oilseed meals nest σ^{os} =2.

A.4.2 Preparation of the DART-BIOFISH dataset

To observe developments in a capture fish and an aquaculture fish sector, the existing GTAP sector for fish production (FSH) must be separated. In addition, an explicit fishmeal sector is required to model substitution effects between fish-based and plant-based protein fodder. For the separations in the GTAP database, the gempack software "Splitcom" is employed (Horridge, 2008). At first, five new sectors are created, namely fresh capture and aquaculture fish production, processed capture and aquaculture fish and fishmeal. In the final model, the two processed fish sectors are aggregated to the food sector. While the sectors for fresh capture (CAPF) and fresh aquaculture (AQUF) fish are originated in the original FSH sector, the sectors for processed fish are separated from the GTAP sector "other foods" (OFD). The fishmeal (FSHMEAL) sector is fueled by both sectors, FSH and OFD. Comparing the GTAP data to FAO FishStat and UN Comtrade data, the transfer of fish from the original sector FSH to OFD is very heterogeneous across countries. In some countries most of the fish is passed through from FSH to OFD, while in others only little fish goes to the OFD sector. Besides different regional characteristics of the fish industry, this could also be due to different interpretations of "processed fish" by the statistical authorities of the respective countries. Also, the values for fishmeal are accounted in FSH for some countries and for others in OFD. To get the targeted shares between capture and aquaculture, fresh and processed, domestic production and imports, in a first step, all production processes of fish are extracted from their initial sectors and then redistributed to the five new sectors named above.

It is important to note that the aquaculture sector only includes fed-fish species. Non-fed species are not explicitly modelled due to unknown cost functions. Up to now, there is no information on the cost structure of filter fish production. Especially in Asia, many filter fish are kept on rice fields or in small ponds and are produced alongside other farm activities without requiring specific inputs (FAO, 2018). Furthermore, while the demand and production for fed-fish are strongly increasing, the market share of filter fish is decreasing and plays only a significant role in China and Oceania (ibid.). Including filter fish in the aquaculture sector would jeopardize the here derived assumption of the production technology for aquaculture and water down feedback effects from higher aquaculture demand on fodder production. Thus, to reveal the linkages of fish consumption and plant-based fodder production, the aquaculture sector can be considered fed-fish aquaculture only, as shown in other studies like Froehlich et al. (2018b). To improve the treatment of non-fed fish, it is planned to include more explicit fish sectors in a later version.

Disaggregating the Fish Sectors

It was decided to create the new fish sectors in a three-step process. At first, with a vague separation of aquaculture and capture values, by taking the GTAP data of the original FSH sector as total fish production and subtracting the aquaculture values for fed fish given by FAO FishStat (FAO, 2019). The reason to only consider aquaculture values is that FAO only reports country-level production values for aquaculture fish production and fishmeal production, but not for capture fisheries. Second, we adjust the aquaculture production values to bring the total production in line with the correct input shares for capital, labor and fodder in the production technology. Finally, aquaculture and capture fish production are rescaled to match the regional production volume shares in 2011, and later 2018.

Since species and region-specific production cost shares are not available, it is assumed that 75% of the total cost in the aquaculture sector comes from fodder inputs. Estimations assume a share of 50-80% in 2010 (Rana et al., 2009; Hasan, 2017). Assuming technological progress, increasing raw material costs, and strongly increasing aquaculture cultivation in Asian low-income countries (e.g. Thailand, Vietnam) in the last ten years, a global average production cost share of 75% for fodder seems realistic. The fodder composition is based on a study by Pahlow et al. (2015). They provide species-specific estimates on 88% of all global commercial feed fed fish. Those estimates are used to calculate the fodder costs by country by weighting the species-specific fodder shares with the production volumes of the fish species retrieved from FAO FishStat (FAO, 2019), and then multiply the weighted fodder volumes with their respective 2011 market price to receive the costs (for feed prices see Table A13). This is visualized in the following equations, where *vs* is the volume share, and *cs* the final cost share:

$$vs_{f,c} = \frac{1}{Q_c}\sum_{s} vs_{f,s} * Q_{s,c} \qquad (A1)$$

$$cs_{f,c} = \frac{vs_{f,c} * P_f}{\sum_f vs_{f,c} * P_f} \qquad (A2)$$

, with *f* indicating the feed item, *c* the country, and *s* the fish species, for the aquaculture fish volume Q and the feed price P.

Apparently, the GTAP database does not account for aquaculture fisheries in many regions, as for several countries, the plant-based intermediate inputs into the FSH sector are much too low. Thus, there is not enough feed entering the sector to reach the FAO production share for fed fish aquaculture production. Therefore, at first, the aquaculture production needs to get scaled down to keep the estimated fodder input shares consistent, which is elaborated in the next section.

Table A13: Feed Prices for 2011

Feed Item	Price in USD/mt*	Source	Detail
Fish Meal	1442	World Bank	World Bank Commodity Price Data (The Pink Sheet)
Fish Oil	1533	FAO	FAO Commodity Statistics Update March 2016; http://www.fao.org/3/a-bl391e.pdf
Soybean Meal	409	World Bank	World Bank Commodity Price Data (The Pink Sheet)
Soybean Oil	1297	World Bank	World Bank Commodity Price Data (The Pink Sheet)
Rapeseed Meal	243	Canola Council	https://www.canolacouncil.org/markets-stats/statistics/historic-canola-oil,-meal,-and-seed-prices/)
Rapeseed Oil	1368	IMF	IMF Primary Commodity Price System
Wheat	301	CMO; World Bank	CMO Historical Data; World Bank Commodity Price Data (The Pink Sheet)
Rice bran	154	USDA	USDA Yearbook: U.S. Rough and Milled Rice Prices, monthly and marketing year
Groundnut	1883	CMO; World Bank	CMO Historical Data; World Bank Commodity Price Data (The Pink Sheet)
Meat and Bone Meal	369	Feedstuffs.com	https://www.feedstuffs.com/search/node/Grain%20%26%20ingredient%20cash%20market?sort=field_penton_published_datetime&order=asc
Corn Gluten Meal	536	Feedstuffs.com	https://www.feedstuffs.com/search/node/Grain%20%26%20ingredient%20cash%20market?sort=field_penton_published_datetime&order=asc
Other feedstuff	279	Feedstuffs.com	https://www.feedstuffs.com/search/node/Grain%20%26%20ingredient%20cash%20market?sort=field_penton_published_datetime&order=asc

*Prices are calculated as 3 year averages from 2010 - 2012

In the next step, the model rescales capture and aquaculture production until 2011. To evaluate the aquaculture feed linkages, keeping the relative shares within the GTAP database consistent is essential. Thus, when calibrating new sectors, it is crucial to ensure that their production volume fits the scale of other sectors. To maintain the relative scale given by the GTAP database, the 2011 regional production quantity shares for fed-fish aquaculture and capture fish relative to total fish production are taken from FAO FishStat to calculate the respective production volumes for the GTAP based data. Considering trade shares, they are assumed to be equal to the share in production. This is a common assumption when detailed bilateral trade data is absent (Natale, et al., 2015).

Manipulation of the GTAP SAM

As already indicated above, a major issue of calibrating the inputs of the aquaculture sector according to the shares in fodder composition is that the least available fodder item limits the initial aquaculture production in a region in the base year. To be available for the aquaculture fish feed composition, the respective fodder item must have already entered the original FSH sector. For instance, if it is assumed that 20% of fish fodder in a particular country is based on soybean meal and after the default separation of aquaculture and capture fish (according to FAO aquaculture production data) the fodder share of soybean meal is lower, than the production quantity of aquaculture fish is reduced, so that the share of soybean meal in the fodder compositions approaches the targeted 20%. The excess aquaculture production is shifted back to capture fisheries. When calibrating the model to the real 2011 production shares, a very high substitution elasticity between capture and aquaculture in private and intermediated consumption is implemented. This allows the model to move consumption from the capture to the aquaculture fish sector easily, when the production of aquaculture gets heavily expanded.

The calibration of the capture fish sector is implemented by scaling the endowment of natural resources. This endowment is nested Leontief in the highest nest of the production structure (see Figure A14). Thus, a decrease/increase in the availability of natural resources immediately translates into a decrease/increase in total production. The aquaculture and fishmeal sectors do not have natural resources as an endowment. For most regions, the aquaculture sectors are calibrated via a production quota. However, for four regions (DEU, BRA, USA, ANZ) an artificial endowment at the price of zero is included in the production block. This technique is borrowed from the application of emissions in a production structure (Delzeit et al., 2021b). Similar to the natural resources, a change in the endowment is fully transferred to a change in total production of the respective sector. The endowment technique allows for stronger manipulation of the production than the quota and was therefore required for those four regions. However, using the quota for the other regions simplifies the modelling after the manipulation of the SAM.

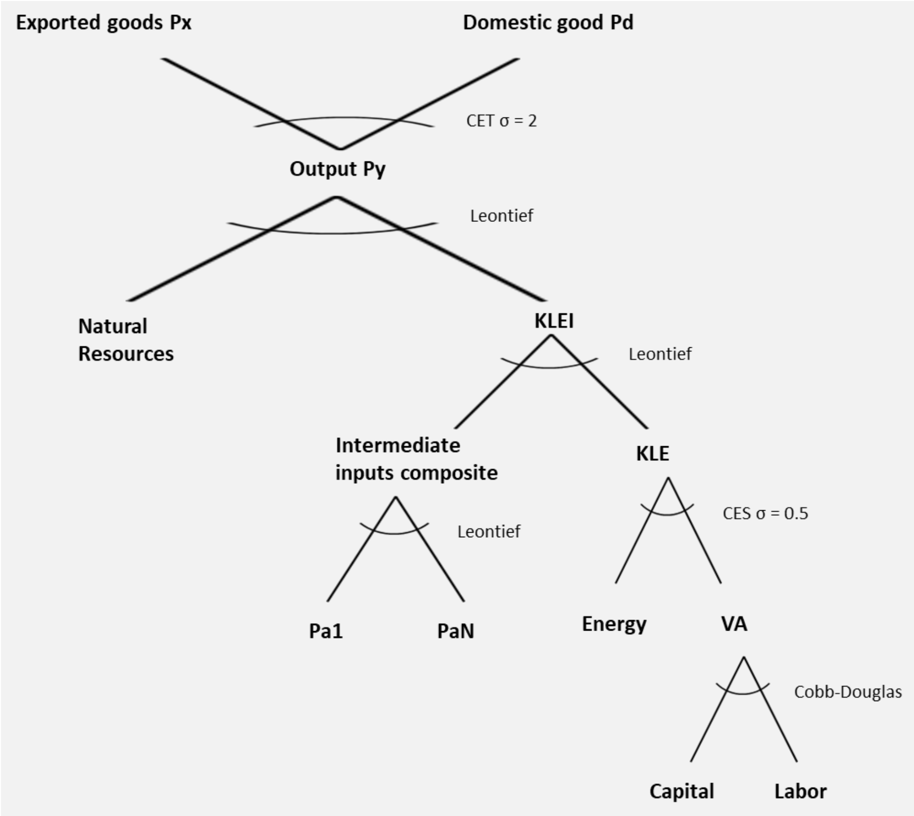

Figure A14: Nesting of capture fish production in DART-BIOFISH

The calibration of the fish sectors as elaborated above, bears a major shortcoming for further evaluation. After scaling production to a multiple of its initial quantities, the output prices of those sectors are highly distorted. Even while allowing for easy substitution in consumption of capture fish and aquaculture, the prices of the sectors are strongly affected.

To deal with this obstacle, the save-and-restart procedure has been developed. First, we let the model run from 2011 for eight years and calibrate towards the FAO fish sector production shares for 2011. This run is conducted without implementing any dynamics in the model. Population and total factor productivity growth are zero for all periods. Thus, in theory, we could just let the model run for one year as we only focus on shifting production factors and intermediates to or from the fish sectors to reflect 2011 production shares. However, the shock size, particularly on the aquaculture sector, is too high for the model to handle within one period. Hence, we allow the model to smoothly adjust the sectors over multiple periods. While calibrating the fish sector, we only allow for very low substitution (0.1-0.5) between the intermediate inputs of the aquaculture sector to keep the cost shares constant. The substitution elasticities are big enough to give the model some flexibility when increasing the production of the sector but sufficiently small to not significantly alter the desired cost-share distribution.

The results of this fish sector calibration run are saved, and we read out all relevant parameters to recalculate the values needed to construct a new base data for 2011. A CGE model naturally works with relative prices so that in the initial start year, all prices must be equal to 1. Thus, the GTAP base data can be understood in terms of values with the price of 1. To obtain a new base data, we just need to multiply quantities with prices to get the new values. Since there are no dynamics in the model, all sectors not affected by the calibration of the fish sector have very similar values compared to the original base data. Sectors affected by aquaculture production receive different values now since the aquaculture sector has only been covered fractionally by the original database. After recalculating the base data, the value shares of aquaculture and capture fish sectors differ from the targeted 2011 production volume shares, because of the price distortion. Especially increasing aquaculture production by a factor of 30-40, as done for some regions, leads to low prices and thus to too low values in the new base data. As a result, we include a quota that calibrates the production shares of the fish sectors until 2018 for every model run based on the restart data. All scenario analyses start from that year on and vary only in the period from 2018 to 2030.

While we technically could directly calibrate the fish sectors in the model with the dynamics and then keep on running the model until 2030 for scenario evaluation, it is not practicable. In the fish sector calibration run, we must increase aquaculture production in most regions by more than factor 10, and for some even by factor 30-40. As already mentioned, this strongly distorts the sector prices, which in turn would affect the scenario analyses. After the restart, we only have to adjust by max. 1.3 for major aquaculture producing countries to match 2018 FAO production volume shares. Thus, prices are only distorted marginally, and calibrating the fish sectors does not interfere with the scenario analysis.

Authorship Contribution Statement I

Paper Title: *"Yet another reform of the EU biofuel policies: Impacts of the latest reform of the European Union's Renewable Energy Directive"*

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, and agree to the conclusion of the study. They confirm compliance with the "*DFG-Leitlinien zur Sicherung guter wissenschaftlicher Praxis*". Below, a list indicating the individual author contributions to this study. If not indicated differently, the order of the authors ranks the work share in the respective part.

Study Design: Ruth Delzeit, Tobias Heimann, Franziska Schünemann, Mareike Söder (equal contribution)

Data Preparation: Tobias Heimann, Franziska Schünemann, Ruth Delzeit, Mareike Söder

Modelling Exercise: Ruth Delzeit, Tobias Heimann, Franziska Schünemann

Analysis: Ruth Delzeit, Tobias Heimann, Franziska Schünemann, Mareike Söder (equal contribution)

Writing: Tobias Heimann, Franziska Schünemann, Ruth Delzeit, Mareike Söder

Author Signatures:

Ruth Delzeit | Tobias Heimann | Franziska Schünemann | Mareike Söder

Authorship Contribution Statement II

Paper Title: "*Land for Fish: A scenario based CGE analysis of the effects of aquaculture consumption on agricultural markets"*

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, and agree to the conclusion of the study. They confirm compliance with the "*DFG-Leitlinien zur Sicherung guter wissenschaftlicher Praxis*". Below, a list indicating the individual author contributions to this study. If not indicated differently, the order of the authors ranks the work share in the respective part.

Study Design: Tobias Heimann, Ruth Delzeit

Data Preparation: Tobias Heimann

Modelling Exercise: Tobias Heimann

Analysis: Tobias Heimann, Ruth Delzeit

Writing: Tobias Heimann, Ruth Delzeit

Author Signatures:

Ruth Delzeit Tobias Heimann

Eidesstattliche Erklärung

Ich erkläre hiermit, dass ich meine Doktorarbeit

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selbstständig und ohne fremde Hilfe angefertigt habe und dass ich als Koautor maßgeblich zu den weiteren Fachartikeln beigetragen habe. Alle von anderen Autoren wörtlich übernommenen Stellen, wie auch die sich an die Gedanken anderer Autoren eng anlehnenden Ausführungen der aufgeführten Beiträge wurden besonders gekennzeichnet und die Quellen nach den mir angegebenen Richtlinien zitiert.

16.08.2021

Datum Unterschrift