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# Toward a caring and (re)productive bioeconomy? A feminist analysis of socio-technical innovations and sustainability shortcomings

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**ABSTRACT**

The bioeconomy is touted as an innovative economic approach to make economies more sustainable through the use of biological resources and processes. In many bioeconomy policies, the expansion of biomass is key and is enabled by new biotechnologies and precision agriculture (PA). We respond to the demand for critical approaches to sustainability and ask: How can feminist (sustainability) research – specifically feminist ecological economics and feminist science and technology studies – help to assess the sustainability shortcomings of socio-technical innovations in the bioeconomy? We have drawn from these two fields to construct a framework of analysis and illustrate its application by looking at the field of PA, which has emblematic socio-technical innovations for biomass production in the agricultural bioeconomy. We illustrate how this analytical framework can reveal manifold sustainability shortcomings linked to these innovations, such as the reinforcement of power relations; the promotion of productivism; the undermining of precaution, sufficiency, and cooperation in technology development; the fetishization of data; and the delegitimization of local knowledge. While the application of the analytical framework is only exemplary, it shows how such an analysis allows for a fine-grained and multifaceted assessment of a specific field of innovations in the bioeconomy and how it can draw attention to structural and systemic sustainability shortcomings which are often overlooked.

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## Introduction

The bioeconomy has been propagated by European Union (EU) institutions, industries, and policymakers as an innovative economic concept that aims to provide a response to key sustainability challenges (EC 2018). The goal of bioeconomy strategies worldwide, although with different emphases, is the transition from a fossil-based to a bio-based economy. The expansion of biomass use, such as energy crops or residues from the timber industry, and the increase of yields and productivity of biomass production enabled by new biotechnologies and precision agriculture (PA), are key in many bioeconomy policies. The belief in increased productivism and growth through established and new high technologies plays an important role (Boyer et al. 2022; Eversberg et al. 2023), which is why current articulations of the bioeconomy could even be termed high-tech bioeconomy. Political and technological developments related to the bioeconomy shape society-nature relations and social organization, especially in the field of agriculture (Tittor 2021; Puder and Tittor 2023), which is why researchers need conceptual tools to assess their sustainability.

Technology, knowledge, and innovation politics in the bioeconomy tend to have a rather narrow focus that insufficiently accounts for social, ecological, and political implications (Backhouse 2021; Ramcilovic-Suominen 2023). As a response to such narrow notions of innovation, feminist scholars have highlighted important factors such as asymmetric knowledge politics, unequal power relations, and dependencies (e.g., Haraway 1988; Preston and Wickson 2016). These are important to consider for more holistic assessments of the sustainability of innovations (social as well as technological) within (bioeconomy) transformations. In response to the demand for approaches that allow for critical integrated assessments of sustainability, we have developed a feminist framework to analyze sustainability shortcomings related to socio-technical innovations in the bioeconomy. We will illustrate the application of the framework using the example of PA as a field with a number of emblematic socio-technical innovations for biomass production in the agricultural

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bioeconomy. The key question of this article is: How can feminist (sustainability) research – specifically feminist ecological economics and feminist science and technology studies – help to assess the sustainability shortcomings of socio-technical innovations in the bioeconomy?

With socio-technical innovations, we include in our focus technological innovations together with the related social practices around their development and use. In doing so, we account for the fact that technological innovations are not separate from their societal context (Winner 1980). Our aim is to provide a framework to better understand innovations, including the practices and paradigms in which they are embedded, and their implications. We investigate sustainability shortcomings, since bioeconomy innovations, and also specifically PA, are developed with narratives and claims of sustainability.

Our investigation addresses a question which has been partly dealt with in bioeconomy research, that of the sustainability of such an envisioned transition. Here, bioeconomy policies have been criticized as a continuation of ecological modernization due to their growth- and technology-centered solution-seeking and related optimism, and for their economistic reductions regarding notions of innovation, technology, risk, and the economy. The growing demand for biomass creates conflicts between production and nature conservation, while new technologies lead to socio-ecological tensions and conflicts over the valorization of nature (Boyer et al. 2022; Eversberg et al. 2023; Hackfort 2024). The substitution of fossil raw materials in the Global North requires enormous – and increasing – quantities of biomass, which further increases the pressure on soil and ecosystems, not only in the Global South. To make biomass use possible at a large scale and the production profitable, costs are externalized, with major social and ecological consequences, especially in the South and in the global peripheries (Backhouse et al. 2021; Tittor 2021).

As a response, the focus of many bioeconomy policies is not only on expanding biomass production but also on increasing eco-efficiency. However, efficiency does not solve the sustainability problems inherent in finite production spaces; at best, it shifts them temporally or spatially (Boyer et al. 2022). The paradoxical outcomes of bioeconomy policies, despite claims of sustainability, have led some scholars to characterize the bioeconomy as a "failing project" (Lühmann and Vogelpohl 2023).

Feminist research echoes some of the critical perspectives on society-nature relations in the bioeconomy, especially the critique of ecological modernization and the green economy as sustainability strategies (Salleh 1997; Gottschlich et al. 2014; Harcourt and Nelson 2015; Wichterich 2015; Barca 2020). Feminist perspectives are an eye opener for underlying dynamics of externalization (Saave 2022), power, and inequalities related to innovation and technology policies (Haraway 1988; Wajcman 2010, Nelson, Faxon, and Ehlers 2024; Saave, Brinckmann, and Hackfort 2024). Some of these issues and challenges have been addressed in debates about "responsible research and innovation" (RRI), such as the inclusion of laypeople in decision-making, anticipation in the sense of systematic thinking, reflexivity as a critical examination of assumptions, and responsiveness as a willingness to adapt an innovation to societal reactions (e.g., Stilgoe, Owen, and Macnaghten 2013). Feminist science and technology studies (STS) has taken debates and concepts developed in RRI to the next level. Instead of responding to exclusion with inclusion in existing unequal systems and structures of knowledge production, for instance, they question the underlying discursive and material power relations that enable exclusion in the first place (e.g., Campbell 2009; Grzanka, Brian, and Bhatia 2023).

This is why we assume that the fields of feminist ecological economics and feminist STS can help us to better understand and assess the sustainability shortcoming of innovations in the agricultural bioeconomy. We will draw from debates in these two fields to construct our framework of analysis and then illustrate its application by looking at socio-technical innovations in PA. While much of earlier critical feminist work on precision technologies centered around genetically modified organisms (GMOs) (see, for example, Wickson et al. 2017), we focus on PA as a more recent development that has to date received scant attention. However, both technological developments are manifestations of high-tech agriculture and have much in common (Hackfort 2024).

PA refers to the use of digital technologies such as sensors, satellite imagery, and connected data-based tools and platforms in agricultural production to monitor and optimize agricultural production processes (Miles 2019). PA includes, for example, the application of variable rate technology to apply fertilizers and pesticides with digital data-based spraying systems or big data-based recommendations for seeding and solutions for automatic weeding. With this comes a constantly growing collection of agricultural data stored on platforms and clouds, which is expected to enhance knowledge of the needs of plants or the soil. PA is expected to enable a more precise use of inputs and increase efficiency and crop yields, while supposedly decreasing

environmental externalities and costs. As postulated in the German bioeconomy strategy, through "precision farming, land productivity can be increased in an economically and environmentally sustainable way" (BMBF and BMEL 2020, 41, own translation). Behind these PA innovations stand specific understandings of economy, productivity, and sustainability that merit closer examination. It is necessary to scrutinize the sustainability claims related to the recent trend of digitalization in agriculture as part of the agricultural high-tech bioeconomy which, according to the relevant policies, aims for a sustainability transformation.

This article contributes to filling a gap by highlighting such sustainability shortcomings. Surprisingly, the rich diversity of feminist thinking has not yet been harnessed in the analysis of the socio-technical innovations of PA in the bioeconomy (with just a few exceptions, e.g., Nelson, Faxon, and Ehlers 2024). Yet, feminist research enables such a critical analysis, as it sheds light on the omissions of policies and innovations related to dominant sustainability claims.

By sustainability, we refer to a critical emancipatory feminist understanding thereof, wherein care and justice are highlighted as essential elements. This implies thinking of society and nature not as polar opposites, but instead acknowledging their hybrid and relational character, and viewing sustainability as a highly contested and power-laden concept (Gottschlich and Bellina 2017; Boyer et al. 2022).

The article is structured as follows. Based on established feminist critiques of dominant sustainability discourses, economic systems. and technological innovations, we have developed a framework to analyze the sustainability shortcomings within socio-technical innovations in the agricultural bioeconomy. We then illustrate what our framework brings into view by looking at PA as a growing trend in the agricultural bioeconomy, using examples from empirical research in this field. We will lastly derive some conclusions on transformation perspectives for sustainable technology policy and economy, thereby pointing to possibilities of a caring and reproductive bioeconomy.

## Theoretical reconstruction: Analyzing socio-technical innovations in the bioeconomy from a feminist perspective

We developed our analytical framework by reconstructing key ideas from feminist ecological economics (to delineate a critique of economic thinking and its sustainability) and from feminist STS (which focuses on innovations and risk assessment). As the bioeconomy is both a project of transition toward new forms of doing economy and an approach to achieving sustainability centered around technological innovations processes, we believe that the strengths of these two approaches complement each other for a feminist analysis of this transformation.

### *(Re)productivity as an economic and sustainability critique*

Among the ecological feminisms that have emerged since the 1960s (for an overview see Salleh 1997; Saave 2023), an approach called the "caring economy" (*Vorsorgendes Wirtschaften* in German) has developed a specific critique of sustainability, with roots in feminist ecological economics. Its goal is to make the connection between economy, ecology, and social issues visible, understandable, and thus socially shapable. We select this approach from the broader field of feminist ecological economics (Perkins 2007), because of its strength in connecting the analysis of society-nature relations with more applied research and policy proposals for dealing with nature more sustainably. This approach includes in its economic theory the areas of social provisioning and co-production with nature (TVW 2000, 27). And it seeks answers to multiple current crises by developing new concepts that would enable a democratic, socially, and ecologically sustainable economy. The approach offers fundamental critical perspectives on the economy but can also be applied to the bioeconomy specifically (as for instance already done by Brüll 2020). While other ecological feminisms place greater focus on, for example, commodification (Oksala 2018) or a critique of capitalist accumulation (Saave 2023), the caring economy approach combines both critical perspectives on externalization dynamics of the economy and analyses of society-nature relations.

### *Core critique of economy and notions of sustainability*

Social and ecological crises share a common cause, which is rooted in capitalist market economies (Biesecker and Hofmeister 2010). Such economies are characterized by a separation between production and reproduction: paid labor productivity and reproductive activities, such as unpaid care work and the productivity of nature, are viewed and valued as separate. This leads to a contradictory situation, where reproductive activities are considered a natural resource, and are exploited and used to create profits, but are not valued accordingly (Biesecker and Hofmeister 2010). The caring economy approach instead emphasizes that economic practices are in fact embedded in reproductive processes and

activities. In doing so, the caring economy approach offers analytical tools to dismantle the unsustainability of the current economy. With this analysis they build on earlier work by the Bielefeld subsistence theorists (Mies, Bennholdt-Thomsen, and von Werlhof 1988) but emphasize in their analysis the separation of productive from reproductive processes and respective understandings of productivity.

Classifications and devaluations around what is considered reproductive are often gender-specific and therefore reinforce a sexist social order, which the caring economy approach also strives to move beyond. Unlike the economic mainstream, a caring economy does not consider the so-called reproductive as a self-evident and infinitely available resource. From this feminist ecological critique thus follows an expansion of the sustainability discourse to include this reproductive dimension. Furthermore, and on a more practical level, this perspective argues that caring economies need to be built on three principles: precaution (*Vorsorge* in German[1]), cooperation, and orientation toward what is necessary for life (TVW 2000).

### From productivity to (re)productivity

To address the conceptual omission of reproductive processes within economics, as well as within business practices in capitalist economies, caring economy scholars propose the concept of (re)productivity. (Re) productivity denotes the undivided unity of all productive processes in nature and society. While unity is not separated by devaluations regarding the reproductive, it does acknowledge differences between productive processes (Biesecker and Hofmeister 2006, 19). The term refers to the often-forgotten fact that in every production process, processes of restoration and renewal through human or natural reproduction are already included. As a new category, (re)productivity replaces existing conceptual separations between productive and reproductive processes and activities. It ultimately strives to enable a more sustainable social-ecological metabolism that builds on more appropriate mediations rather than separations between what is currently considered reproductive or productive, as both areas are actually productive. We take from this that productive and reproductive activities and processes are always interlinked and cannot be separated from each other.

This perspective allows for a critique of the economy that does not actively co-create reproductivity but instead takes it for granted. As a result, nature is both a product of natural productivity as well as a product of the economy and society. This is important to note since oftentimes nature is conceived as something outside of society that needs to be preserved (Biesecker and Hofmeister 2010; see also Mölders 2019; Gottschlich and Katz 2020). However, there is no such nature (anymore) and the bioeconomy contributes to this by also creating a hybrid product-like nature (Brüll 2020, 95).

### Implications for the bioeconomy: Ensuring renewability and precaution

Adopting a (re)productivity perspective is key for biomass production. From this perspective, it becomes evident that it is not automatic that so-called renewable resources like biomass are actually renewed. Regrowth depends on the permanent regeneration of suitable growth conditions, such as soil fertility and nutrient availability, biological diversity, and so forth., and these conditions are in question globally today (Brüll 2020, 94). Maintaining the conditions for reproduction is a major sustainability challenge under the current capitalist mode of production. From a (re)productivity perspective, the key aim of sustainable biomass use is to ensure that biomass is not only extracted, but that the reproductive conditions ensuring that this resource is renewable are maintained. In adopting a precautionary principle with regard to sustainable biomass production, it becomes clear that biomass cannot be extracted endlessly. We take from this that a sustainable bioeconomy must ensure that the reproductive conditions of biomass production are renewed, not depleted.

From a (re)productivity perspective, sustainability is facilitated by an orientation toward the three principles of a caring economy (precaution, cooperation, and orientation toward what is necessary for life), which replace the dominant principles of aftercare, competition, and orientation toward monetary measures. Importantly, the third strategic principle points to sufficiency as a sustainability strategy, which differs from current emphases on eco-efficiency and technological optimism within the bioeconomy and unlocks new routes for the sustainable organization of society. Employing precaution implies for any economy that "prediction and control make way for *Vorsorge*, the caring concern for the future present of others" (Adam 2013, 126). Sociologist Barbara Adam further notes that

> [Vorsorge]…entails that we extend both knowledge and concern to encompass our implication in potential outcomes, as they are stretched across space and time. Importantly, we are allowing concerns about what is *right* and *just* (rather than cost effective) to enter considerations (Adam 2013, 123–124).

This attention to time reveals the underpinnings of dominant economic thinking and dominant understandings of sustainability, including their underlying narratives of the control and domination

of nature and innovation, as rather limited. From this it follows that bioeconomy projects need to be aware of a future present and recognize the temporal dimension of sustainability, which can be taken care of by adopting an attitude of precaution.

### *Knowledge in technology development*

Another relevant aspect within feminist research more generally, that of contested knowledge production, is also echoed in the caring economy framework. It is important to address knowledge production when moving toward more sustainable ways of "doing economy." To redesign (re)production processes, some authors of caring economy approach advocate, for instance, for socio-ecological technology and product development that includes not only male "expert knowledge" but also the "everyday knowledge of all affected actors" (Biesecker and Hofmeister 2013, 154; see also Röhr and Weller 2021). According to these authors, such equal consideration would also alter previous gender relations. More sustainable, (re)productive bioeconomies would "produce, maintain and sustain reproductive functions with the help of science, local knowledge, and design, as far as possible" (Brüll 2020, 96; own translation). We derive from this insight that diverse and also non-hegemonic forms of knowing about natures and (re)productivity should be a basis for technology development.

A second feminist research tradition is interesting and fruitful for our framework: the field of feminist STS, specifically work engaged with the ethics of care. At present, forging the bioeconomy follows a predominantly technology-centered way of doing economy. Therefore, it is important to complement a critique of the economy and sustainability with a critique of technology and innovation processes.

## *Ethics of care as a critique of innovation and technology*

While the (re)productivity perspective aims to critique the unsustainability of economic models and processes, a care perspective, as developed in feminist research, offers important insights to critically assess innovations at the intersection of society, nature, and technology: In ecofeminism and feminist sustainability research, care serves as an ethical principle for individual actions and as a transformative principle for a sustainable – in terms of just and precautionary – democracy (Plumwood 1991; Tronto 2013; Gottschlich et al. 2014). For our framework, we now particularly refer to STS scholars who have identified key features of a care perspective on technologies, especially assessing the risks and implications of biotechnology and GMOs (e.g., Groves 2015; Martin, Myers, and Viseu 2015; Preston and Wickson 2016; Puig de la Bellacasa 2011; Whittingham and Wynberg 2021). Our aim is to make this work fruitful for the analysis of other precision technologies in a next step.

### *Social and socio-ecological relations*

Care perspectives emphasize the importance of relationality. They direct attention to how innovations influence relationships among humans – such as farmer-farmer inter-reliance – and to society-nature interactions (Puig de la Bellacasa 2015). The example of GMOs is illustrative here, as the technology shows how property rights have created new and longstanding dependencies for producers and consumers of biomass and food, and thus how a technology can alter existing relationships and create new social and ecological relationships (Preston and Wickson 2016, 53). Traditionally, farmers maintained a close bond with seeds, saving and choosing them meticulously over generations. This connection allowed both crops and farming methods to evolve together. However, the introduction of commercial hybrid and genetically modified seeds disrupted this relationship, demanding annual purchases for consistent results; they are patented, necessitating yearly seed buying and contractual agreements that forbid replanting or further research. Moreover, patented GMOs can strain relationships among farmers, affecting collaborations, and can lead to conflicts between farmers and the farming community, for instance over the challenges of the coexistence of GMO and GMO-free production (Friedrich et al. 2019). This example illustrates the importance of paying attention to how the introduction of innovations can transform relations within society and socio-ecological systems.

### *Context and risk*

With care it is argued that many approaches to innovation policy remain within limited technology and risk-assessment frameworks, which do not adequately consider the existing particularities of specific contexts, including their complexities and scientific uncertainties across space and time. They are thus too narrow to account for unintended effects beyond a positivistic understanding of risks in (natural) science (Preston and Wickson 2016, 49). "Just as other technologies, GM [genetically modified] crops do not exist in a vacuum but operate as socio-technical and eco-social systems. They are shaped by the interests, values, goals and visions that arise from their contexts of development and deployment" (Preston and Wickson 2016, 50). This means, for example, that in addition to the potential

effects of GMOs on human health or the environment, a care approach as developed by Preston and Wickson demands that socio-economic or political factors be included in the assessment of the hazards and sustainability of innovations. This includes the influence of economic interests and the tightening of control of a few powerful actors over food production and the technologies that shape it. From this observation we identify the need to broaden understandings of context to include ecological but also social and economic risks in assessing the sustainability shortcomings of precision technologies in biomass production.

### *Dependence, power, and vulnerability*

A care approach focuses on uneven relationships and directs attention to the interconnected dependencies and power relations within economic or agricultural systems (Whittingham and Wynberg 2021, 5). It is important to note that dependence itself is not inherently problematic; it is an inherent aspect of relationality, life, and economic systems (Preston and Wickson 2016, 52). For our assessment of sustainability shortcomings, it is important to direct attention toward asymmetric and longstanding dependencies together with power asymmetries in agriculture and food production that benefit some actors more than others. From the past, we know how control over the development and use of technologies like GMOs by a few powerful actors – multinational corporations, for instance, which claim ownership of GM crops as patented property – might intensify vulnerabilities and dependencies for organic farming systems, as well as for both producers and consumers (Friedrich et al. 2019). In the context of agriculture, technologies like pesticides, fertilizers, and technical support systems are well-known examples of how innovations can increase the reliance of farmers and consumers on a small but powerful group of corporate actors (Shiva 1991; Clapp 2021). Herbicide-tolerant GMO crops designed by former chemical companies, to be used in conjunction with specific chemicals owned by these same firms, raise significant concerns about the sustainability of new innovations, the underlying motivations behind the fostering of such relationships, and whether the actors behind these innovations are "engaged in the relationship in a caring and nurturing manner or whether the relation is extractive, profit-driven, and destructive" (Preston and Wickson 2016, 52). A care approach urges us to consider structural dependencies, vulnerabilities, and concentrations of power and control that systemically privilege some while marginalizing others in the context of food and biomass production.

### *Affects and emotions*

A care perspective considers the affects and emotions associated with technology use, whether they are perceived as legitimate or not, in political processes and public debate. Feminist perspectives emphasize that individual and collective decision-making also has emotional elements, that societies are not governed by fully rational and autonomous individuals and decisions (Preston and Wickson 2016; Gottschlich and Katz 2020). Both rational and emotional logics are at play, which is why calling for the acknowledgement of affects does not mean excluding reason from decision-making, but rather including otherwise neglected aspects. The debate about GMOs shows how important these neglected aspects are, as "gut reactions or moral doubts are highly important and often 'act as a veto irrespective of people's views on use and risk'" (Preston and Wickson 2016, 54). A care approach does not argue for the perception of affective aspects and emotions as sacrosanct or that they should replace other forms of assessment. It rather calls for the inclusion of more diverse – and currently often excluded – forms of experience in the development and assessment of innovations. From this we derive that concerns raised by lay persons or the public are nottoo emotional" but are legitimate and could inform innovation agendas, and thus deserve attention and further investigation (Whittingham and Wynberg 2021, 6).

### *Narratives and knowledge*

A care perspective calls for listening to a diversity of narratives and "providing room for the voice of those who might ordinarily be excluded" from innovation development, use, and assessments (Preston and Wickson 2016, 54). A care approach thus aims for a more democratic and inclusive process in innovation politics that reflects the "multiplicity of scientific and academic voices but also the voices of the marginalized" (Whittingham and Wynberg 2021, 3). Feminist STS has pointed out that the claim of objectivity is problematic as every theory and innovation is based on assumptions, and knowledge production, including in the natural sciences, is always situated, embedded in society, and inevitably influenced by societal power dynamics (Haraway 1988). Assumptions must be made transparent, different standpoints need to be negotiated, and diverse actors should be included to avoid the exclusion of forms of knowledge and to achieve something approaching objectivity. A care perspective builds on this by highlighting the legitimacy of different knowledge forms and problematizes the existence of patriarchal, technocratic power

relations in knowledge production, as well as in innovation development and related policy decision-making. From this it follows to ask what kinds of narratives and knowledges are associated with innovations, and which are marginalized or excluded in innovation development, use, and assessment.

## A framework for a feminist analysis of sustainability shortcomings related to socio-technical innovations

While the (re)productivity perspective aims to critique the unsustainability of economic models and processes, a care perspective, as we have carved out from feminist STS, asks us, as Whittingham and Wynberg 2021, 1) write,

> [T]o broaden the framing of risk, to consider different knowledges, to re-imagine ourselves as social, rather than economic beings, to tap into the capacity of socio-ecological relations and to recognize and dismantle power structures…Such an approach broadens the scope of what constitutes risk and acknowledges the complexities present in our socio-ecological environment.

In synthesizing these two fields into our framework of analysis for assessing sustainability shortcomings related to socio-technical innovations in the bioeconomy, we discovered some important areas of overlap. We found that both approaches emphasize the mediation of socio-technical innovations with ecological processes ((re)productivity, renewability, and relations). While the STS care perspective places a focus on relations among actors and impacts on socio-ecological systems, the (re)productivity perspective highlights more the material implications of these relations and nature's renewability. We found that the care perspective describes aptly the importance of an awareness of context and risk, while the (re)productivity perspective provides guidance for dealing with them (e.g., precaution, cooperation, and sufficiency strategies). The insights provided by the STS care perspective regarding dependence, power, vulnerabilities, and affect and emotions are not as much mirrored in the (re)productivity approach. However, both approaches show some overlaps regarding the topics of knowledge production and narratives. Based on these commonalities, differences and overlaps, we synthetized some of the categories to build our framework dimensions and to derive key questions for analysis (presented in Table 1 and illustrated in the following section using the empirical example of PA).

## Framework application: socio-technical innovations in precision agriculture

We now illustrate our framework by looking into socio-technical innovations in the field of PA as a key sector of the bioeconomy. For each dimension, we will give examples of the development and use of innovations from PA literature and from our own research in the field including literature reviews, participant observation in workshops, farm visits, and interviews to demonstrate how they shed light on possible shortcomings in sustainability policies and discourse.

**Table 1.** Framework for analysis of the sustainability shortcomings of socio-technical innovations.

| Synthetized Dimension | Derived from (re)productivity concept and/or from care discourse | Questions to analyze the sustainability shortcomings of socio-technical innovations |
|---|---|---|
| (Re)Productivity and Renewability | (Re)Productivity | How do innovations make a transformation of the economy toward mediation, instead of separation, between productive and reproductive more or less likely?<br>How do innovations reproduce patterns that undermine or enhance nature's renewability? |
| Social and Socio-ecological Relations | Care | How do innovations transform and disrupt relations among humans within society and in socio-ecological systems? |
| Context, Precaution, and Cooperation | Care and (Re) Productivity | Do innovations account for the particularities of specific contexts, including their effects in distant spaces and times/the future?<br>Are innovations developed with consideration for precaution and their social, economic or political implications?<br>Are innovations developed and used based on, or to advance, cooperation and sufficiency, rather than only economic growth and profit? |
| Dependence, Power, and Vulnerability | Care | Do innovations emerge from, reproduce, or transform incumbent power relations and dependencies among stakeholders?<br>Do innovations reinforce the vulnerability and marginalization of some individuals, actors, or systems more than others? |
| Affect and Emotions | Care | What kind of affective reactions to innovations can be observed?<br>How are the reactions perceived and integrated into innovation policy agenda setting and public political debates? |
| Narratives and Knowledges | Care and (Re) Productivity | What kinds of knowledges are integrated into innovation development?<br>Are certain narratives marginalized or excluded in the process of innovation development, use, and assessment? |

### (Re)productivity and renewability

Most existing PA applications – such as geographical positioning system (GPS)-enabled smart land machines[2] or digital farm-management platforms – are tailored toward the needs of agro-industrial farming linked to a productivist paradigm (Miles 2019; Montenegro de Wit and Canfield 2023), a term that denotes "the process by which a logic of production overdetermines other activities of value" (Puig de la Bellacasa 2015, 699). This implies understanding agriculture primarily as a productive, efficiency-oriented business, with the maximization of biomass yields through technologies at the center, and thus neglecting the long-term reproductive requirements, such as healthy soils as a precondition for growing. Reproductive processes are thereby excluded from consideration, which does not help to mediate production and reproduction as (re)productive processes. Moreover, this model comes with negative impacts on ecological and social reproductive capacities, including biodiversity loss and high carbon-dioxide ($CO_2$) emissions (Sampson 2018). PA technologies such as data-based variable rate applications for chemical pesticides and synthetic fertilizers come with ambitious promissory claims. While they are marketed as potentially contributing to the reduction of farm inputs that are harmful for the environment, biodiversity, and the climate, empirical evidence about significant environmental gains is lacking. Current data about input reductions is rather scanty and points toward only small gains, rather than a fundamental reversal of currents trends of high petrochemical use (for the German example, see Kehl, Meyer, and Steiger 2021, 119; Kliem et al. 2022, 45). This suggests that under productivism, the problems of structural unsustainability in agriculture, such as biodiversity loss or overfertilization, cannot be solved through PA. Furthermore, due to current techno-economic path dependencies and lock-in effects, PA innovations actually reproduce an agro-industrial productivism that undermines nature's renewability and makes a structural agroecological transformation of agri-food systems less rather than more likely (Hackfort 2023).

### Social and socio-ecological relations

In the context of PA, asymmetric relations and existing inequalities between agri-business and farmers, as well as among farmers, are reproduced. This is particularly the case between large-scale and small-scale farmers, between those who follow a productivist model and those who do not. The more technologies diffuse into agriculture at large, the more small farmers are under pressure to adapt (Hackfort 2021). With digital innovations, social relationships are altered, making farmers even more dependent on corporate technology and service-provider companies such as John Deere. This is the case when farmers are not allowed (legally) or are not able to fix their "smart" machines but need to wait for the company's digital maintenance team. Other examples are farm-data platforms and artificial intelligence (AI)-generated seed recommendations, which replace the knowledge and experience of farmers. Even if such innovations do not impact relationships as much as other precision technologies such as GMOs, they create new and disrupt existing social relationships, such as when earlier ties between advisors and farmers are complemented by AI systems and information-technology specialists (Comi 2020).

### Context, precaution, and cooperation

PA innovations based on current patterns are developed toward and confined by the productivist agro-industrial paradigm. Expensive "smart" land machines or farm-management platforms are designed for large-scale agriculture by leading agri-business and agri-technology firms. Mostly used on farms following a rationality of increasing yields and economic growth, many innovations are not made for diverse farming contexts, including small-scale or sufficiency-oriented production. Designed primarily to serve capital-intensive industrial agriculture, such innovations help reproduce the future path dependencies of unsustainable and poorly precautionary production models (Hackfort 2023; Miles 2019). Moreover, many innovations are characterized by legal or technological lock-ins, often built into products by technology and service providers, that hinder farmers to freely choose other software or hardware equipment according to their needs. These lock-ins reinforce existing power relations and farmers' dependence on corporate technologies and services, and eventually on the agro-industrial farming model. Such proprietary systems offered by corporate technology firms to maintain their market position and profits stand in contrast to the principles of cooperation and sufficiency (Fraser 2021; Hackfort 2023).

### Dependence, power, and vulnerabilities

The PA sector is characterized by monopoly structures, market concentration, and corporate power, with big agri-business companies such as Syngenta and Bayer/Monsanto and agri-technology firms such John Deere as leading innovation developers. Corporate power determines control over the technology and the distribution of benefits and economic value created (e.g., from the collected data). Through

in-built sensors in their tractors that measure soil or crop conditions, and crop yields, or incentives for the direct upload of farm data to their cloud platforms, companies like John Deere collect and control large sets of big data, including the intellectual property rights via the license agreements. Companies benefit from the data that farmers provide, usually without being compensated, while the firms retain the profits generated from that data, for instance through using it for their product and service development. Based on that data, as with the sale of glyphosate and the corresponding GM-resistant seeds in a bundle, Bayer/Monsanto is now selling data-based recommendations (predictive seeding) together with its own company-owned seeds (Hackfort, Marquis, and Bronson 2024). Through such incentives farmers are likely to become path-dependent on the technological systems of the companies whose machinery and software they initially purchase. Agribusinesses have historically used a variety of mechanisms to corner the market on agricultural inputs and machinery, establish exclusive relationships with farmers, and create different kinds of lock-ins and forms of dependency from their economic–technical ecosystems. Such practices strengthen ties between farmers and specific companies, eventually working as lock-ins for farmers and perpetuate oligopoly within agriculture.

Reducing farmers' vulnerability and achieving sustainability transformation requires more than curbing corporate power. However, farms using PA based on these current patterns risk a reliance on innovations that only aim at incremental changes through seemingly efficient technologies, instead of fostering a necessary structural transformation toward food sovereignty and agroecology-oriented food and biomass production. Such alternative strategies, based on different understandings of sustainability and approaches that prioritize concepts like food sovereignty and agroecology, tend to be disregarded by policymakers and deprived of funding and investment (Clapp and Ruder 2020; Lajoie-O'Malley et al. 2020).

### *Affect and emotions*

In addition to scientific assessments based solely on reason and rationality, a care perspective also considers the diverse emotions associated with innovations as legitimate and important, rather than ignoring or disregarding them as "an obstacle to perceived objectivity" (Whittingham and Wynberg 2021, 5). This perspective contrasts with technological rationalism, which views emotions and affects influencing values and preferences as something to avoid. From a care perspective, any affective hesitance and resistance regarding the use of PA innovations can be understood as a legitimate form of what has been termed 'technological sovereignty' (Montenegro de Wit 2021). This includes farmer's decisions to opt against PA and prefer low-tech methods, for instance, when farmers may find drones "threatening" or have "no desire" to delegate tasks to machines, because they "enjoy touching the earth or observing why a particular plant is so prevalent this year" (unpublished interviews 2022; own translation).

### *Knowledge production and narratives*

Feminist research asks what forms of knowledge are associated with technologies, and whether certain narratives are marginalized or excluded by their development. It emphasizes the cultural and ecological relevance of the diversity of local, situated knowledges (Haraway 1988). These include agroecological practices which may not be included in the standardized data-knowledge bases of the algorithms underlying PA innovations (e.g., for pest control). In contrast to modern industrial agriculture that involves heavy use of synthetic inputs aimed at increasing soil productivity, permaculture and other forms of agroecological farming involve slow and labor-intensive practices that draw upon the "inferiorized" knowledges of farmers and farm workers (Puig de la Bellacasa 2017, 169–216). However, with PA, data-driven predictions, recommendations, and platforms appear to be more objective and reliable than human experiential knowledge and intuition (Bronson 2022). This is what Miles (2019, 5) calls "algorithmic epistemology," referring to the fetishization of data that affects notions of legitimate knowledge, such that traditional and local knowledge about plants and pests may be delegitimized. Farmers may no longer trust their own experience, but instead increasingly rely on algorithms and data-based predictions as expert knowledge, which obscures the fact that there are human decisions and prioritizations behind algorithms (Heimstädt 2023).

## Discussion

We have combined two strands of feminist research to offer a framework of analysis that can help to identify sustainability shortcomings in the high-tech bioeconomy which claims to lead to more sustainability. All of these steps have inherent challenges, which we reflect upon in this discussion.

First, the two strands come from different disciplinary backgrounds (feminist ecological economics and feminist STS) and thus focus on different fields of application (economy and sustainability critique, and innovation and technology development).

We have therefore had to interpret them in ways that make their common ground intelligible, even though they use different terminology. For example, feminist ecological economics focuses on the relation of productivity and reproductivity, exemplified in the term (re)productivity, which we interpret as being closely linked to the idea from feminist care ethics in STS that innovation is embedded in social and ecological relations. Furthermore, both approaches aim to bring awareness to relatedness (of society and nature) and embeddedness (of economies).

On one hand, each approach emphasizes specific aspects that the other does not (or not to the same extent). For instance, feminist STS draws explicit attention to power relations and the affective aspects regarding innovations, which is not foregrounded as much in the caring economy approach. This second approach, on the other hand, places emphasis on the materiality of nature, including the renewability of ecological resources that cannot be taken for granted. It also emphasizes the reproductive foundation of any economic process. These are two aspects that are not at the forefront of feminist STS considerations.

Using the case of PA, we have illustrated how our analytical framework can reveal manifold sustainability shortcomings linked to these innovations such as the reinforcement of productivism; the lack of precaution, sufficiency, and cooperation in technology development; the fetishization of data; and the delegitimization of local knowledge. While the application of the analytical framework was only exemplary, it shows how such an analysis allows for a fine-grained and multifaceted assessment of a specific field of innovations in the bioeconomy and how it can draw attention to structural and systemic sustainability shortcomings in reaching more sustainable outcomes which often get overlooked.

The sustainability shortcomings identified above are effects of what could be summarized under the term "precision productivism." This characterizes society-nature relations in the high-tech bioeconomy as denoting a specific articulation of ecological modernization, which has now taken a specific form in centering around precision technologies, such as those in PA studied here. Other technologies that belong to precision productivism include precision breeding (also known as genome editing) and precision fermentation, key innovations that are being promoted in the bioeconomy with the claim of making economic systems (e.g., energy, agriculture) more sustainable through an increase in productivity based on a higher degree of precision in production techniques. At the same time, the underlying mechanisms of separating production from reproduction, as well as dominant production and consumption patterns – which are actually the root causes of the problems that these technologies are aiming to solve – are left untouched. Precision productivism as a paradigm in the bioeconomy hence does not steer in the direction of fundamental sustainability transformations; it rather reveals that established relations of power and (corporate) control in innovation development and knowledge production in the bioeconomy are being reproduced.

A limitation of our study is that our illustration remains rather general in its focus on both technology development and the use of PA innovations. However, this was reasonable considering our more modest aim of illustrating the application possibilities of the analytical framework. As the bioeconomy spans from biotechnology and agriculture to forestry, the possible applications of this framework are manifold.[3] Future research using our framework might focus on one aspect of socio-technical innovations (e.g., design or implementation) to deepen analytical insights.

## Conclusion: toward a caring and (re) productive bioeconomy

Since the bioeconomy is a project that has been characterized as centering around techno-fixes and as another expression of ecological modernization, it warrants precise analysis to assess its sustainability. We have shown how feminist perspectives can help to assess the sustainability shortcomings of socio-technical innovations in the bioeconomy. We had two objectives: to derive an analytical framework from existing research and to illustrate it using empirical examples to show its usefulness. Through its application, we found that PA is embedded within solutions that are commonly focused on technological innovations. Power imbalances – for instance, regarding inclusive knowledge and participation in technology development or key challenges such as ensuring the renewability of biomass production – remain insufficiently considered, which provokes significant drawbacks on the path to sustainability. From this, we conclude that the transformation from a fossil-based to a bio-based economy by means of the high-tech bioeconomy might be a solution for substituting individual products or processes. However, the potential of the bioeconomy as a socio-ecological transformation project is low if it leaves untouched the technology- and growth-centered consumption and production patterns, with their negative effects on human and non-human nature and their reproductivity.

The feminist literature we have synthesized points to the necessities and possibilities of doing economy,

and especially of doing biomass production, differently. It emphasizes the importance of recognizing the relationality and interdependence of society and nature and the need for caring practices and principles as a counterproject to a precision productivism that lies at the heart of the current bioeconomy. Such caring practices and principles would counteract the externalization dynamics at play that threaten sustainability, especially in the long run. In fact, feminist perspectives on the bioeconomy point to an entirely different understanding of the economy and sustainability, bringing into view the entire social metabolism with nature, using new concepts such as (re)productivity.

These critical insights lead to the question of what a caring, reproductive bioeconomy could be. First, there is a need for different and expanded understandings, terminology, and practices of innovation and technology development. On one hand, this includes alternative, emancipatory (digital) technologies that are based, for example, on less proprietary and more commons-based and open-source principles. On the other hand, it requires political and economic policies that go beyond innovation politics, such as anti-trust laws to curb corporate power in the agri-food system and to create more diversity and space for alternative actors, movements, and (low) technologies. Policy makers and other stakeholders concerned with innovation policy and technological development must understand and advance agriculture as a reproductive system.

Second, a feminist perspective illuminates that in addition to better technical solutions (efficiency), strategies for reducing the use of resources (sufficiency) and the precautionary caring for natural resources and nature's productivity must be at the center of sustainability. In particular, the temporal aspect of maintaining the conditions of reproduction is often missing in the technology-centered debates on the bioeconomy and related innovations.

Finally, we conclude that any type of technological innovation, assessment, economic activity, and political governance in the bioeconomy that is not linked to the perspectives of care and (re)productivity – that is not designed to foster reproductive capacities and account for embeddedness – will ultimately prove unable to achieve sustainability. As long as bioeconomy projects, regardless of their technical manifestation, are unable to maintain the reproductive conditions of biomass production, even a bio-based economy cannot be sustainable. We find that a sustainable bioeconomy needs to be a (re)productive bioeconomy, with innovations that are guided by and oriented toward care and precaution.

## Notes

1. The German term *Vorsorge* translates to precaution and to caring for.
2. Tractors that contain built-in sensors that stream data, for example, about soil and crop conditions, to cloud-based data-collection infrastructures.
3. In the case of forestry, for example, the framework could be used to assess the sustainability shortcomings or potentials of digital applications such as LiDAR imaging for forest inventories or satellite-based data for planning forestry roads, which might have complex effects beyond the forestry firm.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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