

Sustainability implications of transformation pathways for the bioeconomy

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ABSTRACT

Countries around the world are devising and implementing bioeconomy strategies to initiate transformation towards sustainable futures. Modern concepts of bioeconomy extend beyond bio-based energy provision and include: (1) the substitution of fossil resource-based inputs to various productive sectors, such as the chemical industry and the construction sector, (2) more efficient, including new and cascading uses of biomass, and (3) a low bulk, but high-value biologisation of processes in agro-food, pharmaceutical, and recycling industries. Outcomes of past attempts at engineering transformation, however, proved to be context-dependent and contingent on appropriate governance measures. In this paper we theoretically motivate and apply a system-level theory of change framework that identifies central mechanisms and four distinct pathways, through which bio-based transformation can generate positive or negative outcomes in multiple domains of the Sustainable Development Goals. Based on emblematic examples from three bio-based sectors, we apply the framework illustrating how case-specific mixes of transformation pathways emerge and translate into outcomes. We find that the observed mixes of transformation pathways evoke distinct mechanisms that link bioeconomic change to sustainability gains and losses. Based on this insight we derive four key lessons that can help to inform the design of strategies to enable and regulate sustainable bioeconomies.

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1. Introduction

A stronger reliance on the use of biological resources across all economic sectors (i.e., a bio-based transformation) is often proposed as a green growth strategy. Besides non-bio-based renewable energy, green growth includes the technology-driven emergence of valuable alternatives to fossil resource-based products and calls for new economic principles (Mathews, 2009; Borgström and Mauerhofer, 2016). Visions of the future bioeconomy, however, tend to rely on strong assumptions about the economic, social, and environmental sustainability of bio-based technologies and models of development (Staffas et al., 2013). Research that scrutinizes whether and under what conditions such assumptions hold

must be informed by theory and guided by appropriate conceptual frameworks (Ostrom, 2009). The lack of interdisciplinary frameworks that identify which components of economic, social, and environmental systems matter for bio-based transformation processes and their outcomes constitutes a major research gap (El-Chichakli et al., 2016). In particular, we need to better understand what drives the emergence of key enabling technologies and what combination of policy incentives is needed to promote sustainable bioeconomic innovation processes under varying contextual conditions (Dietz et al., 2018; Laibach et al., 2019).

Modern concepts of bioeconomy go far beyond the bioenergy framing that dominated the discourse in the early 2000s and include diverse applications, namely: (1) the substitution of fossil resource-based inputs in various productive sectors, such as the chemical and construction sectors (El Kadib and Bousmina, 2012; Lelievre et al., 2014), (2) more efficient cascading uses of biomass (Prins et al., 2006), and (3) a 'biologization' of processes in food,

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pharmaceutical, and recycling industries that require low input volumes and yield high-value outputs (German Bioeconomy Council, 2016). As such, the dominant bioeconomy discourse embraces “efficiency” as a sustainability paradigm, but elements of consistency and sufficiency (D’Amato et al., 2017; Hausknost et al., 2017) are also increasingly entering the debates as the early hype cycle levels off (Biber-Freudenberger et al., 2020).

The current bioeconomy already contributes significantly to national economies around the world regardless of its transformative potential. For example, in the European Union (EU), the bioeconomy is estimated to generate a turnover of €2.2 trillion, a quarter of which comes from the food industry. Approximately 17.5 million people are employed in bio-based economic activities, predominantly in the agricultural sector (KCB, 2020). The bioeconomy in Argentina contributed 16.1% to the country’s GDP in 2017 (Lachman et al., 2020). In Malaysia, bio-based value-added accounted for around 12% of the national GDP in 2016 (FAO, 2018). Clearly, countries differ in terms of natural resources endowments and socioeconomic as well as technological development trajectories. These contextual factors co-determine not only stages and prospects of bioeconomic transformation (Biber-Freudenberger et al., 2018), they also result in different perceptions of priorities among sustainability goals and options for technological change (Laibach et al., 2019).

A growing literature focuses on measuring or assessing sustainability implications of bioeconomic change (Escobar et al., 2018; Haddad et al., 2019; Nong et al., 2020; Robert et al., 2020). Given that bioeconomy strategies in the United States and EU initially focused on the energy sector, much of the early contributions to this literature looked at policies and technological solutions for bioenergy-based transformation processes, as well as their drivers and outcomes (Söderberg and Eckerberg, 2013; Popp et al., 2014a). In a review of early bioeconomy literature, Pfau et al. (2014) found that most contributions identify necessary conditions for bio-based transformation to result in sustainability gains. Such conditions apply to both political and technology-focused bioeconomy strategies and often vary by context, which represents a significant challenge for anticipating and governing transformation. While being aware of the debate on the governability of transitions, we adopt a normative view of transformation and seek to identify entry points for what has been called governance for and of transformations (Patterson et al., 2017).

To analyze sustainability transformations, a number of different analytical perspectives and theoretical frameworks have emerged in the literature to help structure the analysis of technologies or sectors and related transformation dynamics (Köhler et al., 2019; Zolfagharian et al., 2019). The field of bioeconomy research is still dominated by contributions with a sectoral or value-chain focused perspective (see Gottinger et al. (2020) for a systematic overview). Dietz et al. (2018) have proposed elements of a more general conceptual framework that can be used to characterize archetypical bio-based transformations. The framework follows an established Theory of Change (ToC) logic (Thornton et al., 2017), which requires analysts to identify the drivers, contextual determinants, and causal mechanisms through which change processes result in both desirable and undesirable outcomes. Similar highly visible, but system-specific, contributions have recently been put forward in the context of global food system transformation (Bhunoo and Poppy, 2020; Herrero et al., 2020). The global food system can be understood as a subsystem of the bioeconomy.

This paper’s main contribution is to operationalize the framework proposed by Dietz et al. (2018). After summarizing its main elements, we proceed in two steps: First, we theoretically explore how alternative configurations of the framework can result in distinct sustainable and non-sustainable transformation trajectories (Section 2). And second, we apply the framework to three char-

acteristic real-world examples to explore its usefulness as an analytical tool (Section 3). In Section 4 of the paper, we discuss our insights and extract lessons learned for sustainability governance. Section 5 concludes and gives an outlook for theory and practice.

2. A theory of change for bio-based transformation

The underlying idea of a theory of change follows the logic of a recursive impact analysis which is then depicted in a flowchart. In an early conceptualization originally designed for the evaluation of comprehensive community initiatives, Weiss (1995) defines the ToC as a theory of how and why an initiative works. Connell and Kubisch (1998) advance this definition by a systematic and cumulative approach to study the links between activities, outcomes, and contexts of change processes. Starting from an intended long-term outcome, preconditions or activities necessary to achieve this outcome are determined. In a next step, contextual factors are identified that may have an influence on the implementation of these activities and thus affect the intended outcomes. Anderson (2005) understands ToC as an explanation of how a group of stakeholders or analysts expect an intervention or a change process to reach a long-term goal. She emphasizes four core elements, including (1) a pathway of change that illustrates the links between mid-term outcomes (preconditions) and long-term outcomes, (2) the definition of specific indicators to measure outcomes, (3) interventions used to bring the preconditions on the pathway, and (4) assumptions that provide the background for the theory. The ToC can thus be understood as an outline of the building blocks and relationships between them that would lead to an outcome (Stein and Valters, 2012).

2.1. Outcomes

The framework proposed in Dietz et al. (2018) adopts the core elements of the ToC approach to identify key components and mechanisms that can work towards both sustainable and non-sustainable outcomes of bioeconomic transformations. Such outcomes can, for example, be measured in terms of the Sustainable Development Goals (SDG),¹ many of which are thought to be directly or indirectly affected by bio-based transformation processes (UN General Assembly, 2015; El-Chichakli et al., 2016). We note that this does explicitly include the possibility of adverse outcomes. For example, multiple SDG outcome dimensions potentially imply goal conflicts, such as competition between food and bioenergy or biomaterial production leading to indirect land use change (iLUC) or deforestation (Gerssen-Gondelach et al., 2014; Pfau et al., 2014; Cerri et al., 2018) and other forms of environmental degradation or resource overuse (Sheppard et al., 2011; Pfau et al., 2014; Kleinschmit et al., 2017; Zilberman et al., 2018). Beyond impacts on food markets, the mainstream bioeconomy literature has so far rarely addressed social issues (D’Amato et al., 2017; Sanz-Hernández et al., 2019; Dieken et al., 2021).

2.2. Transformation pathways

The interventions or change processes necessary through which outcomes materialize in the bioeconomy are represented by four transformation pathways (TP), which we describe in more detail below. The TP typology arose from both theoretical considerations

¹ Note that we understand the SDG here as a normative statement that reflects desirable outcomes as a result of a negotiation process among members of the global community of nations. This statement is subject to ongoing and future debate, but can serve here as a benchmark against which outcomes of bio-based transformation processes can be evaluated.

and empirical observations. According to economic theory, factor substitution and efficiency gains are key mechanisms through which resource scarcity and technological innovation can interact to result in economic growth and related transformation processes (Ruttan, 2000). Moreover, innovations based on biological principles (e.g., to provide alternative sources of energy and materials) or the use of biological components in pharmaceutical applications are frequently cited as key enabling technologies for bioeconomic transformation (Wohlgemuth et al., 2021). If we consider the bioeconomy to consist of the sectors that produce, process, or otherwise use bio-based resources, the four TP described below represent a convenient (though clearly not exclusive) set of conceptual pathways, through which economic activities may become 'biologized'.

To validate this approach, we asked participants in a global bioeconomy expert survey² about promising technology fields for a sustainable bioeconomy. Respondents of the survey covered a wide range of sectors relevant to bioeconomy such as agriculture, biotechnology, energy, chemistry, forestry, food and nutrition, fisheries, wood and paper, health and pharma, as well as the professionals engaged in environmental settings or social sciences (see Delbrück et al. (2018) for more information on sample description and results). The large majority of responses could be summarized under the four complementary functional categories described in Dietz et al. (2018), which leads us to consider them here as archetypical bioeconomic transformation pathways (TP):

TP 1 - Substitution of fossil- by bio-based resources: This comparatively well-studied transformation pathway is driven by growing environmental concerns, mainly related to scarcity of fossil resources, energy security, and climate change, together with public policies that shape production and consumption decisions, e.g. biofuel mandates (Sharman and Holmes, 2010; Adams et al., 2011; Lin et al., 2011; Jeffers et al., 2013; Popp et al., 2014b). As a consequence, a relatively large share of energy production relies on both agricultural crops and forest biomass as raw materials (OECD and FAO, 2019; WBA, 2019). Additional concerns about waste generation and environmental pollution (e.g. plastic litter) have recently motivated a growing interest in more advanced material applications such as bioplastics (Gironi and Piemonte, 2011; Colwill et al., 2012; Philp, 2014). The corresponding increase in intermediate demand for biomass affects factor markets (e.g., capital, labor, and land as inputs in bio-based primary sectors), which can result in expansion or intensification of agricultural activity depending on local context factors, such as factor endowments as well as mediators including environmental policy effectiveness (Ceddia et al., 2014; Hertel et al., 2019). Subsequent market-mediated responses can have detrimental effects on both environmental and social indicators depending on whether food and non-food biomass production compete for land and other natural resources such as water (To and Grafton, 2015). The risk of such undesired outcomes, however, can eventually be reduced, though not eliminated, by technological innovation in biomass production, processing, or utilization, and related regulatory governance measures (Tokgoz and Laborde, 2014).

TP 2 - Increases in primary sector productivity: Technological innovation is the main driver of productivity increases in bio-based primary sectors. Many countries implement science, education, and agricultural extension policy programs to promote biomass productivity enhancing technological change. The EU and China, for example, have been implementing various policy reforms to improve the total factor productivity in their agricultural sectors (Swinnen and Vranken, 2010; Deininger et al., 2014). On a global scale, increases

in agricultural productivity tend to reduce commodity prices and hence the demand for agricultural land – an effect commonly referred to as the Borlaug hypothesis (Lobell et al., 2013). At national or regional level, however, higher agricultural productivity may lead to increased resource demand – i.e., rebound effects also known as the 'Jevons Paradox' – including land, with negative social and environmental consequences at agricultural frontiers, for example, in the tropics (Angelsen and Kaimowitz, 2001; Ceddia et al., 2013; Villoria, 2019). Under this transformation pathway, market mechanisms and innovation transfers hence interact in mediating behavioral change of economic actors. Technological development and innovation transfer result in spatially heterogeneous patterns of agricultural productivity change, while market mechanisms mediate further adjustments in prices across both commodity and factor markets.

TP 3 - Increases in biomass use efficiency and new biomass uses: A more efficient use of biomass by processing industries and end consumers can be driven by technological innovation and public policies, as well as through changes in societal norms and value systems (Batidzirai et al., 2013; Singh and Setiawan, 2013). It can contribute to the reduction of (1) waste streams, e.g., through recycling, and (2) bio-based commodity prices by alleviating biomass scarcity on local and global markets, and relates to the intersection of bioeconomy and circular economy known as the Circular Bioeconomy (Carus and Dammer, 2018). If technological and institutional innovations create new forms of biomass-based applications, such as material uses or conversion to platform chemicals, new or more complex value chains emerge with complex impacts on material flows (Berg et al., 2018). Depending on the nature of demand for intermediate and end products from such value chains, increased biomass conversion efficiencies can increase the consumption of bio-based resources while generating unexpected rebound effects. As a result, it is difficult to predict the sustainability outcomes mediated by policy, market, and innovation transfer in this important area of bio-based transformation. Uncertainties arise from the limited knowledge about (a) how new technologies disseminate or perform at different scale, and (b) industries and consumers' responses to known products with new attributes or entirely new bio-based products and applications.

TP 4 - Bio-based value added in low-volume/ high-value industries: The introduction of biological principles in technical applications, such as enzymatic synthesis, can produce bioeconomic change with no or negligible impact on biomass flows (Jung et al., 2012). This largely innovation-induced transformation pathway can reduce costs and increase added value in a potentially large range of industry applications (Cockburn et al., 1999). However, this type of bio-based added value is usually knowledge intensive and requires high-skilled labor. For example, the biopharmaceutical industry is considered a science-based industry whose growth and profitability is highly dependent on successful research carried out by a high-skilled labor workforce (Giunta et al., 2016). Thus, economic and environmental benefits from this transformation pathway are likely to accrue primarily, at least initially, in industrialized economies with advanced science and education systems. Promoting innovation transfers is crucial to alleviate future undesired socioeconomic effects from unequal access to technologies between industrialized and developing economies. Access and benefit sharing at the global scale will depend on effective market mechanisms and knowledge, as well as technology transfer to developing countries.

Similar to the "visions" in the typology developed by Bugge et al. (2016) and applied in empirical research by Hausknost et al. (2017) and Peltomaa (2018), the four transformation pathways as outlined above are complementary rather than mutually exclusive as we show in Section 3. Importantly, however, they serve a different purpose. While Bugge et al.'s visions typol-

² The survey was designed by part of the author team and organized by BIOCOM AG on behalf of the German Bioeconomy Council in the context of the Global Bioeconomy Summit 2018.

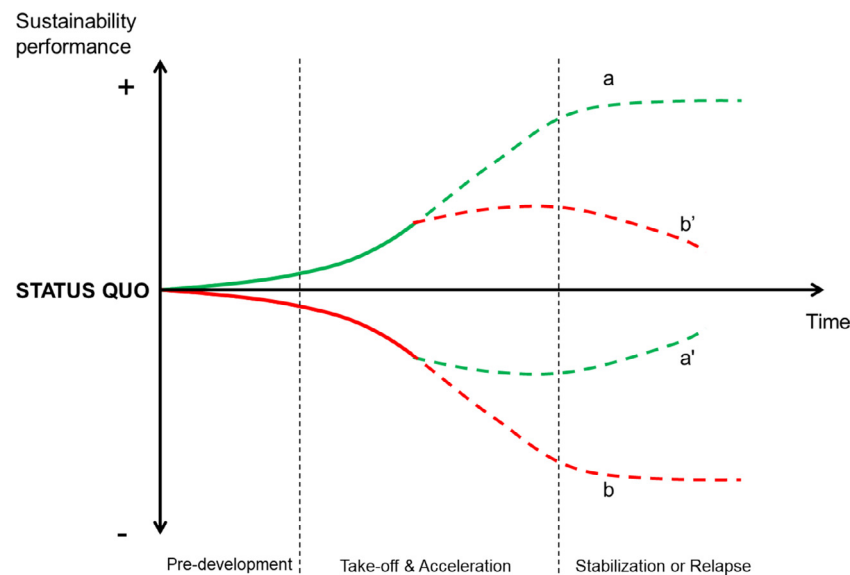


Fig. 1. Enhancing (a, a') and deteriorating (b, b') sustainability dynamics in the four phases of bioeconomic transformation. Source: adapted from Rotmans et al. (2001).

ogy is useful to explain the origin of alternative bioeconomy discourses, the TP framing can be used to identify the key techno-economic mechanisms (e.g. substitution, enhanced productivity or efficiency, product or process innovation) through which a given change process unfolds. Once identified, these mechanisms can inform about potential causal relationships between drivers and outcomes of transformation processes and provide entry points for sustainability governance.

2.3. Drivers, context, and mediators

Factors that determine the relative predominance of TP and their potential outcomes are structured into drivers, context, and mediators (see Fig. 1 in Dietz et al., 2018). Innovation is seen as one of the main drivers of productivity, profitability, and competitiveness in the agricultural sector (OECD, 2013a), is the main and increasing source of growth in OECD countries (OECD, 2013b), and can accelerate the transition towards a sustainable food system (Herrero et al., 2020). Virtually all modern bioeconomy strategies focus on innovation as the central driving mechanism for sustainable transformation (Dietz et al., 2018). Induced innovation and innovation systems theory are two influential schools of thought that can explain how innovation comes to play a key role as a proximate driver of bioeconomic transformation.

Induced innovation theory was first proposed by Hicks (1932) and later restated by Porter (1991) in the context of environmental policy. The Porter hypothesis suggests that environmental regulations, along with resource prices, can be a source of technological change leading to advances in environmental or energy-efficient technologies and lowering compliance costs. Environmental policy is an important factor to steer innovations in desirable directions. Regulatory governance measures such as environmental taxes and regulations lead to reductions in pollution by shifting behavior away from polluting activities and encourage the development of new technologies that make pollution control less costly in the long run (Newell et al., 1999; Popp, 2002; Popp, 2019).

Innovation systems theory provides a complementary foundation for the underlying drivers and the different phases of bioeconomic transformation. The multi-level perspective emphasizes the inseparable and interlinked connections between technological, economic, political and cultural processes of change (Geels, 2002).

Radical innovations emerge in technological niches that are largely outside the general sphere of perception and are supported by a small number of individual, collective or corporate actors. These niches interact with given sociotechnical regimes which are characterized by more or less consolidated actor constellations, rules and conventions, as well as economic and technical structures and can experience occasional changes through niche innovations and, vice versa, influence their development. The sociotechnical regimes, in turn, are embedded in more permanent overarching conditions, i.e. sociotechnical landscapes, that are beyond the direct influence of niche and regime actors, e.g. population growth, economic growth, consumer culture or climate change. Changes in the landscape level create pressure on the regime and can eventually enable breakthrough of niche innovations in mainstream markets (Geels and Schot, 2007).

Demographic and economic development as well as, increasingly, climate change and consumer awareness, thus often act as underlying **Drivers** that trigger (or induce) proximate drivers of change, such as technological innovation or policy programs that anticipate or respond to societal needs. Transformation outcomes on the other hand, are leveraged by **Mediators**, such as market mechanisms and transfers of knowledge or technologies (Fig. 1, top) at multiple geographical scales, which result in behavioral changes of economic actors at different levels (Bisoffi, 2019; Kardung et al., 2021). The predominance and exposure to drivers and mediators are subject to **Context**-specific characteristics, such as natural resource endowment, infrastructure, and science and education systems (Biber-Freudenberger et al., 2018; Hertel et al., 2019).

As the ToC implies a temporal dimension with TP as intermediate outcomes for long-term goals, Dietz et al. (2018) invoke a well-known multi-phase concept (Rotmans et al., 2001), which describes direction, speed and size of transformation in complex systems as a s-shaped curve that goes through four phases: Pre-Development, Take-Off, Acceleration, and Stabilization/Relapse (Bosman and Rotmans, 2016; Göpel, 2016). The s-curve, however, may deceive by describing an ideal-type transformation in terms of a single outcome. Moreover, bio-based transformation may not be the only possible response to the underlying drivers. It is thus necessary to discuss how alternative transformation dynamics can emerge depending on the interaction of drivers, context, and mediators.

2.4. Transformation dynamics

Any system of TP and their drivers, context factors, and mediators must be expected to potentially evolve towards both positive and negative sustainability outcomes vis-à-vis the status quo. Naturally, system complexity increases with the number of drivers, mediators, and related actors involved (e.g. when moving from local to national or global scale) and so does the risk of unexpected outcomes (Liu et al., 2007).

For example, regional or national mixes of transformation pathways and possible spill-over effects will largely depend on the way policy makers and technology developers respond to pressures imposed by underlying drivers in a given national context (Hertel et al., 2019). Specifically, country-specific context-factors, such as comparative advantages in natural resource endowment or labor supply, and historically determined legal and institutional path dependencies, can lock national bioeconomies into certain mixes of transformation pathways – at least in the medium term (van den Bergh and Kallis, 2013). These context factors will then also co-determine the nature of the bioeconomy strategies adopted by decision-makers, and thus influence how and which mediating factors, such as trade with selected world regions, have a bearing on sustainability outcomes.

Potential deviations from the stylized s-curve of transformation are depicted in Fig. 1. Sustainable enhancing (deteriorating) development dynamics – green (red) line segments – can result from favorable (unfavorable) interactions between system dynamics and governance responses (or lack thereof). For example, if an economy has embarked on the solid green transformation curve (a) in the pre-development phase, it can be thrown onto a sustainability deteriorating path (b') if economic rebound effects set in during the take-off and acceleration phase. Alternatively, societies can take corrective action once they have entered the red transformation curve (b), which may enable a gradual switch back to a more sustainability enhancing path (a'). Such adaptive governance of transformation processes, however, requires investments in process monitoring capacity and advanced governance structures that are capable to exert corrective action, ideally in a legitimized and acceptable way. Alignment of alternative sustainability governance modes depending on the state and corresponding outcome in a given transformation process is necessary and will be subject of Section 4 after applying the ToC to real-world cases.

3. Applying the framework to ongoing bio-based transformations

We now turn to three examples of ongoing and potential bioeconomic transformation processes to illustrate the application of the ToC proposed above. The three cases were chosen to illustrate how bio-based transformation can be framed in terms of the four pathways and their related key drivers and mediators. They also represent bio-based sectors that are frequently referred to in the bioeconomy discourse and related political strategies (see e.g. Dietz et al., 2018).

Following the conceptual elements of the ToC, we now refrain from the recursive logic that is characteristic to the ToC and present each case iteratively by first outlining the specific **Context** factors under which a given combination of transformation pathways has emerged and how case-specific combinations of **Drivers** and **Mediators** interact over time, affecting key sustainability **Outcomes** of bio-based transformation. Each case ends with an assessment of how various forms of governance have contributed (or not) to enhancing the overall sustainability of the bio-based transformation described therein.

3.1. Case 1: food and non-food biomass production

Various countries including leading bioeconomies in South America, such as Argentina, Paraguay, and Brazil, have embarked on TP 2 (productivity increase) driven by technological innovation in agriculture and mediated by increasing demand from trade partners engaged in TP 1 (substitution).

3.1.1. Context

From 1985 to 2018, total harvest area of soybeans increased by 135% (FAOSTAT³). This growth is particularly present in countries with a rich natural resource endowment. The contextual factor is depicted by the Status-Quo (SQ, Phase 0) of the transformation curve in Fig. 2a. In South American production countries, total harvest area increased by 399% in Argentina, 242% in Brazil, and over 388% in Paraguay between the years 1985–2018 (FAOSTAT). Soybeans are an important agricultural commodity used in animal feed, human consumption, and industrial purposes globally. Due to the versatile composition of soybeans (high oil and high protein content), they have also become an essential input to the global bioeconomy as an inexpensive protein source for producing bio-fuels, bio-composite building materials, adhesives, inks, lubricants, and solvents (Brentin, 2014). Soybean based food, fiber, feed, and fuel have been heralded as a sustainable and to reduce vulnerability to price fluctuations of non-renewable raw materials (United Soybean Board, 2018). Today, the potential of bio-based products to create new markets for soybeans is supported by governments and industry alike (Westcott and Hansen, 2016).

3.1.2. Drivers & mediators

Technological innovation, economic growth, and policy incentives pushed the economy initially onto the solid green transformation curve (Fig. 2a). Drivers on both the demand and supply side have led to a massive expansion of soybean production worldwide. Soybeans and their derivatives are the most traded agricultural commodity in the world. In total, soybean-based products account for roughly 10% of global agricultural trade annually, and are projected to increase to 22% by 2025 (Westcott and Hansen, 2016) and to reach 23.5% by 2029 (Dohlmann et al., 2020). In the 2016/2017 season, soybean production was estimated to reach 336.62 million tons – 85% of which was processed into soybean meal and oil (Lee, 2016). Strong supply boosts are mainly driven by technological development in production. For instance, the soy-based bioeconomic transformation in South America was mediated by the rapid transfer and dissemination of new GMO-based agricultural production technologies (Phase 1, Fig. 2a), such as no-till planting methods, that increased yields, but also allow for expansion to more marginal regions such as the Gran Chaco in South America (Le Polain de Waroux et al., 2016). Demand side drivers of soybean expansion such as economic growth include the increasing global demand for soybean-based animal feed in pork and poultry production in China or Europe mediated by markets and trade (Phase 2, Fig. 2a), as well as fossil fuel substitution policies in industrialized countries (Westcott and Hansen, 2016; Turzi, 2017).

3.1.3. Outcomes

This soy-based bioeconomic transformation can lead to both positive and negative outcomes in terms of social and economic (Phases 1 and 2), and environmental (Phase 3) dimensions. It has the potential to contribute positively to several SDGs in and beyond South American countries, for example, by bringing employment opportunities and economic development to rural areas or by reducing food prices for poor net-food consumers in developing countries (Richards et al., 2014; OECD and FAO, 2015).

³ All FAOSTAT figures accessed in February 2020: <http://www.fao.org/faostat/en>

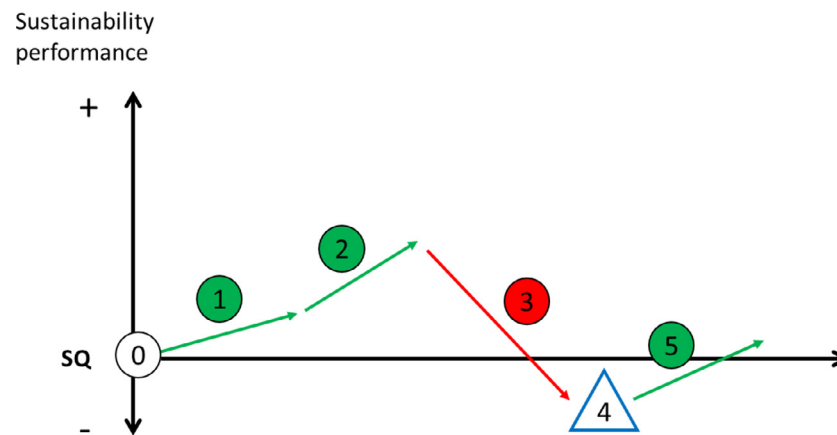


Fig. 2a. Actual (solid line) sustainability enhancing (green)/ deteriorating (red) sustainability development from the Status Quo (SQ) in Phase 0 due to favorable (green circular) or unfavorable (red circular) interactions between system dynamics and governance responses (blue triangular) in the case of food and non-food biomass production. Source: own.

However, an increasing amount of research also indicates negative environmental and social outcomes of the rapid conversion of rural landscapes for soy production in South America including deforestation and increasing inequality (Weinhold et al., 2013; Nascimento et al., 2019). The predominant agro-industrial soy production model in South America is driving a rapid conversion of both forest and smallholder farming areas in the Cerrado, Pampa, and Campos grasslands, the Gran Chaco, as well as the Amazon and Atlantic forests, into soy production. This conversion has myriad delayed impacts on the environment, livelihoods, and social structures in production regions (Gibbs et al., 2010; Gasparri and Le Waroux, 2015; Godar et al., 2015; Boerema et al., 2016; Siegel and Bastos Lima, 2020), leading to the solid red line and outweighing the initial positive outcomes (Phase 3, Fig. 2a).

3.1.4. Governance

To mitigate the negative impacts of soybean expansion in South America and to counter the deviations from the standard stylized transformation towards deteriorating sustainability dynamics (Phase 3, Fig. 2a), there have been several governance interventions, depicted by the triangular (Phase 4) in Fig. 2a, to control or regulate land use by both governments and the private sector. One of the most frequently cited supply chain interventions enacted by the private sector is the 2006 Brazilian Soybean moratorium whereby major soybean traders agreed to not purchase soybeans grown in the Amazon biome on lands that were deforested after 2008 (Gibbs et al., 2015). This policy was hailed as a success for mitigating soybean-based deforestation in the Amazon region. However, feedback loops resulted in iLUC dynamics by pushing compliant soybean production to the neighboring biomes, which fall outside of the moratorium, leading to deforestation in other biomes, most notably the Cerrado region (Nepstad et al., 2019). Governments, such as the Paraguayan government's 2004-deforestation ban in the Atlantic Forest region, have enacted similar regional based moratoria and bans. This policy drastically reduced high deforestation rates due to soybean and cattle expansion in Paraguay's Atlantic Forest region, which in turn created pressures for increased deforestation in the Paraguayan Chaco region that fell outside of the deforestation ban via leakage effects (Baumann et al., 2017). The direct and indirect effects of governance interventions depicted by phase 5 in Fig. 2a are illustrated by a gradual switch to a sustainability enhancing outcome due to corrective action, though less than desired as a result of iLUC. Thus, beyond bioeconomic transformations via technological advances, unintended consequences and perverse incentives created by environmental governance interventions, also have the potential to

impact land use change dynamics in agricultural frontier regions. This further complicates the delicate balance between positively contributing to the SDGs, while also making ecologically sensitive areas more attractive to cropland expansion, as seen in the nascent soybean expansion occurring in the Paraguayan Chaco.

3.2. Case 2: biomaterials and land use

Bio-based platform chemicals can be used in multiple applications such as bioplastics. Polylactic acid and ethanol are the two main raw materials for bioplastic production (bio-PET and PLA, respectively) and account for the largest market shares, while thermoplastic starch (TPS) blends are important in the EU market (Ifbb, 2019; de Jong et al., 2020). In this regard, the bioplastics sector classifies as TP 1 (substitution), TP 3 (efficiency increase), and TP 4 (low volume – high value), depending on the specific feedstocks and production technologies employed.

3.2.1. Context

Bioplastics have rapidly become a widely used commodity in various national economies as a partial substitute for conventional plastics whose application negatively impacts the environment (Aeschelmann and Carus, 2015; de Jong et al., 2020). Favorable infrastructure conditions, advanced technical know-how, and accompanying policy frameworks provide a fruitful basis for transformative change (Phase 0, Fig. 2b). In the case of Germany, Brazil, and many Asian countries, bioplastic producers have benefited from direct governmental support mainly in the form of funds for R&D and biotechnology clusters to attract production hubs. Additionally, countries such as Japan, South Korea, Singapore, Malaysia, Thailand and China, offer financial and non-financial incentives to companies investing in research in bioplastic production (OECD, 2013c). Due to favorable policy frameworks, Asian countries are better positioned for favorable access to bio-based building blocks as a precursor for bio-based polymer production (Aeschelmann and Carus, 2015). Additionally, Brazil has the potential for bioplastic production using existing sugarcane ethanol plants, and could enhance feedstock use efficiency through the use of integrated bio refineries (Escobar et al., 2018). Bio-ethylene production, used as a building block for a variety of bulk materials, is already economically competitive in Brazil, as it is based on established technologies; polylactic acid has the highest economic potential both now and in the long term (Gerssen-Gondelach et al., 2014). So far, the production of second generation bioplastics from lignocellulosic feedstock (i.e., from wood or short rotation coppice)

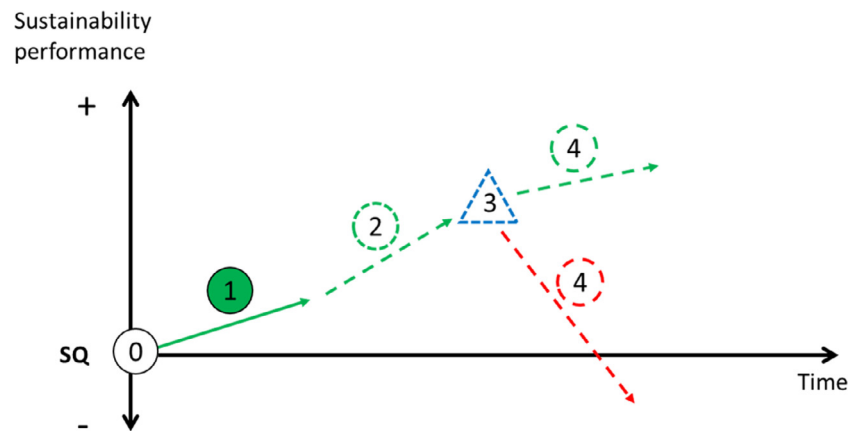


Fig. 2b. Actual (solid line) and potential (dashed line) sustainability enhancing (green)/ deteriorating (red) dynamics from the Status Quo (SQ) in Phase 0 due to favorable (green circular) or unfavorable (red circular) interactions between system dynamics and governance responses (blue triangular) in the case of biomaterials and land use. Source: own.

outside the context of sugarcane biorefineries in Brazil and Thailand (i.e., from bagasse and molasses), is still far from being profitable (Carus and Raschka, 2011; OECD, 2013c; Govil et al., 2020).

3.2.2. Drivers & mediators

The durability of non-biodegradable conventional plastics combined with inappropriate human behavior and limited waste treatment capacities in many parts of the world, for example, contaminates terrestrial and freshwater ecosystems (e.g., plastic debris and micro particles), with negative effects on wildlife (Ogunola et al., 2018) and human health in both production and consumption regions (Thompson et al., 2009; Philp et al., 2013). With its substitution possibilities, global bioplastic production is expanding substantially from 2 million tons in 2018, to a projected 2.4 million tons in 2024 with production capacity being largest in Asia (45%), followed by Europe (25%), North America (18%) and South America (12%) (European Bioplastics, 2019). More advanced technologies/methods, including biowaste valorization techniques and identification, as well as classification of valuable components in the recycling streams, can produce high-value products (Montoneri et al., 2011; Arancon et al., 2013). Additionally, new technology also allows wastewater to be used as a renewable feedstock for bio-plastic production (Amulya et al., 2016).

At its current, pre-transformational state, bioplastic production is largely driven by technological innovation in the private sector, regulatory arrangements, and behavioral change among environmentally sensitized consumers that can influence firms' demand for plastics as an intermediate input (Dilkes-Hoffman et al., 2019), leading to the solid green line in Phase 1 (Fig. 2b). However, the material properties and performances of certain bioplastic products depend on a specific biochemical formula. Many of the PLA- or PBS-based plastics do not yet match the properties of conventional plastics regarding durability, flexibility and rigidity as exposed to variations in temperature, moisture and acidity levels. They are thus compounded with conventional plastic reducing the environmental benefits, including recyclability. Besides packaging, other prominent sectors, such as agriculture and medicine, are expected soon to create further demand for bio-based and biodegradable plastics (Globe Newswire, 2017; Schipfer et al., 2017; Junginger et al., 2019). Thus, transformative change will likely hinge on mediators like further technology development and innovation transfer, the introduction of advanced and cascading waste recycling streams, competitive supply of bio-based raw materials including increased international trade, and appropriate societal and political support, here illustrated by the dashed green line indicating that the associated sustainability enhancing development

is a potential outcome (Phase 2, Fig. 2b). The differential effects of drivers and mediators (i.e., consumer preferences and innovation transfer) depend largely on national political frameworks in producing and consuming countries, mainly in the field of R&D and recycling. These frameworks can reduce market uncertainty via feedback-loops, promote private investment for capacity expansion, and determine the stage of development of the bioplastic sector. At the same time, recycling fees and other legislative ad hoc measures (e.g., in Germany or Italy) can contribute to significant advancements in terms of biodegradability.

3.2.3. Outcomes

A biomaterial-based transformation could produce sustainability gains in various SDG dimensions, such as health, sustainable consumption and production, and terrestrial as well as aquatic life. More environmentally benign bioplastics that potentially encompass new functionalities such as biodegradability, reduced life cycle of CO₂ emissions, and reduced toxic runoff, could contribute to TP 1 (through raw material substitution), TP 3 (by way of biomass waste stream recycling and uses of new biomass, such as wastewater), and TP 4 (by adding value in industrial applications) transformation pathways. Given conflicts with land-use and food production constitute possible feedback-loops that may lead to sustainability deteriorating dynamics.

Just like in first-generation biofuel production, a large-scale substitution of fossil resource-based materials by bio-materials (TP 1) will directly and indirectly compete for land and water resources with food and feed production, unless second generation technologies are implemented on a commercial scale, and is thus not in the focus of future, global bioeconomy (Laibach et al., 2019). Currently, the two main feedstocks used for bioplastic production are corn and sugarcane (van Hilst et al., 2017; Ifbb, 2018). The land footprint of polylactic acid, is around 0.37 ha and 0.16 ha per ton when corn and sugarcane are used, respectively. Although this implies a reduction in footprint relative to diverting the same feedstocks for fuel purposes (0.52 ha and 0.23 ha per ton of ethanol, respectively) (Ifbb, 2018), establishing a high-volume bio-based economy, including bio-based plastics, composites, lubricants and others, can tighten feedstock based land competition further. The development of options to produce biopolymers with lower impacts on land, i.e. from either perennial non-food crops or residual organic materials is developing, as can be seen by an increasing number of studies evaluating their environmental impacts (Escobar and Laibach, 2021). At the same time, as different feedstocks from algae over crop residues to organic waste are being tested to produce biopolymers, integrated facilities to conduct the

conversion are being developed. In state-of-the art biorefinery designs, options to produce high-value compounds in addition to bioplastic are reaching pilot project phases (Beltrán et al., 2019; Hassan et al., 2019; Escobar and Laibach, 2021). However, especially with regards to feedstock flexibility and profitability, these processes still require interdisciplinary R&D and face scaling issues when moving from the lab to the market scale. Even though these technological developments are promising, to achieve sustainably produced and utilized bioplastics a behavioral change from consumers is needed (Laibach et al., 2019; Bröring et al., 2020).

3.2.4. Governance

The use of low volume biomaterials in transformation TP 3 and TP 4 may be less prone to direct natural resource competition, but require well-designed economic support and innovation policies (Phase 3, Fig. 2b) to remain decoupled from primary sector resource demand. Future sustainability dynamics depicted by the dashed green and red lines (Phase 4, Fig. 2b) will ultimately depend on the specific feedstocks and production technologies employed in its implementation, but also on the employed end-of-life options and behavioral change (Bröring et al., 2020). Meanwhile, policy and governance arrangements, also in addition to private corporate governance principles, need to set the regulatory guardrails for such implementation (Dietz et al., 2018; Förster et al., 2020). Possible governance intervention should take the reduction of illegal cropland expansion in the tropics into account, promote sustainable intensification of agriculture (e.g. by using perennials growing on marginal soils), and reconsider regulations affecting the utilization of organic waste as a resource (Bröring et al., 2020; Gerten et al., 2020; Nong et al., 2020). Further suggestions from scientists are to implement monitoring systems with consistent impact categories, sustainability-oriented product design approaches as well as producers' responsibilities beyond the product sale (Helander et al., 2019; Jarre et al., 2020; Moosmann et al., 2020; Escobar and Laibach, 2021). Yet, even though circular, or at least cascading modes of bioplastic production are being more and more pursued, governance actions are required to limit potential rebound effects of over-extensive production as profitability increases (Zink and Geyer, 2017).

3.3. Case 3: biopharmaceuticals

The biopharmaceutical sector mainly classifies as TP 4 (low volume – high value), as the intensity in the use of bio-based inputs is extremely low per unit of output. It also relates to TP 2 (productivity increase) due to fast technological development progress in its production and TP 3 (efficiency increase) through the utilization of new biomass inputs.

3.3.1. Context

The pharmaceutical industry, particularly the EU pharmaceutical industry, is considered the technology sector with the highest value-added per employee, and also the highest ratio of R&D investment to net sales (Efpia, 2018), and hence benefits from a sound infrastructure and science and education system (Phase 0, Fig. 2c). Biopharmaceuticals include a wide range of products, such as vaccines, therapeutic proteins, antibiotics, hormones, blood and blood components, tissues, etc. which are derived from living material and are often genetically engineered production hosts (human, mammalian cell, animal, microorganism, plant or algae) (ITA, 2016). Algae or plant-based options are in continuous development, where transient expression systems, external stimulation or cell-culture approaches are the most prominent alternatives to traditional cultivation of medicinal plants (Corbin et al., 2020; Moon et al., 2020). The use of plant residues or algae to extract compounds with pharmaceutical value in the beginning of

a cascading exploitation of biomass (see Case 2) is already in the proof-of-concept stage, although it may take some time to become profitable (González-García et al., 2016; García Prieto et al., 2017; Junker-Frohn et al., 2019; Escobar and Laibach, 2021). Additionally, even more future-oriented developments are expected with the usage of synthetic biology and biofoundries, which effectively design microorganisms for medicinal applications and compound production (Ye, 2015; Jessop-Fabre and Sonnenschein, 2019; Kitney et al., 2019).

3.3.2. Drivers & mediators

Production of biopharmaceuticals has experienced fast technological development in the last few decades, supporting mass production and the utilization of new biomass inputs from various plants and animals (Fischer et al., 2004; Butler, 2005; Dickson, 2014). Factors driving the bio-based transformation of the pharmaceutical industry, leading to the green transformation curve (Phase 1) in Fig. 2c, include changes in demographic structures and consumer preferences in industrialized and emerging economies, as well as advances in biotechnology and medical research. In response to growing middle-income classes and increased consumer awareness, companies have also increased research in “personalized” medical solutions (EC, 2014). Beyond biopharmaceuticals, functional foods or nutraceuticals are also gaining traction, especially in wealthy countries where preventative measures and a healthy lifestyle, especially plant-based food or cosmetic additives or compositions, are demanded (Bröring et al., 2006; Khedkar et al., 2017). Knowledge and innovation transfer have led to additional increases. Bio-pharmaceutical manufacturing strongly relies on sophisticated R&D that requires considerable financial and human capital investments over long innovation cycles (Deloitte, 2015). As a result, bio-technological advances from several decades ago, such as the monoclonal antibodies (MAb) market segment, dominated the global biopharmaceuticals market in 2018 with about 33.2% market share (Globe Newswire, 2019).

3.3.3. Outcomes

The functional diversification and increased effectiveness of medical treatments represent an obvious direct contribution of biopharmaceutical transformations to sustainability, particularly to SDG 3, Good Health and Well-being. Positive secondary effects to achieve more SDGs (e.g., SDGs 4 and 8), are anticipated from potential related investments in educational and vocational training programs and from increased employment opportunities in the sector. Given the incipient signs of a gradual shift in the geographical balance of the pharmaceutical market towards emerging economies (Efpia, 2015), such benefits may also potentially accrue in the developing world (Deloitte, 2015). Moreover, an increasing demand for undiscovered natural substances as inputs to bio-pharmaceutical research and production can further increase biodiversity option values (Simpson et al., 1996). For instance, by re-discovering and re-focusing research on neglected plants being used for medicinal applications as in the case of the Chinese Yam, the cascading use of plants to extract biopharmaceuticals followed by subsequent utilization for food products, could decrease the need for conversion of fossil-based chemicals and increase crop diversity in agriculture (Epping and Laibach, 2020).

3.3.4. Governance

Innovative bio-pharmaceuticals (and also natural cosmetics, medicinal, natural products, and botanicals) hinge inter alia on Intellectual Property (IP) protection and enforcement (EC, 2014). Nonetheless, significant future potential for economic growth is expected from the development of “biosimilar” drugs with surrendered or lapsed patents and in developing and emerging

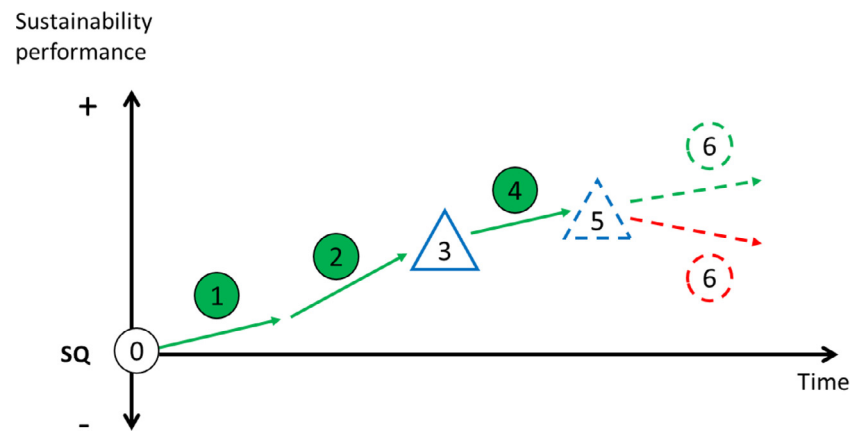


Fig. 2c. Actual (solid line) and potential (dashed line) sustainability enhancing (green)/ deteriorating (red) development from the Status Quo (SQ) in Phase 0 due to favorable (green circular) or unfavorable (red circular) interactions between system dynamics and governance responses (blue triangular) in the case of biopharmaceuticals. Source: own.

economies (Neville and Kenyon, 2011; ITA, 2016). The global market for medicinal, natural products is also expected to grow in the near future (Laird and Wynberg, 2017). Regulation to keep biodiversity utilization within the boundaries of a functioning socio-ecological system might also entail hurdles for socioeconomic development despite best intentions (ibid). This might translate into lengthy and costly administrative procedures, longer clinical trial phases, and higher production costs in general, while at the same time providing a form of legislative protection of indigenous intellectual property rights and safeguarding biodiversity (Förster et al., 2020). In the same vein, and with respect to using bioeconomy for rural development strategies, recent research from South Africa discovered that over-extensive regulations (Phase 3, Fig. 2c) in the development of small-scale businesses for medicinal and natural cosmetics impede small-scale and medium size entrepreneurs and is, together with limited planning security provided by the government, inhibiting a transformation of this sector (Förster et al., 2020) and slowing down the sustainability enhancing development (Phase 4, Fig. 2c). Conditional on the existence and enforcement of appropriate resource access rules and benefit sharing mechanisms, as well as the existence of constraining regulation to safeguard the ecological functions of the biosphere (Phase 5, Fig. 2c), bio-pharmaceutical transformation might develop to contribute to nature conservation and alternative employment opportunities in developing countries with abundant natural resources depicted by the dashed-green line (Phase 6) in Fig. 2c. However, in some biomass producer countries of the global South, the discovery of active pharmaceutical ingredients in plant species have also led to the over-harvesting of such species in the wild and can thus also create adverse effects for biodiversity conservation (Crouch, 2018) as indicated by the dashed-red line segment (Phase 6) in Figure 3c. Despite these opportunities, the long-run sustainability dynamics of bio-based transformations in the pharmaceutical sector will also depend on appropriate institutional preconditions and coordinated action at the international level to function effectively. However, such transformations are also subject to national resources and capacities regarding regulation, implementation, and enforcement (Crouch et al., 2008), while they are also subject to the overall socioeconomic and biophysical contexts in biodiversity-rich developing countries of the global South (Förster et al., 2020).

4. Discussion and implications for sustainability governance

The three cases analyzed above illustrate how the ToC framework can explain both positive and negative sustainability outcomes of real-world bioeconomic transformation processes. Case-

specific combinations of context factors as well as exposure to drivers and mediators determine, which mixes of TP emerge and how fast they translate into outcomes. At least four key lessons emerge:

First, TP1 type of bio-based transformation comes with the risk of causing environmental and other externalities. As shown in Case 1 and 2, this risk increases if bio-based substitution involves internationally traded feedstock, which can cause direct and indirect land use changes mediated via agricultural input and output markets. The sustainability impacts of land use change are highly context dependent. If agriculture intensifies or expands in ecologically sensitive regions, such as tropical rainforests, peatlands, and savanna ecosystems, social marginalization of vulnerable populations, biodiversity loss, and greenhouse gas emissions can be substantial (Seymour and Harris, 2019). Recent evidence also suggests that tropical forest loss can negatively affect agricultural productivity at regional scales (Leite-Filho et al., 2021). On the other hand, moderate intensification of extensively used anthropogenically modified landscapes can be environmentally neutral or even desirable depending on how and where it is done (Tschamntke et al., 2012).

Second, TP2 and TP3 type of bio-based transformations will not necessarily improve environmental outcomes via more efficient resource use. Case 1, illustrates that knowledge is highly mobile and international innovation transfer implies that technologies that boost agricultural productivity may temporarily accelerate rather than reduce the expansion of agriculture into ecologically sensitive ecosystems. This apparent contradiction of the “Borlaug hypothesis” does not invalidate the idea that technological progress in agriculture contributes reducing the global amount of land use for food production (Hertel, 2018). It suggests, however, that productivity boosting agricultural technology change can cause (irreversible) net environmental damages, when it happens to occur at the world’s agricultural frontiers. Cases 1 and 2 further show that combining TP1 with TP2 & TP3 type of transformations likely aggravates the risks to result in non-sustainable outcomes, due to rebound effects (García et al., 2020). Bio-based substitution, unless based on low value waste streams, increases the demand for bio-based feedstock. This makes rebound effects more likely to occur as a result of efficiency gains in primary biomass production and processing.

Third, TP4 type of bio-based transformation is least likely to backfire in terms of undesirable sustainability outcomes that are mediated via international biomass trade. Other technology-specific risks may apply especially as a result of international technology transfer in combination with inappropriate use. However,

Case 3 is also currently one of the few examples for broadly successful TP4 type innovation processes. Given the possibility of disruptive technological change, the sustainability impacts of future TP4 type transformation are thus inherently hard to predict.

Forth, governance is a necessary evil. Cases 1–3 show in line with literature and expert opinions (Biber-Freudenberger et al., 2020; Dietz et al., 2020) that a sustainable bioeconomy will only come off the ground under appropriate governance arrangements. However, Cases 1 & 3 also illustrate that poorly designed or ineffectively implemented attempts to govern transformation can do more damage than good. For example, adverse effects of the biofuel boom in the early 2000s on food markets and the environment could have been much less pronounced without biofuel mandates in Europe and the US.

Taken together, these four insights can help to inform the design of strategies to enable and regulate sustainable bioeconomies. As pointed out in Dietz et al. (2018), the current generation of national bioeconomy strategies focusses on what the authors call “enabling governance”. This form of strategic governance has also been called “governance for transformation” (Patterson et al., 2017) and includes policy mixes with the normative intent to promote transformative behavior as documented in Cases 1 and 3. However, Case 1 and 2 also illustrate that this form of nationally motivated enabling governance inevitable produces global externalities in a world with international trade and innovation transfer.

Regulatory governance or “governance of transformation” (Patterson et al., 2017) thus ideally becomes part of any attempt to steer bio-based sustainability transformations. This second mode of governance stands for steering and possibly readjusting dynamics of both intentional and unintentional transformative change. This involves the adaptation of existing policy instruments and governance modes to cater for processes already set in motion, or to develop additional legislation, as demonstrated in Case 1. However, doing so requires domain-specific foresight and monitoring capacities as well as implementation structures (Wesseler and von Braun, 2017). Such structures are generally less well-developed in developing and emerging economies than in the industrialized regions of the world that currently invest most in enabling their bioeconomies (Bracco et al., 2019; Förster et al., 2020).

Purposefully steering the global bioeconomy towards sustainable outcomes thus becomes a global collective action dilemma, requiring what Patterson et al. (2017) call “transformation of governance”. Transforming the currently fragmented and incoherent global governance system entails changes on the structural level of policy, legislation, and the institutional and organizational architecture readjusting legally binding regulations and incentives to enable or constrain bioeconomic transformations. This is not a new proposition. In fact, the concept of “earth system governance” is being discussed among governance scholars more than a decade (Burch et al., 2019). Making the global governance system fit for bioeconomic transformation also hardly requires radically new concepts or instruments. Rather, the opportunities and risks associated with bioeconomic transformation represent an additional reason for countries to (1) engage in international environmental agreements, such as the Convention on Biological Diversity and the Paris Agreement, (2) push for binding sustainability safeguards in bi- and multilateral trade agreements, and (3) invest in international compensation mechanisms that contribute to socially acceptable forms of sharing the benefits and inevitable burdens involved in any transformation process.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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