An Adapted Indicator Framework for Evaluating the Potential Contribution of Bioeconomy Approaches to Agricultural Systems Resilience

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This study reviews a variety of "bioeconomy approaches" (BAs) to assess their potential contribution to resilience in agricultural systems, focusing on benefits that can improve multi-functionality regarding private and public goods. It is based on Meuwissen et al.'s framework to assess the resilience of farming systems. Drawing on literature and expert knowledge, this indicator framework is adapted to develop a new framework which is then applied to seven contrasting BAs (miscanthus, perennial flowering wild plant mixtures, permanent grassland, nutrient recycling, agrivoltaics, urban agriculture, and microalgae). The major outcomes are: 1) the extended indicator framework can help evaluate BAs for their potential to foster resilience in future agricultural systems, 2) all BAs are characterized by their ability to provide multiple private and public goods simultaneously, 3) the strongest contribution of BAs to public goods is their function in maintaining the good condition of natural resources and resource-use efficiency, 4) all BAs can enhance resilience in agricultural systems by contributing diversity, multifunctionality, environmental sustainability, and autonomy, 5) the mitigation of potential drawbacks of BAs implementation requires ex-ante assessment, favorable BAs combinations, and stakeholder involvement, 6) context-specific analysis of each BAs is required to assess their qualitative and quantitative contribution to resilience.

1. Introduction

Agricultural systems are dynamic socio-ecological production systems that both influence and are influenced by external factors. They are dedicated to the production of multiple functions including economic, environmental, and social outputs in the form of public and private goods integral to society.[1,2] Various factors shape agricultural systems, such as the production activity (crop, animal, or integrated crop/animal production), the organizational form, the climate, and other environmental conditions, as well as socio-economic factors[3] (**Figure 1**).

Agricultural systems are regularly exposed to unpredictable perturbances and changes in the bio-physical or socio-economic environment and face a wide variety of challenges (economic, environmental, social, and institutional) that can impede the ability of these systems to provide desired functions (e.g., food and materials supply, biodiversity protection, rural livelihoods).[4] In addition, agricultural systems presently face a so-called "land use trilemma", in which the goals of mitigating climate change, ensuring food security, and conserving biodiversity may be seen as competing purposes.[5,6] Perturbances affecting agricultural systems differ in magnitude, scale, and duration. These may come in the form of small-scale fluctuations, such as changes in seasonal weather or variations in commodity prices that can be controlled without extreme complexity, or in the form of shocks: largely unpredictable events such as natural disasters, conflict, or pandemics. Over a longer period, these perturbances may be visible as trends such as climate change[7] or as climatic cycles such as the El Niño southern oscillation.

Agricultural systems must be able to adapt and respond to these perturbances as the consequences of failing to do so can be severe, affecting both the ability of the agricultural system to function and the society the system is designed to supply. For instance, import stops or precautionary stockpiling of resources

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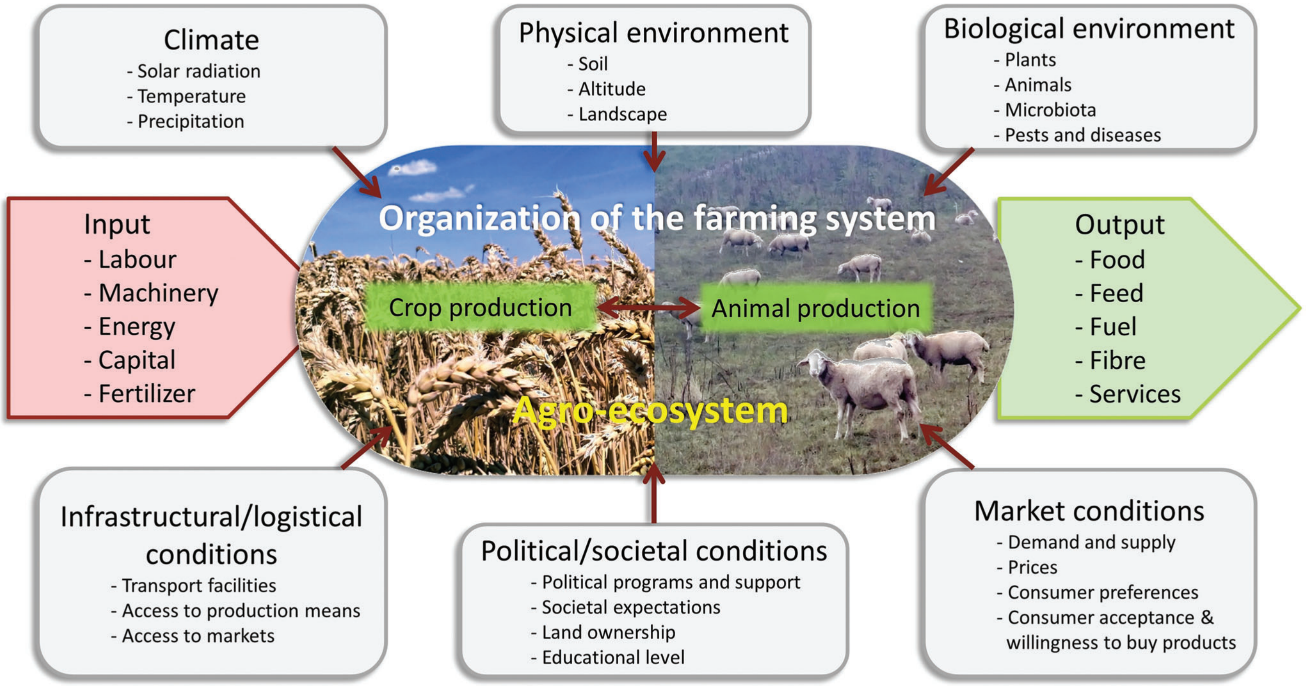

Figure 1. Overview of the multifaceted interrelationships of agricultural systems with society and the environment. Adapted with permission[3] (2018, Springer).

as a response to shocks in the agricultural system have the potential to cause food shortages.[8] Austerity and food scarcity as a result of decreased agricultural production have been noted as a factor in numerous conflicts and have been correlated with increased internal displacement within countries.[9,10]

Various studies have examined the sources of vulnerability in agricultural systems and their ability to maintain productivity.[4,11–13] Three intertwined factors can be distinguished as contributing to the increasing vulnerability of these systems to perturbances[11]: a lack of diversity within the food systems components, for example in agricultural systems, a high degree of interconnectedness within the system, and a lack of decision-making autonomy for individual farmers. Agricultural systems built solely on the principles of optimization, specialization, homogenization, command- and control-style approaches, and yield maximization lead to a decrease in their diversity.[13–15] This lack of diversity is manifested in the steady decline in the number of species cultivated. Low-diversity systems lack alternatives and result in low adaptability in the face of unexpected perturbances. This exacerbates problems such as biodiversity decline, loss of soil fertility, and loss of genetic diversity, thus increasing the vulnerability of these systems.[16] At the production process level, diversity reduces reliance on any one input or activity, allowing greater adaptability when perturbances arise.[11]

A high degree of interconnectedness leads, for example, to greater susceptibility to crop and animal diseases that are easily transmitted through highly connected systems creating a ripple effect (e.g., swine flu). In systems that are highly consolidated and connected, shocks can be rapidly transmitted throughout the whole system. This is especially the case in agricultural systems, where centralized processing can spread animal or plant viruses across wide distances. Modularity allows openness between system components, and for individual components to adapt to changes in conditions.[17] Due to specialization, the number of companies involved in and controlling production is decreasing, leading to high interdependency, weak points, and centralized structures. In this way, the specialization logic is perpetuated. Rotz and Fraser[11] suggest that producers are increasingly reliant on a small number of processing companies and manufacturers in order to access the market. They are thus unable to exercise autonomy as power is concentrated in the hands of manufactures and agribusiness corporations. A lack of autonomy for individual farmers under pressure to conform to industrial norms means more difficulty adjusting to ecologically friendly business models. Resilient systems tend to allow individual farmers and actors a larger amount of autonomy, allowing them to adapt to change, and adopt different behaviors over time.[11]

Society as a whole, and farmers in particular, are therefore faced with the challenge of finding active solutions to manage different perturbances and reduce the vulnerability of agricultural systems by increasing their resilience.[18]

Resilience of agricultural systems is defined here as the ability to preserve their intrinsic functions through flexibility[19,20] and plasticity to "*respond to changes,* (...) *reorganize their structure,* (...) *anticipate future changes,* (...) *take advantage of new opportunities*",[2,21] and "*ensure the provision of system functions in the face of increasingly complex and accumulating economic, social, environmental and institutional shocks and stresses, through capacities of robustness, adaptability and transformability*".[4] This means maintaining or recovering productivity and profitability, enhancing human well-being and farmers' livelihood options, and supporting ecosystem services and biodiversity conservation.[22]

Fostering resilience in agricultural systems is both a precondition and an objective of the biobased economy (referred to here as "the bioeconomy") as a pathway toward a sustainable society. This is a consequence of the nexus between ecosystems, agriculture, and an economy built upon biomass as an elemental and renewable resource. A sustainable bioeconomy strives for sufficiency, efficiency, and consistency as three key sustainability strategies by replacing non-renewable resources, changing consumption and production patterns, using locally available biomass, closing material and energy loops (i.e., circularity), and increasing biomass use (e.g., cascading and biorefineries).[23] It is based on the sustainable production and use of renewable biological resources (i.e., biomass) as well as the use of biological knowledge to deliver a variety of biobased products (e.g., food, feed, materials, and energy) and services (e.g., agritourism, biological air and water filtration, pollination, and many other ecosystem services) to fulfill human needs and maintain earth-supporting functions.[24]

The emergence of the inter- and transdisciplinary research field of "bioeconomy", and particularly the area that deals with its resource base (i.e., biomass), has led to the continuous and increasing development of a variety of what we refer to as "bioeconomy approaches" (BAs). These BAs have the potential to reduce the vulnerability and increase the resilience of agricultural systems. Bioeconomy approaches represent novel approaches that apply novel technologies or innovative practices that complement existing farming approaches in a manner that increases the overall robustness of a farming system. A particular feature of bioeconomy approaches is the integrality and multi-dimensionality of their design. This allows their focus to be extended beyond agriculture to consider biomass processing and products as well as the interplay between context factors and multi-level interactions that influence their performance. BAs strive for a different efficiency approach in which land use systems are designed for the simultaneous achievement of a range of societal demands and goals including, for example, productivity, ecosystem services, and resilience, in such a way that conflicting goals are minimized, and synergies are optimized. The greatest potential of BAs can be seen in their strong focus on providing ecosystem services on the same agricultural areas where known/established outputs are produced. This focus on ecosystem services is an integral part of the BAs.

We argue that the holistic and systems thinking rationale of the bioeconomy concept, i.e., from the agricultural production of biomass to the use and post-use phase, and its practical implementation through a variety of integrated BAs can contribute to the reduction of vulnerability of agricultural systems. It can also enhance the adaptive and transformative processes toward multifunctional and more resilient agricultural systems.

This paper presents a variety of "bioeconomy approaches" (BAs), which are assessed for their potential to contribute to the resilience of agricultural systems. Based on a framework adapted from Meuwissen et al.,[4] we focus in particular on potential benefits for improving the multifunctional capacity of agricultural systems in terms of private (e.g., biomass provision) and public (e.g., provision of ecosystem services) goods.[25] The evaluation of the BAs is done on the assumption that they are integrated into a system built on a sustainable and circular bioeconomy. However, the major intention of this study is not a conclusive evaluation of the selected BAs, but the design of a new indicator framework, based on that of Meuwissen et al.,[4] that enables an improved evaluation of BAs in the future.

2. Experimental Section

2.1. Choice and Assessment of Bioeconomy Approaches

In this study, the seven BAs shown in **Figure 2** were selected for assessment, because: 1) they are expected to have a large potential to contribute to the multifunctionality, diversity, and thus resilience of agricultural systems; 2) they cover a broad range of technological approaches including new crops and cropping systems, recycling of waste streams, integration of food and energy production systems, vertical farming, and algae production; and 3) they represent the core expertise of the authors, the interdisciplinary team of the department "Biobased Resources in the Bioeconomy" at the University of Hohenheim.

Based on literature reviews and expert knowledge, the indicators for the measurement of system functions were assessed qualitatively for the following BAs:

(a) Miscanthus as a novel, perennial biomass crop for bioenergy and biobased products,
(b) Wild plant mixtures (WPM) as a novel perennial mixed cropping system for bioenergy,
(c) Grassland management for various biomass uses,
(d) Nutrient recycling in agricultural systems,
(e) Agrivoltaics (APV) for the combined provision of electricity and agricultural products,
(f) Urban agriculture, comprising both high-tech indoor farming and urban community gardening,
(g) Microalgae for nutrient recycling, production of protein-rich food or feed, bio-stimulants, and bio-pesticides, and as feedstock for 3rd-generation bioenergy/biofuels and biogas.

2.2. Development of the Assessment Framework

A literature review of various frameworks suitable for the assessment of the resilience of agricultural systems was first conducted. From those reviewed (using Science direct; Google Scholar; Ebsco host; search algorithm: farming systems; farming systems research; integrated farming systems; farming systems analysis; resilience and farming systems; robustness and farming systems; risk and uncertainty and farming; vulnerability of farming systems; systems functions and farming systems; risk and adaptation of farming systems; farming systems approach; financial profitability of farming systems, resilience indicators and farming systems), we selected the framework of Meuwissen et al.[4] as a basis for our assessment which focuses on the provision of public and private goods as indicators for the resilience and sustainability of farming systems. We used the chosen framework as a platform into which we integrated additional indicators in order to address all three pillars of sustainability. In particular, we added indicators for the assessment of values that can be ascribed to the social pillar, and which are difficult to measure quantitatively.

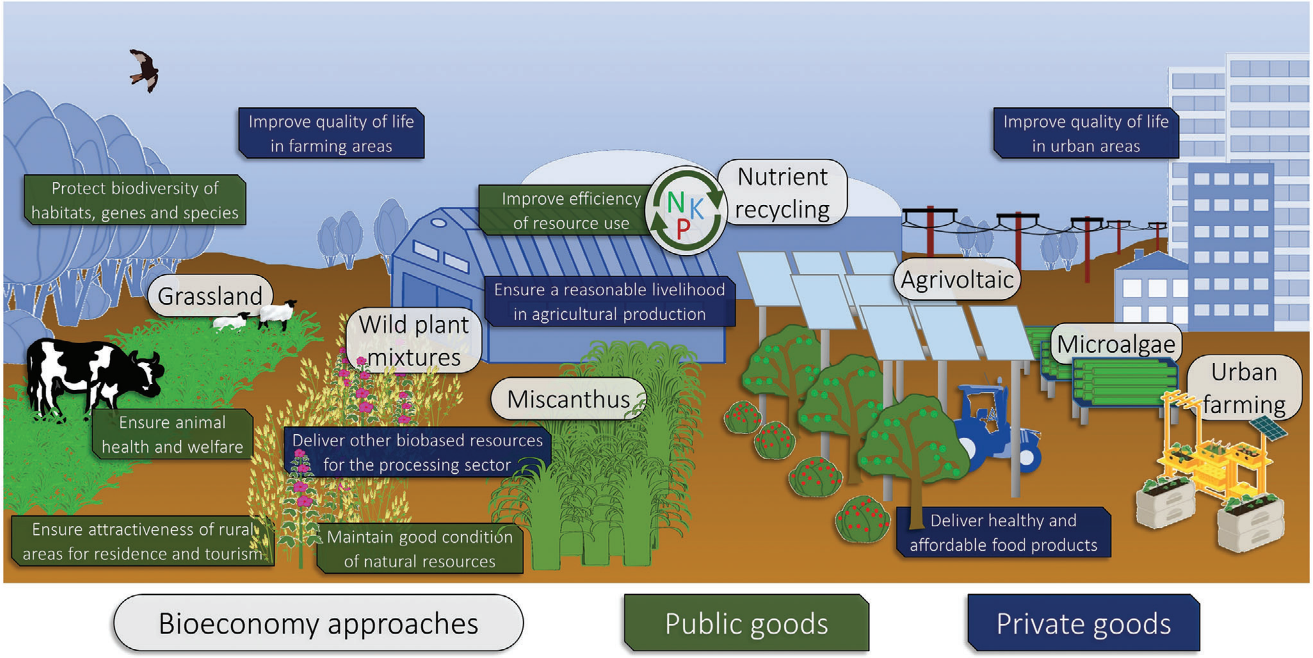

Figure 2. Locating the bioeconomy approaches analyzed in this study along the transect from natural to urban areas.

An iterative approach to the literature review approach was applied to ensure that all seven selected BAs could be assessed under one framework given their heterogeneity, their various technology readiness levels (TRLs), and their different perspectives of agricultural systems, including the field level through to the connecting of urban and rural agricultural systems.

Due to the relative novelty of the BAs, it is not yet entirely possible to determine "good agricultural practice" for each approach. For this reason, the review excluded, for example, frameworks that rely on: precise historical data for concrete policy recommendations,[26] benchmarks for measuring performance,[27] a single aspect of resilience such as climate resilience,[28] participatory approaches with stakeholders.[29] As there are currently only a small number of practical application cases of the BAs, and most of these are on only a small or laboratory scale, an evaluation of the seven BAs presented here needs to be based on a framework that allows the assessment of their system functions without requiring experiential knowledge. Such a framework must be able to assess the contribution of the BAs to the multifunctionality, diversity, and ultimately resilience of agricultural systems and must be feasible based on their scientific design and initial results from show cases and exemplary implementation cases.

Meuwissen et al.'s[4] definition of resilience of farming systems focuses on output (i.e., production functions, see ref. [30]) and considers a socially determined flexibility in this output, i.e., the set of desired functions. Meuwissen et al.'s[4] framework takes account of "*economic, environmental, social and institutional challenges that can impede the ability of a farming system to deliver the desired public and private goods*".[4] The farming system's functions are thus divided into the provision of private and public goods. The framework provides a set of indicators to assess these farming system functions.

The seven BAs are very diverse in their nature, yet they provide a modular approach for an alternative agricultural system. The decision to concentrate on conducting the assessment of the BAs at the level of private and public goods provision is justified by the results of various studies which assess the resilience of farming models in a number of possible future scenarios. All of these studies concluded that public goods in particular are one of the key functions to aim for when it comes to resilience of systems.[26,29] Thus, we considered the framework of Meuwissen et al.[4] to provide the best starting point for our comparative, ex-ante assessment of the seven BAs, given the large variations in both their stages of development and the availability of empirical data, with the intention of evaluating their potential future contribution to agricultural systems.

Meuwissen et al.[4] developed their framework for an arable farming system, one of the most common farming systems in the world. While performing the assessment of the BAs in our study, it became evident that the list of indicators for public and private goods provided by Meuwissen et al.[4] is too narrow for a complete assessment of the system functions delivered by BAs. In an agricultural context, the bioeconomy introduces new production activities or more efficient uses of side and waste streams.[31] BAs can provide additional functions to an agricultural system, intended to increase its resilience. Thus, indicators were added for these additional functions. The new indicators were chosen according to their capacity to depict resilience attributes, as described in the approach of Meuwissen et al.,[4] and to show the kind of desired functions (private and public goods) a future system should have.

2.3. Structure and Content of the Developed Indicator Framework

Based on the seven BAs (Figure 2), the functions related to private goods were complemented by aspects of improving the quality of life in urban areas. In addition, the improvement of resource-use efficiency was added to the list of indicators in the public goods section.

2.4. New Indicators for the Assessment of Bioeconomy Approaches

For the assessment of BAs, the indicators from the framework of Meuwissen et al.[4] to assess the resilience of arable farming systems were complemented at five levels:

2.4.1. Rewording

"Real costs" was replaced by "true costs" to make it clear that conceptual approaches to measure the indicators are being referred to. "True Cost Accounting" considers the complete societal costs of a product. In addition to direct production costs, ecological and social follow-up costs are also included as external costs in the product price and thus in the operating profit and loss account. As such, externalities are internalized.[32]

"Farming" was rephrased to "agricultural production" (not indicated in **Table 1**) to reflect the extended view of the assessment from the farming system only to agricultural production systems from field to regional level. It also allows urban agriculture to be accounted for as an integral part of the agricultural production system since the two systems are interconnected along the urban–rural gradient.[33]

2.4.2. Extension of the Target Function

For example, "crop diversity" was extended to "crop diversity, plant diversity" because, in terms of biodiversity protection, plants other than the targeted crops also contribute to this function. Another example is the indicator "total amount (t, l) of major non-food products". This was complemented by "and their properties (e.g., energy content, concentrations of valuable components)" because these properties are relevant for the use of biomass in biorefineries in terms of usability, resource-use efficiency, product quality and emissions occurring during the production process or use of biobased products.[34,35] The indication of these properties is critical for a sustainable life-cycle design process because this information can direct the biomass into the right value chain from the very beginning.

2.4.3. Introduction of New Indicators

Diversity is an important resilience attribute.[36] For this reason, new indicators were included that describe how BAs contribute to the diversification of agricultural systems. Examples are "on-farm processing (creation of additional income)" and "degree of income diversification".[37]

Strengthening the decision autonomy of individual farmers is considered one of the three important pillars for reducing the vulnerability of agricultural (food) systems.[11] To account for this, several new indicators were added, including "level of self-sufficiency for raw materials/energy", "inclusiveness of smallholder farmers (in terms of access to technology, markets, participation in value-adding activities)",[38] "non-regional market dependence for the supply of inputs", "keeping the added value of products on the farm".

BAs are often applied because they can deliver functions that go beyond the pure maintenance of the good state of natural resources by actually improving them. Indicators added to the framework in order to measure functions that contribute to a stronger resilience of agricultural systems in this respect include "contribution to landscape elements (landscape appearance, habitats, and corridors)", "water protection (e.g., avoidance of eutrophication)" and "aesthetic value (cultural ecosystem service)".

2.4.4. Addition of New Categories of Private and Public Goods

Two new categories were added: 1) "improve quality of life in urban areas" in private goods, and 2) "improve efficiency of resource use" in public goods.

As can be seen from the assessment summary in Table 1, a number of BAs (e.g., WPM, Grassland, Urban agriculture, and Microalgae) contribute to improved quality of life not only in rural but also in urban areas. The framework of Meuwissen et al.[4] was developed for rural areas only. However, improved quality of life in urban areas is also considered a relevant resilience attribute (see also ref. [39]) because it addresses consumer awareness and behavior, therefore affecting a large societal group. Happiness and well-being are important resilience attributes for producers and society as a whole.[40,41] BAs can integrate greening elements that benefit the urban climate and aesthetics, and urban areas are supplied with locally produced food and resources.

Resource-use efficiency is identified here as an important resilience attribute because it decreases the dependence of agricultural systems on the external supply of inputs and increases their capacity to provide outputs.[42] Indicators for resource-use efficiencies in agricultural systems include the productive utilization of previously un- or underutilized areas, the efficient use of the production resources land, water, and nutrients, the implementation of circularity, and the recycling rates applied in production systems. Nearly all the BAs assessed here contribute to the provision of functions in the category "resource-use efficiency" (Table 1).

2.4.5. Reorganization of the Indicators

The indicators were rearranged and grouped according to a what-how-why classification. This was done in order to make the large number of indicators more accessible and operational.

The "what" category refers to all indicators that are quantifiable. For example, "gross margin per hectare" (private goods) or "number of insects and other invertebrates such as spiders, earthworms, and centipedes" (public goods) are factors that can be measured. In an empirical context, the elicitation could

Table 1. Matrix and indicator framework developed and applied to the assessment of bioeconomy approaches (BAs)[a)] with respect to private goods; adapted from Meuwissen et al.[4] (in a darker color) and complemented (in a lighter color) by indicators specifically relevant to the description of the contribution of BAs. For each indicator, abbreviations are provided for the seven BAs used in this study for which that indicator may be relevant. All indicators are characterized according to the systematic of "what", "how", and "why".

Indicator categories for private goods									
Deliver healthy and affordable food products		Deliver other biobased resources for the processing sector		Ensure a reasonable livelihood for people involved in agricultural production		Improve quality of life in farming areas by providing employment and decent working conditions		Improve quality of life in urban areas	
What [b]									
Total amount (Mg, dm^3) of major food products	Ⓐ Ⓒ Ⓤ Ⓥ	Total amount (Mg, dm^{3}l) of major non-food products and their properties	Ⓐ Ⓒ Ⓜ Ⓤ Ⓦ	Gross margin per hectare (for arable farms), gross margin per livestock unit (for livestock farms)	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ Ⓦ	Number of workers employed on farms and related businesses including contract and part-time workers	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ Ⓦ	Integration of green elements	Ⓐ Ⓒ Ⓤ Ⓦ
Yield (Mg ha^{-1}, dm^3 livestock unit^{-1}) of major food products	Ⓐ Ⓒ Ⓝ Ⓤ Ⓥ	Yield (Mg ha^{-1}, dm^3 livestock unit^{-1}) of major non-food products	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ Ⓦ	Proportion of farm income coming from agricultural production (excluding subsidies and direct payments)	Ⓝ Ⓤ	Level of registered psychological disorders (e.g., suicides; doctor visits due to psychological issues)	n.a.		
Increased productivity of agricultural soils (for food production)	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ	Production of renewable resources / energy in the agricultural system	Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ Ⓦ	Degree of income diversification	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ Ⓦ	Number of farm associations and learning platforms	Ⓐ Ⓒ Ⓝ		
How [c]									
True costs of food products for consumers	Ⓐ Ⓒ Ⓝ Ⓤ Ⓥ	Synergies between existing agricultural activities and bioeconomy approach/ technology etc.	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ Ⓦ	On-farm processing (creation of additional income)	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ Ⓦ	Provision of decent conditions for farmers (in terms of respect of human rights)	n.a.	Contribution to self-sufficiency for raw materials or energy	Ⓐ Ⓝ Ⓤ
		Proportion of biomass usable/convertible through processing	Ⓐ Ⓒ Ⓜ Ⓤ Ⓦ	Inclusiveness towards smallholder farmers (in terms of access to technology, markets, participation in value-adding activities)	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ Ⓦ	Provision of additional income opportunities	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ Ⓦ	More sustainable consumer behavior	Ⓐ Ⓒ Ⓤ Ⓦ
		Potential end uses of biomass and its components	Ⓐ Ⓒ Ⓜ Ⓤ Ⓦ	Non-regional market dependence for sale of products	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ	Creation of "green" and sustainable job opportunities and business concepts	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ Ⓦ	Creation of communities for social inclusion	Ⓐ Ⓤ Ⓦ
		Shortening of supply chains	Ⓝ Ⓤ Ⓦ	Non-regional market dependence for supply of inputs	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ	Better work organization (e.g., reduction of workload, avoidance of peaks)	Ⓒ Ⓜ Ⓝ	Awareness of need for sustainable food production	Ⓐ Ⓒ Ⓤ Ⓦ

(Continued)

Table 1. (Continued)

Indicator categories for private goods									
Deliver healthy and affordable food products		Deliver other biobased resources for the processing sector		Ensure a reasonable livelihood for people involved in agricultural production		Improve quality of life in farming areas by providing employment and decent working conditions		Improve quality of life in urban areas	
		Supply of regional products	Ⓐ Ⓖ Ⓜ Ⓝ Ⓤ Ⓥ Ⓦ						
		Substitution of fossil-based resources/products	Ⓐ Ⓖ Ⓜ Ⓝ Ⓤ Ⓥ Ⓦ						
Why[d]									
Proportion of fruits and vegetables in total production	Ⓝ Ⓤ			Forced exit rates of farms for economic reasons	Ⓖ Ⓝ Ⓥ Ⓤ	Feeling proud to be a farmer in the region - cultural identity of rural inhabitants	Ⓝ	Increased happiness and well-being	Ⓖ Ⓝ Ⓤ Ⓦ
				Keeping the added value of products on the farm	Ⓖ Ⓝ Ⓥ Ⓜ	Increased happiness and well-being	Ⓖ Ⓝ Ⓥ Ⓜ		
				Level of self-sufficiency for raw materials / energy	Ⓐ Ⓝ Ⓤ Ⓥ	Safe health conditions for farmers (in terms of exposure to pesticides, dangerous chemicals, dust, noise, odors)	Ⓖ Ⓜ Ⓝ Ⓥ Ⓦ		

[a] Abbreviations for the bioeconomy approaches (BAs): agrivoltaics (Ⓥ), grassland (Ⓖ), microalgae (Ⓐ), miscanthus (Ⓜ), nutrient recycling (Ⓝ), urban agriculture (Ⓤ), wild plant mixtures (Ⓦ), not applicable (n.a.); [b] What – indicators that are measurable and can deliver quantitative information; [c] How – indicators that point the way toward the desired function; [d] Why – indicators that describe a desired state or why this state is desirable.

theoretically be done via a questionnaire, a technology that measures the volume, or even by accessing secondary data.

The "how" category refers to indicators that describe processes or actions such as "use locally available, native species" (public goods) or "on-farm processing (creation of additional income)" (private goods). These can be addressed, for example, through observations, discussions with stakeholders, or based on the scientific literature.

The "why" category refers to the most complex of the desired functions in a resilient system, which would probably require investigation in empirical studies using a number of methodological approaches to provide a good understanding of their meaning and interrelatedness. Functions such as "increased happiness and well-being" (private goods) or the cultural ecosystem service "aesthetic value" (public goods) were allocated to this category. The indicators in this category may require special experts from a certain discipline or complex modeling approaches to derive adequate data for policy recommendations, for example.

Although the approaches in the "why" category also refer to how resilient systems can be achieved, this category provides indicators that are often used to justify why we want to achieve sustainability and resilience from a holistic system perspective and also addresses many social aspects of sustainability.

3. Results of the Assessment of the Bioeconomy Approaches (BAs)

As can be seen from the summary in **Tables** 1 and 2, the seven selected BAs contribute to most of the functions for which indicators are listed in the framework. Several BAs contribute to food production, some directly and some indirectly through improved soil productivity, but overall, there is a stronger contribution to the delivery of biobased resources for the processing sector. There is also a strong contribution to ensuring a reasonable livelihood for people involved in agricultural production. All BAs provide additional income opportunities in agricultural production, a diversification of business activities, and a regional supply of healthy food and resources.

The strongest contribution of BAs to public goods is the provision of functions contributing to the maintenance of the good

Table 2. Matrix and indicator framework developed and applied to the assessment of bioeconomy approaches (BAs)[a)] with respect to public goods (in green); adapted from Meuwissen et al.[4] (in a darker color) and complemented (in a lighter color) by indicators specifically relevant to the description of the contribution of BAs. For each indicator, abbreviations are provided for the seven BAs used in this study for which that indicator may be relevant. All indicators are characterized according to the systematic of "what", "how", and "why".

Indicator categories for public goods									
Maintain good condition of natural resources		Protect biodiversity of habitats, genes and species		Ensure attractiveness of rural areas for residence and tourism with balanced social structure		Ensure animal health and welfare		Improve efficiency of resource use	
What [b]									
GHG emission intensity (per ha or per product)	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ Ⓦ	Proportion of ecological focus and protected areas, including forests, set-aside land etc.	Ⓒ Ⓜ Ⓤ Ⓦ	Net migration	Ⓤ Ⓥ	Use of antibiotics	Ⓒ	Recycling rates in the production system	Ⓝ Ⓤ
Water withdrawal by agriculture as % of total withdrawal	Ⓐ Ⓒ Ⓥ	Number of insects and other invertebrates such as spiders, earthworms and centipedes	Ⓒ Ⓜ Ⓤ Ⓥ Ⓦ	Number of tourists visiting the area per year (excluding big cities)	Ⓒ Ⓤ Ⓥ	Proportion of farms enrolled in certification schemes for animal welfare	n.a.	Improved land-use efficiency	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ
Use of agroecological practices (e.g., biological pest control, syntropic agriculture)	Ⓐ Ⓒ Ⓝ Ⓤ Ⓥ Ⓦ	Bird numbers and species	Ⓒ Ⓜ Ⓤ Ⓦ	Proportion of villages with a school and at least one supermarket	n.a.	Percentage of animals free from stress/discomfort	Ⓒ		
		Habitat quality based on common birds	Ⓒ Ⓜ Ⓤ Ⓦ	Rate of pluri-active farms	Ⓝ Ⓥ	Longevity of animals	Ⓒ		
		Crop diversity, plant diversity	Ⓒ Ⓜ Ⓤ Ⓦ	Percentage of women among farmers, contract workers and part-time workers	Ⓐ Ⓒ Ⓜ Ⓤ Ⓦ				
				Average age of farmers and part-time workers	Ⓐ Ⓒ Ⓜ Ⓤ Ⓦ				

(*Continued*)

Table 2. (Continued)

How [c]							
Capacity to avoid soil erosion	Ⓐ Ⓒ Ⓜ Ⓝ Ⓥ Ⓦ	Use of locally available, native species	Ⓒ Ⓤ Ⓥ Ⓦ	Extent of public access (e.g., footpaths and bridleways)	Ⓐ Ⓒ Ⓤ Ⓥ	Land/water/nutrient-use efficiency	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ
Frequency/number of social debates on water/air issues related to agriculture	Ⓒ Ⓝ					Circularity - inclusion of options to make material or energy streams circular	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ
Contribution to landscape elements (landscape appearance, habitats etc.)	Ⓐ Ⓒ Ⓤ Ⓥ Ⓦ					Productive utilization of un- or underutilized areas (urban, industrial, agricultural)	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ
Water protection (e.g., avoidance of eutrophication)	Ⓐ Ⓒ Ⓝ Ⓤ						
Why [d]							
Soil compaction	Ⓐ Ⓒ Ⓜ Ⓝ	Diversity of ecosystem service provision	Ⓐ Ⓜ Ⓤ Ⓥ Ⓦ	Broadband coverage	Ⓐ		
Nutrient surplus	Ⓐ Ⓒ Ⓜ Ⓝ Ⓤ	Pollination	Ⓜ Ⓤ Ⓦ	House prices relative to urban areas	n.a.		
Water retention	Ⓐ Ⓒ Ⓝ Ⓤ Ⓥ			Aesthetic value (cultural ecosystem service)	Ⓒ Ⓜ Ⓝ Ⓤ Ⓥ Ⓦ		
Land-use-change impacts (direct or indirect)	Ⓐ Ⓒ Ⓤ Ⓥ Ⓦ						

[a] Abbreviations for the bioeconomy approaches (BAs): agrivoltaics (Ⓥ), grassland (Ⓒ), microalgae (Ⓐ), miscanthus (Ⓜ), nutrient recycling (Ⓝ), urban agriculture (Ⓤ), wild plant mixtures (Ⓦ), not applicable (n.a.); [b] What – indicators that are measurable and can deliver quantitative information; [c] How – indicators that point the way toward the desired function; [d] Why – indicators that describe a desired state or why this state is desirable.

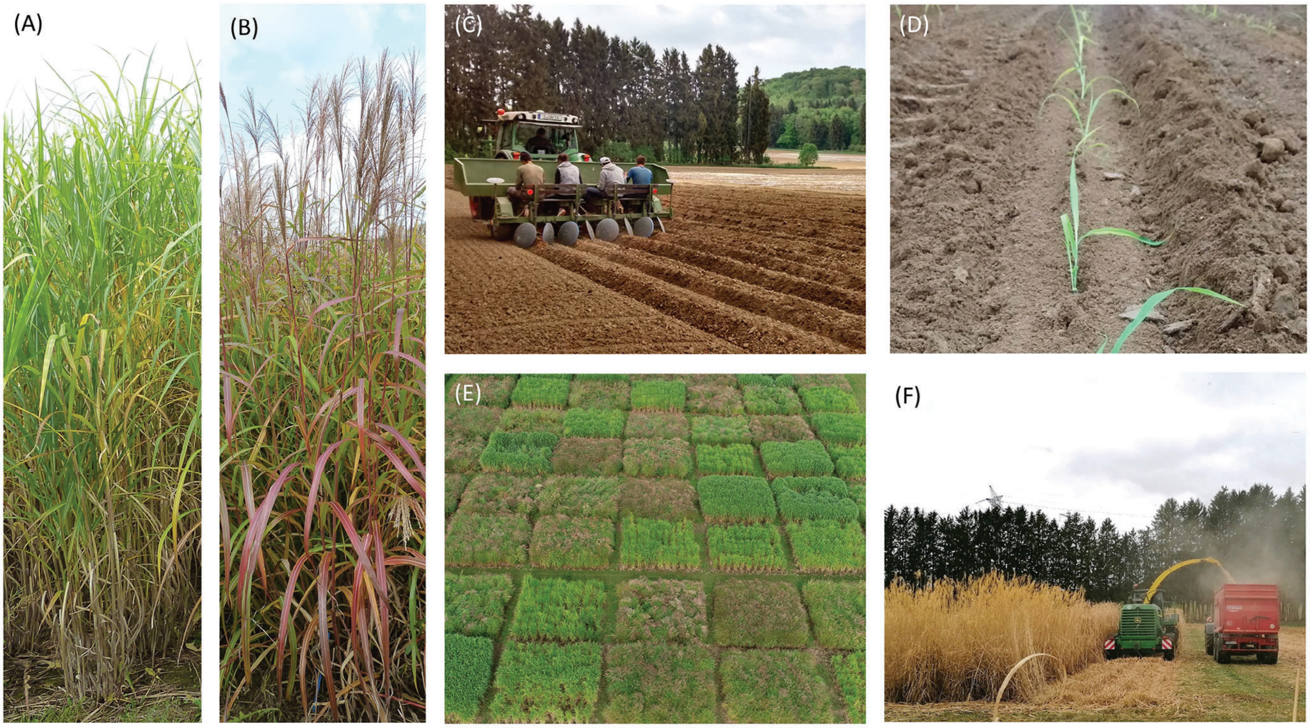

Figure 3. A,B) Novel seed-based hybrids, e.g., *Miscanthus sinensis* x *sinensis* (A), are compared with the rhizome-based standard hybrid *Miscanthus* x *giganteus* (B) in multilocation, plot-scale field trials on marginal land (E). C) Establishment of rhizome-based miscanthus hybrids using a commercial-scale planter. D) Seed-based miscanthus plantlets after planting. F) Direct harvest of standing, dry miscanthus crop after winter using conventional agricultural machinery (Source: Elena Magenau).

condition of natural resources and to resource-use efficiency. For this reason, a number of new indicators were added in this category. The cropping systems miscanthus, WPM, and grassland contribute to the protection of biodiversity and habitats through their perennial character, an important feature for the resilience of agricultural systems.[43] Urban agriculture introduces completely new and highly diverse production systems into areas so far un- or underutilized and thus contributes to the protection of biodiversity, genes, and species.[44–46]

The following sections describe the seven BAs assessed in this study, starting with a short description of the technology. Each description summarizes the functions related to private and public goods that the approaches can contribute to agricultural systems. A detailed assessment of all indicators applied to measure the system functions is presented in **Tables A1–A14**.

3.1. Miscanthus

Miscanthus is a genus of several C_4 perennial rhizomatous grass species which are very common in East Asia. The natural, triploid hybrid *Miscanthus x giganteus* was first cultivated in Europe in the 1930s and is still the most important commercial hybrid in Europe. Breeding and selection are making progress in the development of novel inter- and intraspecific hybrids from *Miscanthus sinensis* and *sacchariflorus*.[47] The crop miscanthus delivers non-edible, lignocellulosic feedstock for both bioenergy and material uses and is characterized by a high input:output ratio, with significant progress being made in the development of cultivation technology[48] (**Figure 3**).

Miscanthus represents a bioeconomy approach that aims to combine the provision of feedstock for the bioeconomy produced in an environmentally friendly way and the provision of additional environmental services by the agricultural sector (Tables A1 and A2). This approach is based on the cultivation of miscanthus as a low-input, perennial biomass crop and the development of novel business models for farmers to valorize the biomass as feedstock for the bioeconomy.

3.1.1. Private Goods of Miscanthus

Of all functions delivered by miscanthus, the provision of biomass as a biobased resource for the bioeconomy has the highest value.[49] Biomass yields vary strongly with site conditions, climate, and harvest date[50,51] with, for example, 12–15 Mg ha^{-1} yr^{-1} harvestable yield being achieved on marginal land in Germany.[52]

Currently, miscanthus biomass is mainly used for combustion, animal bedding, and as mulch material in gardening.[53] However, higher-value applications are being intensively researched and developed, allowing increased on-farm valorization, the development of new business models for farm enterprises, and new business opportunities in rural areas. Novel applications include fractionation of miscanthus biomass for a range of material applications, e.g., lightweight concrete (www.grace-bbi.eu), insulation materials, acoustic panels (https://mogu.bio/), and composite materials,[54] and also on-farm pre-processing for chemical applications, e.g., 5-HMF as a platform chemical.[55,56] The use of miscanthus as feedstock in these applications often generates lower greenhouse gas emissions and provides additional environmental benefits compared to fossil reference products.[57,58]

Miscanthus cultivation systems can indirectly support food production by stabilizing and/or increasing the productivity of agricultural soils through the functions of increased soil carbon content, reduced soil erosion, enhanced soil biodiversity, and remediation of heavy metals.[59,60]

3.1.2. Public Goods of Miscanthus

The cultivation of one hectare of miscanthus can provide society with environmental services to the value of 1008–2888 € annually.[49] This environmental benefit is achievable as commercial cultivation requires minimal inputs (e.g., fertilizer and plant protection) due to the crop's perennial nature, high nitrogen-use efficiency, efficient nutrient recycling, and high competitiveness against weeds after successful establishment.[60,61] Through the avoidance of soil tillage for a period of over 20 years, the formation of a mulch layer by leaves and harvest residues, and the crop's deep rooting system, miscanthus cultivation effectively helps prevent soil erosion and nitrate leaching and increase water infiltration capacity during heavy rain events.[62,63] Additionally, cultivation on former arable land increases soil organic carbon content by 0.7–2.2 Mg C ha^{-1} yr^{-1} and is a good measure for promoting soil health and soil arthropod biodiversity.[59,60,64] The low intensity of cultivation operations and the late harvest in early spring enable miscanthus to provide suitable habitat conditions and winter shelter for a range of belowground and aboveground species.[65]

Its high water-use efficiency and stress tolerance render miscanthus a suitable candidate crop for marginal or abandoned land, thus helping to make effective use of such often underutilized lands and minimize land-use conflicts. Furthermore, miscanthus can be cultivated on heavy metal-contaminated soils where food production is not possible or accompanied by health risks (introduction of contaminants into the food chain). Phytostabilization of contaminants minimizes the risk of further distribution of heavy metals by wind.[66,67]

3.2. Wild Plant Mixtures (WPM)

The term "wild plant mixtures" (WPM) refers here to a perennial intercropping concept developed within a German national project in (2008–2011) to provide biomass for biogas production as well as to enhance the faunistic biodiversity of agricultural systems[68] (Tables A3 and A4). The WPM are composed of over 20 annual, biennial, and perennial flowering wild plant species (WPS) that provide high biomass yield and both good ensilage quality (for storage) and anaerobic digestibility (for biogas production).[68–70] Most of these WPS are non-bred genotypes[71,72] such as common tansy (*Tanacetum vulgare* L.) (**Figure 4**). Consequently, WPS do not require plant protection measures except for mechanical weed control in the year of establishment, if necessary.[73]

The combination of biomass provision and high plant diversity, which varies dynamically over time and space, renders WPM a very promising innovative bioeconomy approach for "land sharing" (aiming to unify biomass use and nature conservation on the same area).[74,75] It helps to provide renewable energy, sequester carbon in the soil, and at the same time promote biodiversity in agricultural systems and positively contribute to landscape esthetics.[68] A major contribution of WPM to the diversification of agricultural systems is the partial replacement of maize or other crops grown in monoculture as a biogas substrate.[76–78]

3.2.1. Private Goods of WPM

After successful establishment, the WPM can yield average annual harvests of ≈12 Mg dry matter ha^{-1}.[76–79] The species spectrum in the plant stands changes over the years according to the WPM life cycles mentioned above.[72] Since self-seeding of individual WPS cannot be ruled out, annual and biennial WPS may still occur in the plant stand from the third year onward, further increasing the probability of achieving high spatial heterogeneity of WPM composition.[78] Long-term studies are not yet available on the potential total cropping duration of WPM, but there are WPM cultivations in southern Germany that are already older than ten years and still provide acceptable biomass yields (data not yet published).

WPM deliver lignocellulosic biomass, mainly used for biogas production,[78] but initial studies have also reported feasibility for combustion.[80] A later harvest in winter (instead of summer) with pellet combustion rather than anaerobic digestion of the biomass could deliver more than twice the energy yields from biogas use.[80,81]

The potential of WPM to replace other energy crops, however, is limited because WPM are more tenuous in energy yield and thus land-use efficiency than, for example, miscanthus or maize (*Zea mays* L.).[82,83] These tradeoffs in terms of biomass provision and feasibility also stem from the fact that WPM cultivation is a relatively new cropping system.[76,78,79,84] Future WPM research therefore will focus, among other things, on the option of combining WPM in strip cropping with miscanthus and other higher-yielding perennial biomass crops.[85]

The diverse and long-lasting flowering of WPM improves the recreational value of an area by enhancing its landscape beauty. Depending on the season, flowers can also be picked, replacing cut flowers grown outside the region. WPM cultivation can thus improve the reputation of agriculture and enable a better quality of life in the region.[78]

3.2.2. Public Goods of WPM

WPM make a significant contribution to the protection of habitat, gene, and species biodiversity.[68] They provide a diverse spectrum of ecosystem services (e.g., habitat provision) through a wide range of (endemic) food sources (nectar, pollen, leaves, stems, roots) and nesting material, recreational value, provision of genetic resources through a wide range of sown and sponta-

Figure 4. Inflorescences of common tansy (*Tanacetum vulgare* L.) with beneficial honey bee (*Apis* L., 1758) (A, Source: Moritz von Cossel) and small copper butterfly (*Lycaena phlaeas* L., 1761) (B, Source: Moritz von Cossel) in mid-September 2023. Field trials with common tansy ongoing since 2011 (C, Source: Moritz von Cossel), with stands still providing acceptable biomass yields 12 years after sowing. Late summer harvesting of tansy for biogas use is practically feasible using standard silage maize chopper technology (D, Source: Michael Bischoff). Initial studies are underway on root morphology and adaptability to marginal soil conditions (E, Source: Moritz von Cossel).

neous wild plants at higher levels than annual crops or perennial monocultures such as miscanthus and cup plants.[68,72,86]

WPM provide various types of nectar and pollen.[68,77] These are available over a very long period of time[87] and give pollinators (e.g., wild bees) the opportunity not only to survive but also to optimally provide for their offspring during flowerless periods of arable crops.[77] The latter constitute a major problem in modern agriculture, which is why this ecosystem function of WPM is particularly relevant for the resilience of agricultural.[86,88,89]

WPM cultivation can also provide high-quality habitats for many bird species because numerous endangered bird species can thrive in WPM cultivation areas or on their borders (depending on the season and growth height of the WPM).[77]

3.3. Grassland

Grassland refers to an agricultural area with grass-dominated vegetation. It occurs where conditions are favorable for the growth of this vegetation, but not for the growth of trees and shrubs. Succession to woody vegetation is prevented by regular cutting or grazing (**Figure 5**), but also by unfavorable conditions such as limited water supply or short growing seasons (e.g., steppe and savanna).

Permanent grassland is one of the most widespread vegetation types and serves as the primary feed base for ruminant livestock. As a bioeconomy approach, it demonstrates multifunctionality, has great potential for biodiversity conservation, stores large amounts of carbon in the soil,[90,91] and delivers biomass for feed, as well as for material and energetic uses, and for biorefineries[92–94] (Tables A5 and A6).

3.3.1. Private Goods of Grassland

Grassland biomass production is highly variable in quantity and quality depending on management, site conditions, and botanical composition.[95]

The main function of grassland is to support animal production of milk and/or meat. It provides forage for regional use and forms the basis of sustainable dairy farming.[96] In the coming decades, it is expected that a decline in dairy farming will lead to more grassland biomass becoming available for material and energetic utilization. Depending on the intended use, the content of valuable biomass components (e.g., fiber and protein) can be adjusted by appropriate grassland management.[97] Thus, an increased use of grassland biomass in biorefineries can be expected in the future.

3.3.2. Public Goods of Grassland

Grassland biomass is mainly produced on marginal sites unsuitable for crop production and thus there is little competition with

Figure 5. Grasslands encompass a wide range of diverse agricultural land and biomass use systems from intensive, mowed grasslands (A) to various pasture systems (B); examples shown here are from the Swabian Alb in southwest Germany. Extensive grassland management can increase the supply of flowering forbs such as oxeye daisy (*Leucanthemum vulgare* Lam.) (C). D) This can be of great benefit to a range of pollinators, such as wild bees and the common blue butterfly (*Polyommatus icarus*, R. 1775) (D), and help create habitat networks, especially in regions of more intensive land use. However, more biodiversity-friendly grassland management often results in lower biomass yields and forage qualities than more intensive systems (Source: Moritz von Cossel).

food production. With the decline in dairy farming, it offers the opportunity to exploit a sustainable biomass source previously used for animal feed.

Grassland also has a significant impact on landscape aesthetics and plays an important role in recreational areas. Grassland regions are usually attractive to tourists,[98] with grazing in particular being perceived positively as a manifestation of animal welfare.[99] Grazing can indeed promote animal welfare and the use of grassland biomass as fodder can benefit the health of dairy cows, if best management practices are followed.[100]

Biomass production from grassland is always associated with fundamental ecosystem services (e.g., water quality, landscape, and soil protection) and therefore an important part of a multifunctional land-use system.[91] In Germany, 15% of grassland areas are designated as high-nature-value grassland,[101] where, depending on location and management, up to ≈90 plant species can be found. Grasslands also host a species-rich animal community, both below and above ground.[102] Flowering grassland plants in particular are of great importance as insect habitats.[103,104]

Grassland has a higher potential for water protection than cropland. Due to the lack of tillage and high soil nutrient storage potential, the transfer of nitrates to groundwater is much lower than in arable land, even where N fertilization is high. In this respect, pastures are less favorable than meadows due to the uneven nutrient distribution.[105] As a permanent cropping system, grassland increases soil fertility, prevents erosion, and accumulates soil carbon. Its carbon sequestration potential is mainly affected by management and site conditions.[106,107]

Plant diversity can mitigate the yield risks associated with extreme weather events. Grassland is thus a resilient land-use system adaptable to climate change. This is evidenced by the wide environmental range of global grassland distribution.[33] Positive interactions among species increase the ecosystem functioning of diverse plant communities.[108,109]

3.4. Nutrient Recycling

Nutrient recycling in an agricultural context is the use of nutrient-rich side streams and organic residues from agricultural production, in particular animal husbandry, or bioenergy production to complement or substitute mined or synthesized fertilizers (Tables A7 and A8). Such materials include manure, digestates, biomass ash, and postharvest residues (**Figure 6**).

They can be applied to the field either directly or following treatment, which can range from simple to advanced

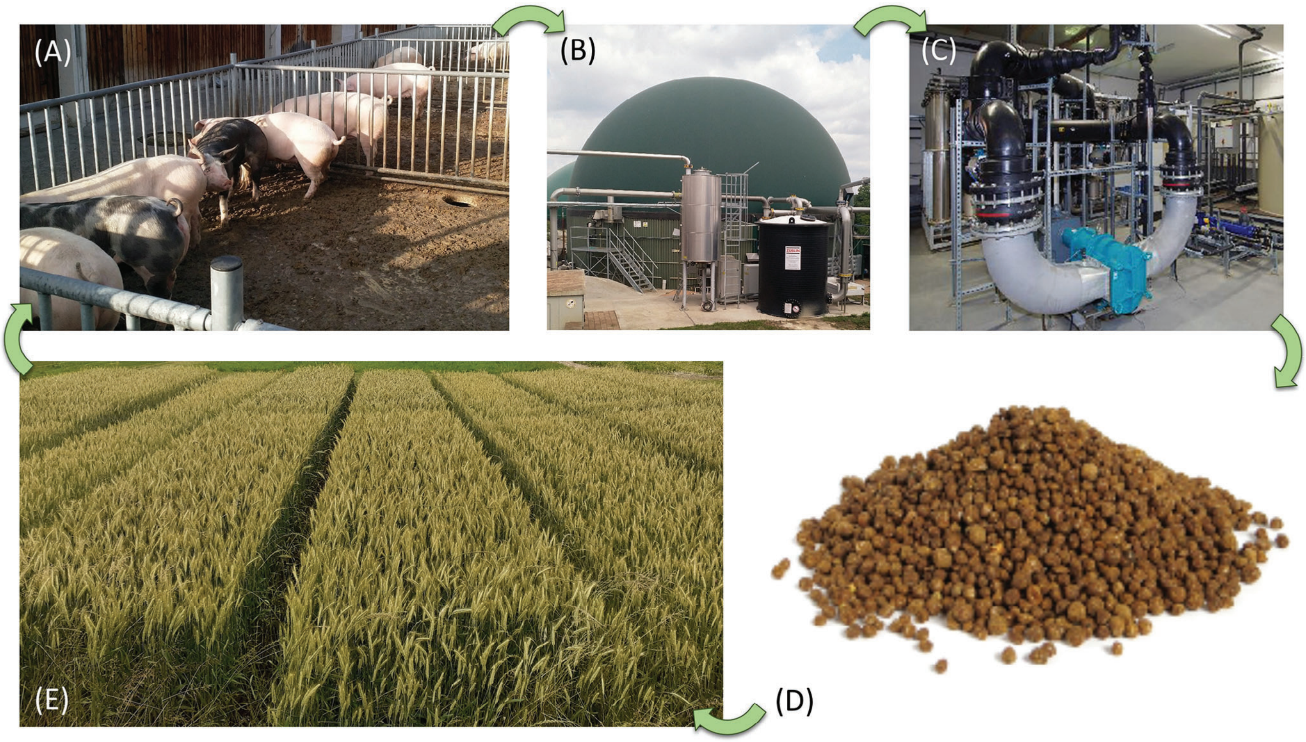

Figure 6. A–D) An example of circular nutrient recycling is where a nutrient-rich side stream or organic residue from agricultural production, e.g., from pig fattening (A), is used for energy generation via anaerobic digestion (B), and then treated in a nutrient recycling plant (C, entirely or partially powered by the energy from anaerobic digestion), where nutrients and organic solids are recovered and further processed into biobased fertilizers (D). E) These biobased fertilizers are intended for targeted application to cereal crops such as winter triticale, which are then harvested, stored, and fed to finishing pigs (A) (Source: A,B: Moritz von Cossel; E: Andrea Bauerle; C: Thomas Karle; D: Biofa GmbH).

approaches.[110,111] Advanced treatment approaches allow the complete utilization of a residue with separate recovery of macronutrients, organic solids, and water (e.g., NutriSep).[112] The recovered nutrients can then be processed into recycled or biobased fertilizers (BBFs). Nutrient recycling constitutes a bioeconomy approach because the use of fertilizers produced regionally from available residues can close nutrient cycles and increase the resilience of farms.

3.4.1. Private Goods of Nutrient Recycling

BBFs and organic residues improve humus content and both water and nutrient retention capacity of soils.[113–115] Fertilization with BBFs can result in crop yields comparable to those treated with mineral fertilizers.[116] Due to the wide range of BBFs (organic, organo-mineral, mineral; degree of processing; source material) and the significant influence of climate and site conditions, it is difficult to make a general statement about the fertilizing effect of all BBFs. Anaerobic digestion of suitable organic residues with subsequent nutrient recovery and BBF production can increase local renewable energy production.[117,118] BBFs can deepen existing synergies between agricultural activities and the bioeconomy as they represent potential substitutes for synthetic fertilizers that require large amounts of energy to be manufactured and mined fertilizers that are mostly imported.[117–120] Regionally produced BBFs can increase the resilience of farms by decreasing dependence on non-regional markets for inputs, while additionally opening up opportunities to export/sell BBFs.[121,122]

3.4.2. Public Goods of Nutrient Recycling

The production and utilization of BBFs can help maintain the condition of natural resources through the reduction of emissions[121,123–126] and the climate impact of conventional fertilizers.[127] We assume that BBFs emit less odor than, for example, unprocessed manure, thus increasing their acceptance by society and improving the attractiveness of rural areas. Where the temporal release of nutrients can be adapted to coincide with the crops' needs, BBFs can enhance nutrient-use efficiency[128,129] and improve the circularity of nutrients[120] in agriculture.

3.5. Agrivoltaics (APV)

Agrivoltaic (APV) systems are photovoltaic systems specifically adapted for their application in combination with agricultural production (Tables A9 and A10). They are installed on or above agricultural fields with certain technical adaptions that enable the integrated generation of renewable electric power and cultivation of agricultural produce on the same area (**Figure 7**). Various APV systems are now available. These include: 1) open systems

Figure 7. Agrivoltaics as an example of a multifunctional land-use approach combining agriculture and power generation in an elevated (A, C) and a vertical, close-to-surface system (B, D). Uncultivated areas directly beneath the modules/around the supporting structure can help promote biodiversity (B) (Source: A,C: Andrea Bauerle; B,D: Elena Magenau).

installed on arable fields or grassland; 2) semi-closed systems, often installed for specific crops, e.g., fruits, that fulfill additional functions such as shading and protection from rain and hail; and 3) closed systems which are integrated into greenhouse systems. Open APV systems can either be installed high above the ground (>2.1 m height) or mounted close to the ground (<2.1 m height).[130] Elevated systems allow crop production to take place on arable land underneath the APV installation. The modules need to be installed at least 4 m above the soil surface to enable the operation of agricultural machinery, involving higher installation efforts than for systems mounted close to the ground. Here, crop production or animal grazing takes place between the modules, which are often bifacial and mounted vertically to minimize shading.[131]

APV is considered a bioeconomy approach because it is an innovation that can improve land-use efficiency. Through the integration of renewable energy generation and agricultural production, it contributes to the reduction of GHG emissions compared to conventional energy production. Elevated APV systems have higher installation costs than close-to-surface systems. On the other hand, they provide a higher land equivalent ratio (LER) of 1.4–1.8, compared to 1.2–1.4 for close-to-surface systems.[130,132]

3.5.1. Private Goods of APV

The combination of electric power generation and agricultural production on the same area provides the opportunity to increase land-use efficiency and support farmers in developing new business models, including income diversification and reduction of farm operation costs by consumption of electricity generated on their own farm. However, the installation of APV systems on agricultural land can lead to a trade-off between the expansion of renewable energy production on the one hand and both agricultural productivity and the preservation of agricultural production resources on the other. As 8.3% of the arable area is taken up by the APV installations,[133] the total amount of food produced will be reduced by the same amount. In temperate regions, 10–30% lower yields have been observed in APV systems.[134,135] By contrast, potential yield stabilization in drought years has also been observed, and for crops that benefit from partial shading (e.g., berries) or protection (e.g., apple: hail protection), higher yields are to be expected.[133]

Crop production costs are higher under APV due to higher time demands (slower working speeds and inefficiencies). However, gross margin per hectare can be increased compared to crop production alone, as electricity generation accounts for the largest proportion of gross margin per hectare.[136]

Whether and to what extent farmers benefit from APV depends on the participation model. If the farmer is (at least partially) the owner of the APV system, it will provide the farm with secondary income. If they lease their land, farmers are likely to benefit less from APV, since they have to cope with the loss of agricultural land and obstacles in farming operations caused by the installations without profiting from the electricity generation.

3.5.2. Public Goods of APV

The GWP of APV is considerably lower than that of the separate production of crops and electricity.[137] It has been found that, in

Figure 8. The bioeconomy approach 'Urban Agriculture' comprises private and community gardening activities (A + D) as well as vertical indoor cultivation and professional (roof-top) greenhouses (B + C) (Source: Bastian Winkler).

Germany, a change from an agriculture-only to a dual-use APV system leads to overall significant environmental benefits, especially in the categories of climate change (40%), freshwater eutrophication (24%), and fossil resource use (23%).[137] Synergies have also been reported for animal production. Compared to conventional meat (rabbit) and electricity production, the agrivoltaic system produces 98.5% less emissions and requires 98.7% less fossil energy.[138]

The partial shading provided by APV systems reduces water withdrawal (14–29%) through reduced evaporation. The effect on biodiversity is however not yet clear. The uncultivated land under modules/around pillars can potentially increase habitat spaces for native species.

On the downside, 10–15% of arable land is directly affected by conversion into APV systems because it is required for the installations and cannot be used for agricultural production. Additionally, the surrounding area may be affected by lower yields due to shading, resulting in lower area yields and potentially contributing to indirect land-use change (iLUC). The aesthetic value of landscapes may decrease if APV systems are installed in exposed areas or at high regional densities. A loss of attractiveness of the region may result, with knock-on effects for tourism.

3.6. Urban Agriculture

Urban agriculture has evolved from a trend into a global key concept of urban lifestyle and sustainable urban development.[45,139,140] Urban agriculture comprises both urban farming and urban gardening (**Figure 8**). Urban farming is the production of food and biomass in commercial high-tech, vertical indoor cultivation systems. Urban gardening by contrast refers to production in community gardens in public and private areas. Urban gardening is usually soil-based, utilizing garden plots, raised beds, mount cultures, pots, and containers,[46,140] whereas urban farms often apply re-circulating, soilless hydroponic, aeroponic, or aquaponic cultivation in vertically stacked systems under controlled environments in large buildings dedicated to crop cultivation.[139,141]

Urban farming can provide substantial amounts of food and biomass with high resource-use efficiency independent of climatic conditions.[139,141] Urban gardening by contrast is a socializing activity performed by urban inhabitants in diverse community gardens, that foster social engagement and participation in urban development.[46,140,142]

Urban agriculture is therefore considered a key driver in the bioeconomy by (i) providing additional food and biomass production on new areas, (ii) creating multiple ecosystem services through the implementation of nature-based solutions in urban areas, and (iii) actively engaging consumers in agricultural activities and biobased value nets, thus contributing to the transition of cities into circular bioeconomy hubs (Tables A11 and A12).

3.6.1. Private Goods of Urban Agriculture

According to the Worldwatch Institute, 15–20% of global food production takes place in urban and peri-urban areas.[44] Another study estimates that urban production alone accounts for

1–5%.[143] Urban food production can provide locally produced food with short supply chains.

Urban agriculture yields are often expressed in terms of productivity compared to conventional agriculture. For example, Aerofarms[144] produces nearly 1 Gg of greens annually and claims to have 390 times higher productivity than conventional open-field agriculture, requiring 95% less water and omitting pesticides. Skygreens[145] declares that they produce 10% of Singapore's vegetables using a system that is 10 times more productive compared to open-field agriculture.[146] Despommier[147] estimates that a vertical farm with 30 floors covering a 2 ha ground area can produce food for ≈10 000 people. Similarly, the German Aerospace Centre projected that a vertical farm with a ground area of 44 m × 44 m (1936 m^2) and 37 floors (167.5 m height) is as productive as 216 ha of conventional farm land.[148] Considering that the global average farm land footprint is 2000 m^2 (0.2 ha) per person and year,[149] this exemplified vertical farm would be able to produce food for 1080 people every year – on the farm land currently allocated to just one person.

Both types of urban agriculture, urban farming and urban gardening, integrate food and biomass production into urban metabolisms. Sustainable urban agriculture could become a key concept for food production in the bioeconomy,[150] connecting consumers and producers. Food is either produced by the consumers themselves (urban gardening) or by professional producers in cities (vertical indoor farming). Through urban crop production, consumers – by nature a large societal group – learn about agriculture (e.g., seasonality, resource use, and labor input) with its associated (negative) impacts on natural ecosystems, biodiversity, and the climate. They also become aware of potential solutions for more sustainable agricultural biomass production and more sustainable consumer behavior, including the purchase of more regional and seasonal food and the elimination of food waste.[46,151]

Urban gardens provide a wide variety of ecosystem services (e.g., air quality and city climate improvement and biodiversity enhancement), while urban farms allow for the integration of multiple production systems (e.g., crops, fish, algae, mushrooms, insects, and renewable energy) with low land requirements. Organic wastes, residual energy, and (gray) water from the surrounding buildings can be put to productive use in circular production systems with enormous productivity. Consequently, food and biomass production in close vicinity to urban inhabitants or by the inhabitants themselves actively engages this huge societal group in finding solutions to the great challenges of the 21st century.

3.6.2. Public Goods of Urban Agriculture

Urban gardens increase biodiversity through their very high crop diversity.[46,152,153] In Germany for example, the consumption of native fruit and vegetable varieties has increased by 25% since urban inhabitants have started to garden.[46] In Los Angeles, a total of 707 different plant species have been observed in urban gardens.[154]

Urban gardeners in Germany favor soil-based cultivation with organic practices.[46] Biological pest control is suitable for (rooftop) greenhouse and indoor cultivation. Indoor farming with controlled environments is managed without pesticide use, and agroecological practices (e.g., mixed cropping) are often applied in urban (community) gardens.

Urban agriculture focuses on the productive use of un- and underutilized spaces in urban areas, including vacant lots, backyards, facades, roofs, balconies, and buildings.[140] This is accompanied by a high potential for green roofs and other areas that in turn provide multiple ecosystem services through nature-based solutions (including filtration of air pollutants, cooling of city climate, water retention, building insulation, and quality of life).[45,155] As a side effect, urban food production can reduce pressure on agricultural lands[44,45] and the negative impacts of intensive biomass production on natural ecosystems, water bodies, and the climate.

3.7. Phototrophic Cultivation of Microalgae

Microalgae are one of the oldest forms of life and are found all over our planet. They mainly live in water but are also found on the surface of all types of soils in a wide range of environmental conditions.[156] They are unicellular or simple multicellular structured organisms with chlorophyll *a* as their photosynthetic active pigment and a thallus not differentiated into roots, stem, and leaves. This definition includes both eukaryotic and prokaryotic autotrophic organisms.[157]

Microalgae can be cultivated for industrial production in two main categories of cultivation systems: open ponds and closed photobioreactors (**Figure 9**). The growth conditions in these systems range widely from phototrophic or mixotrophic in transparent glass or plastic cultivation systems with artificial (indoor) or natural sun light (outdoor) to heterotrophic in fermenters, and from salt (seawater), brackish to fresh water.[158] The type of system used depends on several considerations: the biology of the microalgae, the cost of land, labor, energy, water, and nutrients, the climate (outdoor cultivation), and the type of final product. The different systems also vary in their light utilization efficiency, their ability to control temperature, the hydrodynamic stress placed on the microalgae, and their scalability from laboratory to industrial scale.[158,159]

In the bioeconomy, microalgae will have the potential to recycle both agricultural and urban waste streams in the near future. This can reduce the ecological impact of agricultural activities, wastewater treatment, and drinking water treatment, indirectly through oxygen generation for bacterial activity and directly through the uptake of inorganic and organic phosphorus and nitrogen compounds (Tables A13 and A14). Aerobic fermentation of microalgae can provide additional valuable biomass as feedstock for 3rd generation bioenergy and biofuels or biogas.

3.7.1. Private Goods of Phototrophic Cultivation of Microalgae

Microalgae-based products can also be used directly in agriculture. By extracting bio-stimulants and bio-pesticides such as amino acids, peptides, and polypeptides as well as phytohormones (e.g., auxin- and cytokinin-like compounds) and other valuable molecules, plants can be positively influenced in a number of ways including root and fruit development, growth promo-

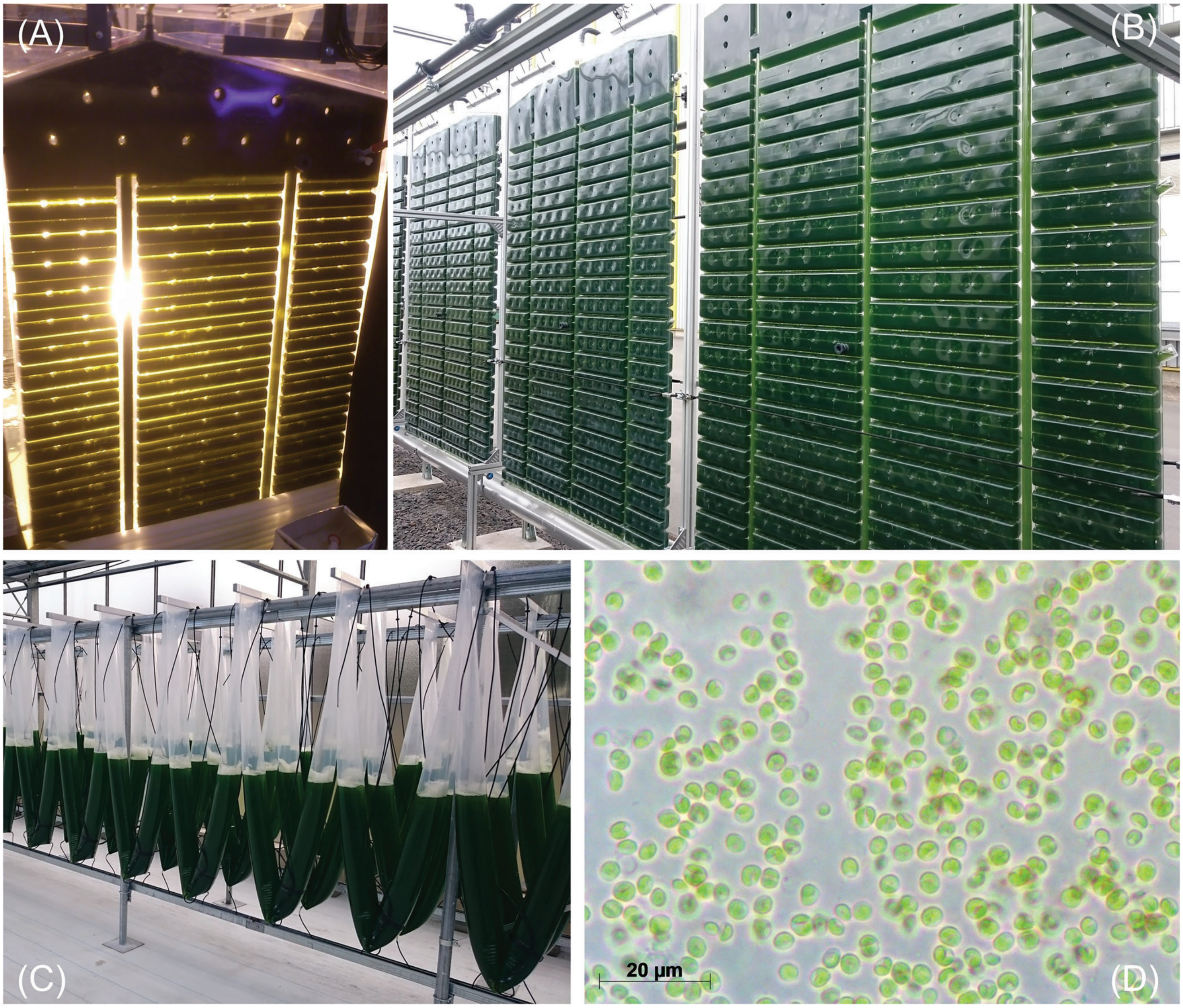

Figure 9. A) 30-liter Flat Panel Airlift photobioreactor (PBR) with artificial illumination distributed by the Germany company Subitec GmbH. B) Outdoor plant with 180-liter Flat Panel Airlift PBR distributed by the company Subitec GmbH, shown here on the premises of CropEnergies Bioethanol GmbH in Zeitz, Germany. C) Plastic bag PBR at the Algae Science Center of the Jülich Research Center, Germany. D) *Chlorella sorokiniana* in DSN medium at 400x magnification (Source: Sebastian Weickert).

tion, increase in water and nutrient uptake, increase in stress tolerance to adverse conditions, and protection against pathogenic fungi and bacteria. This leads to a general reduction in the use of conventional pesticides and also fertilizers.[160]

3.7.2. Public Goods of Phototrophic Cultivation of Microalgae

Through the integration of flue gases, microalgae can play a decisive role in the storage of CO_2.[159,160] Microalgae cultivation has to potential to make a significant future contribution to addressing critical societal challenges such as EU carbon neutrality, as well as promoting the transformation toward a sustainable and circular European bioeconomy.[161]

4. Discussion

The assessment of diverse bioeconomy approaches revealed their high potential to deliver multiple private and public goods simultaneously. In the following sections, we discuss how these multi-functional BAs can improve the resilience of agricultural systems in practical ways. We then reflect on key factors for their implementation. As the focus of this paper was to assess the potential delivery of desired functions by the BAs, we also discuss how the risks of negative impacts of their implementation could be dealt with. Possible drawbacks and trade-offs need to be given appropriate attention. Finally, we provide an outlook for potential approaches for measuring the contribution of BAs to resilience.

4.1. How Bioeconomy Approaches Can Contribute to the Resilience of Agricultural Systems

All seven BAs are currently in the process of being developed as new elements of future farming systems in the context of a sustainable and circular bioeconomy. Most of the BAs offer new forms of farming that differ in their patterns from the current system of good agricultural practice. However, the determination of "good agricultural practice" as an underlying basis for a comparative assessment of BAs has not yet been completed.

The assessment of the seven BAs revealed that all of them are characterized by their ability to provide multiple private and public goods simultaneously while contributing to the diversity of agricultural systems. The interlinked diversity and multifunctionality of the BAs can contribute to greater adaptability of agricultural systems if their implementation in the spatial and site-specific context is well planned.[11,150,162]

One important contribution of the BAs to adaptability is that all of them offer farmers a diversification of business and income opportunities. Classical diversification enables the establishment of new fields of business activity that do not originally form part of agricultural production.[163] Economic diversification through BAs can be horizontal, vertical, and lateral (see ref. [164]). Horizontal diversification includes new products on the same value chain. These are provided when biomass production, e.g., through miscanthus, WPM, or grassland, supplies biomass for additional products, such as construction material or biomethane, or when ecosystem functions, such as carbon sequestration or pollination services, are simultaneously delivered. This can also feed into vertical diversification, i.e., contributing new fields of business activity within the value chain, when farmers process agricultural products on their own farm and sell these biobased products instead of raw biomass. Electricity from biogas, e.g., from WPM, miscanthus, or grassland, is a practical example of the further on-farm processing of biomass and higher-value generation by farmers. Other examples of on-farm processing are realized when miscanthus biomass is processed into animal bedding or building material.[50] The on-farm recycling of organic wastes, such as animal slurry and biogas digestates, into mineral fertilizer can not only help close nutrient cycles on the farm but also result in a marketable product with high profit margins for the farmer.[165] Agrivoltaics and microalgae, as well as urban farming concepts, offer the opportunity for lateral diversification as they represent completely new fields of business activity or novel agriculture methods. Other assets of BAs relevant in this category include potential future business opportunities for farmers provided by public functions, such as carbon sequestration (miscanthus, WPM, grassland), reduction of GHG emissions (APV, miscanthus, WPM, grassland) and pollination services (WPM, grassland).

The BAs are characterized by their potential to deliver many of these functions. Such functions, including those commonly neglected in the full value of natural assets, need to be integrated into a diversified value provided by resilient agricultural systems (i.e., internalization of positive externalities). This implies redefining the value of goods such as food products.[166] A combination of governance approaches and mechanisms, including emerging market-based mechanisms such as payment for ecosystem services (PES), CO_2 credits, and eco-certification schemes, could function as financing and economic compensation options for farmers.[58,167] In fact, guaranteeing the profitability of resilient agroecosystems is key in supporting rural livelihoods.[22,168] Designing such incentives requires the consideration of current limitations and barriers as well as fundamental criticisms and practical challenges of mechanisms such as PES.[169–172]

Diversification helps a farm to add value and spread the entrepreneurial risk over several sources of income, thus better arming it against crises and securing its income or long-term maintenance.[164] We argue that, through their multifunctionality, the BAs contribute to the resilience markers of diversity, environmental sustainability, and autonomy. The bioeconomy provides farmers with business models that help them better participate in the value creation of biobased products.[173] This strengthens their position in the system and provides them with opportunities to adapt to changes, e.g., in market conditions.[11] Examples of BAs that allow farmers to sell products of higher value than unprocessed biomass include APV, where electricity is produced, and the on-farm recycling of nutrients, which results in marketable fertilizers. The latter is based on the biorefinery concept, which is an integrative overall concept for the processing or use of biological resources for the production of diverse products making the fullest possible utilization of the raw material source.[174] On-farm modular biorefineries in particular (e.g., Hohenheim on-farm biorefinery concept[175]) can allow the stronger involvement of farmers in value chains. Here, especially the recycling of nutrients into fertilizers, but also the production of fibers and biochar, are considered suitable activities for on-farm biorefining.

Nutrient recycling can significantly help reduce the dependence of agricultural systems on external inputs, such as mineral fertilizers. Bauerle[176] estimated that, in Germany, almost 30% of the N demand and (more than) the entire P demand could theoretically be met by recycling the nutrients from pig slurry and biogas digestates. Reducing the need for external inputs in agricultural systems and circularity of energy and material flows strengthen the autonomy of farms and agricultural systems.

In this study, the new indicator category "improve the efficiency of resource use" was added to public goods because it is an important resilience marker and bioeconomy principle. Circularity of energy and material flows is the major principle leading to better resource-use efficiency when BAs are integrated into agricultural systems. On-farm nutrient recycling helps close nutrient cycles at a regional level and improve nutrient-use efficiency. This reduces the demand for external inputs and energy and thus reduces GHG emissions in agricultural systems.[50,120,122] Increased nutrient-use efficiency has been reported as a decisive strategy in agricultural production systems for the reduction of environmentally harmful emissions while simultaneously securing productivity.[177,178] Urban agriculture can be based entirely on nutrients recycled from organic household wastes,[46,141,179] and as such, urban areas can become bioeconomy hubs for resource circulation.[180] Similarly, microalgae cultivation can be based on residues, e.g., the use of purified exhaust gases.[159]

All BAs have in common a high potential to contribute to improved environmental sustainability of agricultural systems because they have been designed for the purpose of delivering private and public goods simultaneously. They can contribute to the reduction of GHG emissions (Table 1) via a range of mechanisms, including soil carbon sequestration, replacement of fossil resources, circularity, and more efficient resource use. The BAs also contribute to higher resilience to climatic changes by increasing the crop spectrum, as the diversification of production systems contributes effectively to resilience.[162,181]

Perennial cropping systems – in this study grassland, miscanthus, and WPM – can all make a contribution to **biodiversity** protection.[65,78,91] But the BAs urban agriculture also contributes to biodiversity through the introduction of new agricultural production systems into spaces so far unused for agricultural production.[180] This is particularly the case with the introduction of new habitats and plant species that, when in flower, provide food for insects, for birds that feed on these insects, and for animals that feed on the plants.[44–46,155]

Urban community gardening, a typical form of urban agriculture, is an example of a BAs that efficiently combines public goods that contribute not only to environmental but also social sustainability by improving the quality of life in urban areas and promoting food security, especially in developing countries.[182] Urban agriculture also encourages more sustainable consumer behavior and the reduction of food waste.[46]

4.2. Key Drivers for and Limitations to the Implementation of BAs

As described and discussed in detail above, BAs are characterized by their ability to deliver biobased products as well as diverse other functions and services defined as private and public goods. However, to date, the provision of public goods does not benefit farmers in any way – there is no economic compensation for the (intentional) provision of these goods.[58,183]

4.2.1. Support Required for the Design and Implementation of BAs

A prerequisite for BAs implementation is their suitability for and adaptability to local biophysical and socio-economic conditions based on a systemic value-web perspective that takes into account all sustainability dimensions in the context of social-ecological, institutional, economic, and technological factors.[184] The implementation of BAs as the pursuit of a socio-technical transition toward resilience requires such long-term, adaptive processes to be approached from a multi-level perspective, understanding and considering interactions at the micro level (i.e., farms), meso level (i.e., landscape, region), and macro level (globally).[30,185,186] In this way, during the change process at the farm level (i.e., BAs implementation and adaptation), processes and the assembling of BAs and system elements (process-relational perspective) can be adapted in response to feedback from the context, the meso, and the macro level.[185] This can contribute to understanding which relationships are change enablers and which constrainers and indicates the importance of a context-dependent and holistic rationale for the design, implementation, but also governance of BAs, in order to avoid failures that could undermine the overall goal of fostering resilience. For instance, a certain bioeconomy approach may contribute to diversification at the farm level, but its massive adoption at the regional level may lead to a low level of diversification of the agricultural landscape. Accordingly, both coordination between the various BAs stakeholders and continuous monitoring of their multi-scale performance are necessary for the true pursuit of resilience and diversification.

A major contributor to the implementation of BAs in existing farms is a coherent and incentivizing political framework.[187] At the European level, several key strategies have been framed in the European Commission's (EC) "Green Deal", addressing and connecting agriculture, industry, biodiversity, and climate change in a "fair transition toward climate neutrality" by 2050.[188] However, these strategies can only enable a sustainable and resilient bioeconomy if there is policy consistency at all levels. The ambitious goals set by the Green Deal to direct Europe toward sustainability and resilience are listed here.

For agriculture, the major tasks are: i) to shift to organic production systems (25% of cropland by 2030), ii) to improve landscape heterogeneity,[189] and iii) to cut the use of chemical-based pesticides by half, while reducing chemical fertilizers (external input) by 20% and nutrient losses by 50% in order to protect natural ecosystems and biodiversity.[190]

The interconnected challenges of our time require sectoral strategies with concrete approaches (such as the BAs presented here) that are embedded in a concise, systems framework and connect the approaches into value webs. The BAs are supported by both the European and national bioeconomy political, research, and innovation strategies.[180] The common ground in these strategies is the production and provision of biomass produced in an environmentally sound manner from multifunctional agricultural and forestry systems (including their combinations).[180,191] At best, several BAs are combined in a biobased resource production-conversion-utilization-recycle/reuse metabolism. This is reflected in the reform of the Common Agricultural Policy (CAP) through the re-allocation of payments from the first (76.8%) to the second pillar (23.2%).[192]

Reversing the decline in both biodiversity and the important service of pollination, as well as increasing the organic carbon content in cropland is of crucial importance.[188] The "List of potential agricultural practices that eco-schemes could support"[193] includes, among others, agroecology, agroforestry, and high nature value farming, which all target the provision and utilization of ecosystem services from and within agricultural systems. The BAs presented here make a large contribution to the aim of i) reducing nutrient losses (e.g., nutrient recycling, urban agriculture, and microalgae), ii) supporting biodiversity, iii) increasing soil fertility, and iv) reducing the use of chemical fertilizers (WPM, miscanthus, grassland). These and other properties provide the BAs's ability to foster the resilience of agricultural systems against climate change and the associated challenges of our time.[194]

The CAP Strategic Plans[195] envision a number of interventions that may become powerful measures to accelerate the implementation of BAs. These include modernization investments to enable nutrient recycling, technologies to optimize fertilizer and pesticide use, but also biomass processing technologies, and precision farming. For example, the New Research and Innovation Agenda[196] aims to complement rural innovation ecosystems with digital and in particular deep-tech innovations to boost the long-term vision of rural development. Digital systems such as the Farm Sustainability Tool for Nutrients,[197] can support the adoption of sustainable fertilizer use through free access to advisory services. However, investments for the implementation of

BAs require a long-term commitment from farms, and this depends on the farmer's ability to adopt BAs in terms of capital access, farm size, and structure, willingness to engage in additional (on- and off-farm) activities, access to technology, knowledge, and technical advice, among other factors. The willingness to make such investments and the associated risks are however closely linked to the existence of a functioning market for the individual biobased products under consideration, a supportive political framework, and a societal system that has a circular bioeconomy concept at its core.

While the political will is there, other questions arise that may limit the implementation of BAs, such as (i) how technology can best be implemented sustainably and in a decentralized way – where the feedstock is available, and (ii) how quality parameters of biomass feedstock can be exploited for various industrial processes. Science-based concepts for technology implementation are available to process the biomass feedstock,[175] but these technologies necessary for successful implementation currently often lack TRLs higher than 7 (demonstration level).[198] Markets for biobased products are already emerging, but the value chains for biobased raw materials are not fully established and lack profitability.[187] New biobased products and processes have to compete with cheap, widely available, fossil-based substitutes, which is particularly difficult when consumers are unaware of the bioeconomy.[187]

A simple and cost-effective measure to increase the competitiveness and profitability of biobased products is carbon pricing. As the BAs presented here have the potential to reduce greenhouse gas emissions relative to their fossil substitutes, a well-established price for carbon could facilitate the transition toward a sustainable bioeconomy.[199] In addition, supply-side measures should be complemented by demand-side measures, such as public procurement, mandates, directive incentives, tax relief, and labeling. This indicates the importance of understanding consumer behavior at individual and aggregated levels and how a redefinition of the value of agricultural-based products can match dynamic consumer motivations and drivers.[200,201]

From a systems innovation perspective, BAs could "grow" within protected niches and scale up when the political bioeconomy landscape and concurrent socio-technical regime converge[202] and new markets and clusters (e.g., for biobased products and public ecosystem services) are created.

4.2.2. Dealing with Potential Risks and Trade-Offs in BAs Implementation

It has to be emphasized that the proposed BAs are neither sustainable per se nor suitable in every context. The BAs considered here serve as potentially more sustainable alternatives to the purely fossil-based processes and technologies used today. For each locality and socio-economic context, they may require adaption, combination, and integration into existing infrastructures.

The inclusion of all seven BAs into the existing framework gave rise to additional indicators. In contrast to the study of Meuwissen et al.,[4] these additional indicators do not serve as part of an assessment of the status quo of an existing farming system intended to derive policy recommendations or provide recommendations on how to improve its resilience. Instead, they were integrated to understand the sum of desired functions provided by the selected BAs. Together, the seven BAs are very well suited to providing these functions as they approach the bioeconomy farming system from various angles, enriching it with their different contributions. The resulting expanded framework enables a holistic assessment of potential desired functions in a future resilient farming system.

The inclusion of this set of additional functions not only allows an assessment of the resilience of current systems but extends it to encompass visionary desired functions for future systems. This can point the way to the transformation toward more sustainable agricultural systems.

The additional indicators can thus help to identify the gap between current systems and the potentially more sustainable systems of the future. This is useful for providing guidance in policy recommendations when interacting with stakeholders and discussing possible transition pathways. As such, the additional indicators can serve as concrete functions of a desired system and support empirical efforts aimed at, for example, conducting a foresight study or developing action plans for the integration of sustainable practices.

Thus, the focus of this study is on the assessment of the potential of BAs to deliver desired functions. However, there are also risks and potentially negative impacts of their implementation, which we address here as trade-offs. The major trade-off to be dealt with is that between the provision of food/biobased resources and the provision of public goods, such as GHG emission intensity and biodiversity protection (see also Feike et al.[177]). This can be seen in the example of WPM. On the one hand, these contribute greatly to supporting biodiversity (Section 3.2). On the other hand, their methane yield potential for biogas feedstock production is only 50–70% of that of annual cropping systems, such as maize, and the specific biogas yield is also lower due to both lower biomass yields and higher lignification of the biomass.[83] Another example is APV, which combines food and electricity production on the same area of land. Trade-offs were identified between the provision of these two different products as well as with the maintenance of the productivity of agricultural soils (Section 3.5). There is a high risk that the implementation of APV will lead to the loss of agricultural land, as ≈8% of the land is required for PV installation.[133] Another relevant risk is that, where APV requires high investments, farmers are not adequately involved.[133] In the face of the growing demand for food and renewable resources, the competing claims on land, water, plant nutrients, and biomass are considered a major bottleneck for the implementation of those BAs that have the delivery of non-food products, such as electricity or biomass, as their main purpose.[42] This also applies to the large-scale implementation of miscanthus, which requires arable land. For this reason, it is recommended to implement BAs with land requirements on agricultural land characterized by marginal conditions for food production or to combine them with the provision of other functions.[203] In the case of APV, this can for example be the protection of crops from heat or hale.

The identification of appropriate BAs and/or their combinations first requires a status-quo analysis of challenges to the resilience of a specific and spatially explicit agricultural system, as well as a context-specific prioritization of desired functions and ex-ante assessment of potential risks. One or a combination of BAs are then chosen that can best deliver the functions required to ensure the resilience of the agricultural system under consideration. These processes of prioritization and selection of appropriate BAs require the participation and cooperation of farmers and other stakeholders along the value chain, ultimately including the community in which this bioeconomy approach is to be realized. For the structuring, assessing, and selecting of desired functions and outcomes, multi-criteria decision analysis (MCDA) is state-of-the-art in environmental and sustainability studies.[204,205] For example, Winkler et al.[206] applied MCDA to the participatory selection of locally appropriate renewable energy technologies for smallholder farmers in South Africa and India, based on qualitative and quantitative social, environmental, technical, institutional, and economic criteria.

Value chain integration and participatory approaches ensure that the interests of all stakeholders in a value chain are met, thus contributing to its societal acceptance, inclusiveness, and respect of the normative dimension based on people's values and beliefs. This is for example the case when the biomass quality characterized is well adapted to the processing demands or when the risks associated with biomass production are shared between farmers and biomass users through cooperation models.[42,207,208] The acceptance of biogas projects has been much higher in communities where community members were aptly informed by the mayor during the planning phase of the biogas plant.[209] The early involvement of stakeholders in the planning of BAs implementation is therefore an important part of the risk mitigation strategy.

Digital optimization tools can support sustainability, productivity, and resilience in agriculture by increasing knowledge, precision, monitoring, documentation, and assessment, as well as decision-making capabilities.[186,210] These tools are relevant for planning BAs and their integration into existing (biobased) value webs. They can perform the analysis of function webs, i.e., the bundles of functions delivered by BAs and their interactions, and thus support their implementation. In addition, digital tools support the assessment of material and resource flows as well as a detailed evaluation of positive and negative externalities in agricultural systems in monetary terms, e.g., supported by life-cycle assessment (LCA), which culminates in holistic true-cost accounting.[58,211] Digital tools can also support the consideration of spatial aspects in the planning of BAs implementation in order to promote biodiversity, maintain the multi-functionality of landscapes, and avoid land-use conflicts.[150]

4.3. What Is Required to Estimate the Contribution of BAs to Resilience?

The extent to which functions are realized when a bioeconomy approach is integrated into an agricultural system depends on site conditions, the farming system, available infrastructure, and the societal context (Figure 1). For example, the biomass yield of miscanthus varies greatly across Europe according to climate and soil conditions.[31] The extent to which miscanthus can contribute to an increase in soil organic carbon (SOC) content depends on the soil type and the original level of soil carbon. It can be high if miscanthus replaces annual crops, but potentially negative if it replaces permanent grasslands.[60] The SOC can even further increase after the reintegration of a miscanthus site into arable cropping.[212] However, the farm can only realize synergies through miscanthus cultivation if i) areas are available that are difficult to manage for other crops, ii) miscanthus can be used as structural elements in the farm, e.g., for erosion control, or iii) the biomass can be used on the farm for animal bedding or as heating material.[213] An additional source of income for farmers is only realizable if there is a market for biomass or if higher value-added products can be generated through on-farm use or processing of miscanthus biomass, e.g., for energy or fertilizer production.[176] Therefore, context-specific studies are required to assess the concrete contribution of BAs to the resilience of agricultural systems. It is only through such context-specific studies that the value of the addition of a bioeconomy solution can be assessed, including the way it changes the informational content of indicators applied in the framework of Meuwissen et al.[4] Changes in informational content occur when, for example, the main product of a production system, (e.g., biomass) becomes a side product and another function (e.g., erosion control) becomes the main goal of the production system.

4.4. Approaches for Assessing the Value of Functions

The theoretical concept of public and private goods does not investigate the quality of the goods and therefore provides no indication of the value of the good itself, making it very difficult to measure. This is critical in respect to the monetary valuation and rewarding of sustainable behavior of all actors in an agricultural system, particularly the farmers.[214] Moreover, in the context of ecosystem services, the fundamental question of "how to value nature" is rather complex. Monetary evaluation is an established approach for this purpose, despite being rather instrumental and monistic and its limitations in capturing the plural, complex, and subjective characteristics of the value of nature.[171,172] There is a vast body of literature that aims to elicit preferences for, and the value of public goods produced, such as ecosystem services.[49,167,215] These hypothetical elicitations will yield a monetary value on paper, but critical assessment exposes their weaknesses in the context of the desired increase in sustainable production in current agricultural systems to enhance their resilience.[215,216] To overcome the shortcomings of complicated theoretical calculations, "The Economics of Ecosystems and Biodiversity for Agriculture and Food Evaluation Framework"[217] provides a substantial, comprehensive basis for the measurement of positive and negative externalities of agricultural value chains and proposes a common language.[211] It characterizes agrifood value chains (baseline), exploring both positive (provision of private and public goods) and negative (harm to private and public goods) externalities in line with true cost and benefits accounting.[58] The framework describes biobased value chains based on the four forms of capital (human, social, natural, and produced) that create them (inputs) and also the impacts of value chain activities on these capitals (positive or negative impacts / private and public goods). While the TEEB AgriFood Framework provides the theoretical foundation, Sandhu et al.[216] developed a practical framework to capture, measure, and value the provision of public and private goods by individual farms, relying on farm-level data. This framework is equally applicable to the BAs evaluated in this study.

Another significant approach for assessing the value of the positive functions delivered by a bioeconomy approach is the quantification and monetization of ecosystem services (ES)[25,49] a fundamental concept that endeavors to specify an economic and possible market value for functions under the category of public goods. This type of business model is particularly beneficial for BAs, as they provide diverse ecosystem services that cannot yet be monetized in a targeted and comparable manner. So far, ecosystem services have mainly been analyzed and monetarily evaluated in natural ecosystems at the biome level.[218,219] The Ecosystem Service Valuation Database (ESVD Version Mar2023V1.0)[220] currently lists only 1144 monetary values for agricultural land worldwide (including arable land, grassland, pasture) and only one for Germany (pollination).[220]

The development of a quantitative measurement and evaluation system requires the development of transparent and evidence-based information on ecosystem services, which can be used as a prerequisite and basis for monetization. A major challenge lies in defining the societal decision-making mechanisms in dealing with the common good of ecosystem services that take into account the complexity and fluidity of natural and social systems.[221] Context-specific scenario analyses are necessary for this. The procedure for the assessment of area-based biodiversity, water, and climate protection services developed by the German Association for Landscape Conservation[183] provides an important basis for this. Land-use forms (arable land, grassland, landscape elements) and gross farm-gate nutrient balances (N & P) are recorded at the individual farm level and evaluated using a point system in order to determine a farm-specific public interest bonus. The advantage of this procedure is that the data used for evaluation is almost exclusively data that farmers (are) already (obliged to) collect.

The approaches discussed above all lead to the "calculation of the true costs" of (biobased) value chains (True Cost Accounting), with the production costs, the ecosystem services of a crop (or combination in a cultivation system), and the environmental impacts (collected through life-cycle assessment) being combined and recorded as a positive or negative value.[58,221] These are assessments from an external perspective that may imply compensation schemes in which the valuation of the agricultural activity per se is not included.

5. Conclusion

The outcome of this study is an indicator framework that can be helpful in future ex-ante ad foresight studies on the potential of BAs to deliver desired functions for the transition to resilient agricultural systems, from the field to the regional level.

BAs can contribute to a higher land-use efficiency by combining the provision of diverse private and public goods on the same area of land, as long as certain site-specific requirements for successful implementation of the BAs are met. In order to optimize the contribution of BAs to the resilience of agricultural systems, we recommend identifying context-specific approaches that simultaneously improve resource-use efficiency within the agricultural system, deliver synergies with existing agricultural activities, and provide a range of public and private functions.

The integration of BAs into agricultural systems should be performed with the objective of maximizing benefits and minimizing trade-offs, e.g., with food production or the economic viability of farms. The latter requires a mind shift toward remuneration for the provision of ecosystem services. However, methods for the valuation of systems functions and public goods still need to be developed. Only if farmers are incentivized to provide public goods will they invest in BAs that can deliver them. A major bottleneck for the implementation of BAs is the fact that their development and implementation must occur in parallel with the development of supporting frameworks. Providing these is a crucial task for policy makers and a compelling matter in view of the societal and environmental challenges that need to be urgently addressed, such as climate change mitigation (Sustainable Development Goal (SDG) 13, "Climate change mitigation") and biodiversity conservation (SDG 14, "Life below water", and SDG 15 "Life on land"). In conclusion, BAs can make a significant contribution to tackling these challenges by improving the resilience of agricultural systems.

Appendix

Table A1. Potential contribution of miscanthus to the bioeconomy through provision of private goods, structured by indicator categories adapted from Meuwissen et al.s "*framework to assess the resilience of farming systems*".[4]

Private goods of miscanthus				
	Indicator category			
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions
Indicator	Increased productivity of agricultural soils (for food production)	Yield (Mg ha^{-1}, dm^3 livestock $unit^{-1}$) of major non-food products	Gross margin per hectare (for arable farms), gross margin per livestock unit (for livestock farms)	Number of workers employed on farms and related businesses including contract and part-time workers
Potential contribution of the BA	As a perennial crop miscanthus contributes to soil carbon increases (up to 1 Mg ha^{-1} a^{-1}). • Cultivated on arable land: 0.7–2.34 Mg C_4-C ha^{-1} a^{-1}.[59,60] • Cultivated on grassland: can decrease SOC but likely to be recovered during the lifetime of the crop.[60] • SOC sequestration rate 0–10 cm: 0.68; 10–30 cm: −0.13, 0–30 cm: 0.55 Mg C ha^{-1} a^{-1}.[212] • C and N stocks one year after reversion increase significantly (+15% and +12%, respectively), and in the second to fifth year no significant change.[212] • Remediation: Miscanthus has been shown to exclude heavy metals allowing its cultivation on contaminated lands.[67] The large genetic variety within miscanthus has been shown to affect its ability to accumulate heavy metals[66] and soils with low levels of contamination may even be cleaned from heavy metals, but only long term (decades; high contaminated soils >1000 years). Miscanthus thus improves the productivity of agricultural soils. • *Miscanthus × giganteus* can absorb 55 g Cd, 85 g Pb, and 720 g Zn per hectare per year in wasteland[222,223] • Miscanthus can remove up to 97.7% As in soil, and under certain conditions 86.4% Cu, 77.5% Pb, 61.0% Ni, 56.2% Cd, and 42.9% Zn.[224] • Perennial crops like miscanthus can be used as a break crop on overused arable land and can help to restore soil fertility and solve problems with herbicide-resistant weeds. This can contribute to higher yields and lower input demand in the crop rotation following miscanthus. • Miscanthus reduces soil erosion.[62,225]	Strong variation with site conditions, climate and harvest date with a range of 8–38 Mg dry matter ha^{-1} a^{-1} across Europe[226]; realistically achievable yield on marginal land in Germany: 12–15 Mg ha^{-1} a^{-1} harvestable yield.[227]	The gross margin typically ranges from 300 to 1.500 € ha^{-1} a^{-1} depending on production costs and biomass valorization.[213] While production is greatly affected by transportation distance and the applied harvest technology, the biomass valorization generally depends on the value created by the final product. In practice, companies active in miscanthus business, such as Terravesta and Novabiom, often offer long-term grower contracts with guaranteed prices resulting in gross margins of ≈500 € ha^{-1} a^{-1}.	If only biomass production: low workload and low demand for workforce (except during planting). Higher demand for skilled workforce for biomass processing and production of biobased products (e.g., if biochemicals replace fossil chemicals).

(*Continued*)

Table A1. (Continued)

Private goods of miscanthus				
	Indicator category			
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions
Indicator		Potential end uses of biomass and its components	On-farm processing (creation of additional income)	Provision of additional income opportunities
Potential contribution of the BA		Miscanthus has a variety of end uses Farm uses: animal bedding, solid fuel for heating, biogas substrate. On-farm processing for material use, e.g., building material,[35] possible; most relevant current uses: animal bedding, heat production; promising future uses: bioethanol, biochemicals, bio composites, building material (concrete systems, particle boards: conventional particle boards, binderless fiberboards, insulation panels), feed additives.[228] Other potential uses include as a feedstock for industry,[229] anaerobic digestion or saccharification to produce biofuels such as biogas or bioethanol.[230,231]	Yes, for animal bedding, heating. Cooperative: biorefinery (first processing step), e.g., for fiber extraction.	Miscanthus can represent an income diversification option for farmers that also helps mitigate weather risks through its stress tolerance. On marginal land in particular, it has the potential to provide additional income due to lower annual costs and higher yield stability than for annual crops. Additional income opportunities can be achieved, if farmers not only sell the biomass but also increase on-farm value creation through its (pre-)processing.
Indicator		Production of renewable resources / energy in the agricultural system	Inclusiveness of smallholder farmers (in terms of access to technology, markets, participation in value-adding activities)	Creation of "green" and sustainable job opportunities and business concepts
Potential contribution of the BA		Miscanthus biomass can be used for material applications, as a solid fuel for combustion and as a substrate for biofuel production.	Accessibility to technology is given, as necessary technology is also used for other crops. Participation in value-adding activities in cooperatives is possible.	Miscanthus can support creation of green and sustainable jobs and business concepts in rural, since the low density of the biomass makes it more suitable for regional value chain supply or requires at least decentralized pre-processing.

(Continued)

Table A1. (Continued)

Private goods of miscanthus				
	Indicator category			
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions
Indicator		Supply of regional products	Degree of income diversification	Safe health conditions for farmers (in terms of exposure to pesticides, dangerous chemicals, dust, noise, odors)
Potential contribution of the BA		Biomass can be used for regional supply of fuels and biobased materials, e.g., building materials.	Miscanthus can provide opportunities for income diversification for the farmer and rural communities, since this new crop is currently only cultivated on a small scale in Europe. Further (pre-)processing of the biomass allows increased value creation on the farm or in the rural context thus increasing the degree of income diversification.	Completely mechanized field cultivation. Herbicide application only during establishment. High dust generation during harvest, however no direct contact due to mechanization.
Indicator		Substitution of fossil-based resources/products	Non-regional market dependence for sale of products	
Potential contribution of the BA		biogas can replace natural gas; solid fuels replace fossil oil; 2nd generation ethanol replaces fossil gasoline; fossil building materials such as rockwool are replaced; biobased chemicals replace fossil-based chemicals such as HMF.	Miscanthus is currently not traded on the agricultural commodity futures exchange. For this reason, prices are mainly affected by regional demand and supply. However, international crises will certainly impact regional prices to some extent, e.g., through the development of energy prices, as miscanthus cultivation requires fuel and miscanthus biomass can be used as heating fuel.	

(Continued)

Table A1. (Continued)

Private goods of miscanthus				
	Indicator category			
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions
Indicator		Proportion of biomass usable/convertible through processing	Non-regional market dependence for supply of inputs	
Potential contribution of the BA		100%; The complete harvested biomass is used for any energetic application, such as biogas substrate or combustion. For material uses specific fractions of the biomass may be used, e.g., the pith for isolation material. In that case the remaining material is used for other material applications or energetically.	As a perennial crop, miscanthus requires much fewer inputs than annual crops (lower fuel use as no soil cultivation necessary, in practice generally no mineral fertilizer application) and is for this reason is less dependent on the non-regional supply of inputs. After successful establishment, the main input required is diesel fuel for harvesting the crop.	
Indicator		Synergies between existing agricultural activities and bioeconomy approach/technology, etc.		
Potential contribution of the BA		Miscanthus can be grown on those areas on a farm that are difficult to manage and generate an income from these areas; Miscanthus can be used as structural elements in the farm, e.g., for erosion control; the biomass can be used on the farm for animal bedding or as heating material.		

Table A2. Potential contribution of miscanthus to the bioeconomy through provision of public goods, structured by indicator categories adapted from Meuwissen et al.'s *"framework to assess the resilience of farming systems"*.[4]

Public goods of miscanthus				
	Indicator category			
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes and species	Ensure animal health and welfare	Improve efficiency of resource use
Indicator	GHG emission intensity (per ha or per product)	Proportion of ecological focus and protected areas, including forests, set-aside land, national parks	Use of antibiotics	Productive utilisation of un- or underutilised areas (urban, industrial, agricultural)
Potential contribution of the BA	Due to ist perennial nature and low input requirements, miscanthus biomass can be produced with low GHG emissions.[57] This results in considerable GHG savings compared to annual biomass crops and fossil reference products.[35,232]	Miscanthus is eligible for production on greening areas and factored in with 0.7.[233]	Miscanthus bedding material has a higher water absorption capacity than straw commonly used. Dryer bedding material is key to improving health in poultry farming and can contribute to decreased overall antibiotics demand.	Miscanthus shows broad genetic variability and specific genotypes are tolerant to marginal production conditions such as drought, salinity, heavy metal contamination.[234] Wild miscanthus grows in a wide range of climatic conditions in its native range and thus there exists a strong genetic basis for tolerance of various stress conditions such as chilling, salinity, and drought.[235–238] There is also promising potential for the development of genotypes capable of growing on heavy metal contaminated areas.[66] Contaminated soils can be utilized for biomass production without risk of introducing contaminants into the food chain, for example when biomass is used as a building material. Miscanthus has been shown to exclude heavy metals allowing its cultivation on contaminated lands.[67] The large genetic variety within miscanthus has been shown to affect its ability to accumulate heavy metals.[66] Thus, miscanthus is suitable for cultivation under marginal conditions, allowing the utilization of lands that are otherwise not suitable for cultivation.
Indicator	Nutrient surplus	Crop diversity, plant diversity		Land/water/nutrient use efficiency
Potential contribution of the BA	Miscanthus mitigates leaching of nitrate to groundwater because it is deep rooting[239,240] and nitrogen fertilizer is generally unnecessary, except on soils of low fertility. N_2O emissions from unfertilized miscanthus can be five times lower than from annual crops and up to 100 times lower than from intensive pasture.[60]	Miscanthus is a crop not commonly grown in Europe. Cultivation could increase habitat functions, especially in intensive arable regions. Large areas of maize cultivation have resulted in landscape homogenization. Introducing another bioenergy crop could increase spatial landscape diversity or temporal diversity if it is implemented as part of a rotation.		Miscanthus is a C4 crop with high water and nutrient use efficiencies [numbers for water and N use efficiency]. This also leads to a comparatively high biomass yield potential, especially under marginal production conditions. Lewandowski and Schmidt[61] calculated a nitrogen use efficiency of 0.35 t dry biomass per kg of applied nitrogen. High water use efficiency (e.g., 5.5–9.2 g aerial DM $(\text{kg } H_2O)^{-1}$, 78–92 kg DM ha^{-1} $(\text{mm } H_2O)^{-1}$.[60]

(*Continued*)

Table A2. (Continued)

Public goods of miscanthus				
	Indicator category			
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes and species	Ensure animal health and welfare	Improve efficiency of resource use
Indicator	Capacity to avoid soil erosion	Diversity of ecosystem service provision		Circularity - inclusion of options to make material or energy streams circular
Potential contribution of the BA	As a perennial crop, miscanthus strongly reduces the exposition to erosion once the crop is established. Miscanthus reduces soil erosion to 0.2–1.0 Mg ha^{-1} a^{-1}.[241,242] In the first 2 years after planting, soil losses can be reduced by 29% through a 2-m miscanthus strip (on an average slope of 11%).[62]	A study by von Cossel et al.[49] estimates that one hectare of miscanthus provides environmental services to society with a potential value of 1200–4183 € $year^{-1}$. Raw material provision reveals the highest value, followed by CO_2 sequestration and moderation of extreme events.		Low nutrient offtakes if harvested in spring due to nutrient recycling: At the plant level, miscanthus recycles≈40% N and 36% P and 45% K[59] during senescence from the above-ground stems (=harvested biomass) to the below-ground rhizomes (=overwintering organ) and leaf fall.[243] At farm level, miscanthus biomass can be used for applications such as animal bedding and biogas substrate, where the plant nutrients are accumulated to be provided to the fields as compost or digestates.
Indicator	Soil compaction	Bird numbers and species		Improved land use efficiency
Potential contribution of the BA	As perennial crop, miscanthus only requires soil cultivation in the year of establishment; there is little machine traffic in miscanthus fields. This facilitates the formation of a stable (natural) soil structure and reduces the risks of soil damage compaction.[213]	Miscanthus can serve as habitat for semi-woodland bird species, which are commonly no longer present in intensive agricultural areas.[244–247]		Miscanthus production can improve land use efficiency as it combines a comparatively high biomass yield potential with the provision of diverse ecosystem services, such as carbon sequestration and soil improvement.[59]
Indicator	Contribution to landscape elements (landscape appearance, habitats, and corridors)	Number of insects and other invertebrates such as spiders, earthworms, and centipedes		
Potential contribution of the BA	Provision of additional habitat functions in intensive arable regions. When harvested for combustion, miscanthus remains standing in the field over winter providing shelter and habitat functions during this time period.[82]	Higher insect abundance than in annual crops[65,247,248]		
Indicator		Pollination		
Potential contribution of the BA		Benefits are highly context-dependent.[249]		
Indicator		Habitat quality based on common birds		
Potential contribution of the BA		Similar to annual crops, however, strongly species-dependent.[65,247]		

Table A3. Potential contribution of wild plant mixtures (WPM) to the bioeconomy through provision of private goods, structured by indicator categories adapted from Meuwissen et al.'s "*framework to assess the resilience of farming systems*".[4]

Private goods of WPM				
	Indicator category			
	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions	Improve quality of life in urban areas
Indicator	Total amount (Mg, dm^3) of major non-food products and their properties (e.g., energy content, concentrations of valuable components)	Gross margin per hectare (for arable farms), gross margin per livestock unit (for livestock farms)	Number of workers employed on farms and related businesses including contract and part-time workers	Awareness of need for sustainable food production
Potential contribution of the BA	Biomass dry matter production in Germany currently roughly 10 Gg a^{-1} (given an estimated area of 10 km^{-2} cultivated with WPM, mainly used for biogas production, and an average dry matter yield of 10 Mg ha^{-1} a^{-1}). This amount of WPM biomass can produce roughly 2200 m^{-3} heating oil equivalents in form of methane from anaerobic digestion in the biogas plants per year (given an average substrate-specific methane yield of 240 dm^{-3}$_\mathrm{N}$ CH$_4$ kg^{-1} volatile solids and an average ash content of 7% of dry matter; 1 m^3 CH$_4$ equals 1 dm^{-3} heating oil equivalent[250]).	Deducting the special costs results in a contribution margin of 200–400 € per ha and year.[251,252] However, depending on the biomass yield level and current wheat price, the contribution margin can fluctuate even more. Due to the relatively high lease prices (on good soils 400 € and more per ha and year), a subsidy amount of 250–500 € per year is therefore generally proposed and already implemented in some German states.	Low workload and low demand for workforce (except during planting and harvesting). Higher demand for skilled workforce for bioenergy pathways such as biogas production and combustion.	The cultivation of WPM on land close to urban areas could help to sensitize residents to the acute contrast between species-rich and species-poor cropping systems in agriculture. This could further promote awareness of the need for more sustainable food production.
Indicator	Yield (Mg ha^{-1}, dm^3 livestock unit^{-1}) of major non-food products	Degree of income diversification	Provision of additional income opportunities	More sustainable consumer behavior
Potential contribution of the BA	Biomass dry matter yield on average 10 Mg ha^{-1} a^{-1} (strongly dependent on soil and climatic conditions).[79]	Due to the positive effect of flowering WPM plant stands on local residents and tourists, additional income diversification would be conceivable in various ways, such as establishing a WPM maze (similar to corn maze) or nature trail, as well as flower picking for payment.	As additional income opportunities for farmers include production of honey from wild plant mixtures and offering self-cutting of fresh flowers for ornamental purposes. It may also be possible to increase the cultural value of the landscape and thus increase the possibility of generating income through tourism.	The colorful and diverse cultivation of WPM on land close to settlements could help generate or strengthen residents' interest in agricultural sustainability issues. This interest could also encourage more sustainable consumer behavior.
Indicator	Potential end uses of biomass and its components	On-farm processing (creation of additional income)	Creation of "green" and sustainable job opportunities and business concepts	Increased happiness and well-being
Potential contribution of the BA	Lignocellulosic biomass, mainly used for biogas production,[78] but first studies report on feasibility for combustion.[81,253]	Additional income if farmer is (co-)owner of the biogas plant.	Biogas production activities can generally be considered green job opportunities. If biogas production is proportionally based on co-substrates such as WPM, the environmental sustainability aspect is more emphasized. However, there is a trade-off between the promotion of biodiversity and maximum electricity and heat production, which is higher, for example, for maize and cup plant than for WPM.	The cultivation of WPM on areas close to settlements and in recreational areas could increase the well-being of residents and tourists in a region[254] as there is a lot of nature to discover in WPM plant stands, e.g., butterflies, wild bees and numerous flower species.

(*Continued*)

Table A3. (Continued)

Private goods of WPM				
	Indicator category			
	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions	Improve quality of life in urban areas
Indicator	Production of renewable resources / energy in the agricultural system	Inclusiveness toward smallholder farmers (in terms of access to technology, markets, participation in value-adding activities)		Creation of communities for social inclusion
Potential contribution of the BA	Bioenergy and, for biogas production pathway, organic fertilizer in form of digestate.	The technology required, especially for sowing WPM can also be used for other crops such as grassland or catch crops. The biomass could also be supplied to external biogas plants if the WPM-growing farm does not operate its own biogas plant.		There have already been numerous approaches to promote the cultivation of WPM with the participation of communities of interest. This can create or strengthen a sense of unity within a rural or urban region, in turn contributing to the readiness for further innovations and joint efforts with respect to more sustainable agricultural production.
Indicator	Supply of regional products			Integration of green elements
Potential contribution of the BA	Improve recreational value by enhancing landscape beauty. Depending on the season, flowers can be picked, replacing cut flowers grown outside the region. Some species keep fresh for over a week in a vase, such as common knapweed (*Centaures jacea* L.).			Growing WPM in areas close to settlements can help raise public awareness of the versatility and resilience of the many plant and animal species to be found in WPM. This newfound knowledge can also enable the integration of these plant and animal species as green elements in urban areas, for example on balconies, roof terraces, and traffic islands.

(*Continued*)

Table A3. (Continued)

Private goods of WPM				
	Indicator category			
	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions	Improve quality of life in urban areas
Indicator	Shortening of supply chains			
Potential contribution of the BA	There is no information on supply chain shortening for the main WPM biomass use (biogas production or combustion). However, for the use of flowers as ornamentals (bouquet decoration), there could be a proportionate shortening of supply chains.			
Indicator	Substitution of fossil-based resources/products			
Potential contribution of the BA	See above, currently ≈2200 m^{-3} heating-oil equivalents of fossil energy can be replaced in Germany per year (minus the energy needed for biomass cultivation, storage, and biogas production).			
Indicator	Proportion of biomass usable/convertible through processing			
Potential contribution of the BA	For the biogas production route (biogas production and use of the digestate as organic fertilizer), a high proportion of the fresh biomass can be used in the long term. During ensiling, minor biomass losses are to be expected (leachate), but a certain proportion of these could also be utilized in the future, e.g., for the extraction of basic chemical substances such as lactic acid.			
Indicator	Synergies between existing agricultural activities and bioeconomy approach/technology, etc.			
Potential contribution of the BA	There are numerous synergies (biodiversity conservation, wild boar regulation, improving landscape aesthetics, erosion mitigation, climate change adaptation, etc.), but also tradeoffs (lower land use efficiency compared with silage maize, risk of establishment failure, etc.).[78]			

Table A4. Potential contribution of wild plant mixtures (WPM) to the bioeconomy through provision of public goods, structured by indicator categories adapted from Meuwissen et al.'s "*framework to assess the resilience of farming systems*"[4] (GHG = greenhouse gas).

Public goods of WPM			
	Indicator category		
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes, and species	Ensure attractiveness of rural areas for residence and tourism with balanced social structure
Indicator	GHG emission intensity (per ha or per product)	Proportion of ecological focus and protected areas, including forests, set-aside land, national parks	Percentage of women among farmers, contract workers and part-time workers
Potential contribution of the BA	When biogas from WPM replaces natural gas, a significant reduction of GHG is achieved.[82]	WPM cultivation in ecological focus and protected areas is generally not recommended.[255] However, cultivation of WPM offers the opportunity to build bridges between ecological focus and protected areas in the agricultural landscape, which can contribute to improved population genetics of openland bird and game species.[78]	Regarding the WPM cultivation concept, there are no restrictions on the employment of women, so this indicator can also be considered to evaluate the contribution of WPM cultivation to the bioeconomy. Overall, only ≈36% of women are employed in agriculture in Germany. The proportion of women holding a managerial position is even significantly lower at 11.8%.
Indicator	Capacity to avoid soil erosion	Crop diversity, plant diversity	Average age of farmers and part-time workers
Potential contribution of the BA	WPM is a perennial system that leads to a reduction of the potential for soil erosion compared to annual crops.	WPM show high dynamics of species composition over 5 years and longer.[72] Since herbicide measures are completely avoided, a weed flora can develop in gaps in the plant stand, which can further benefit plant diversity.	The average age of German farmers is 53. However, a WPM cultivation-specific evaluation of the average age of cultivators does not yet exist.
Indicator	Contribution to landscape elements (landscape appearance, habitats, and corridors)	Diversity of ecosystem service provision	Aesthetic value (cultural ecosystem service)
Potential contribution of the BA	WPM make a positive contribution to the landscape appearance as they are in bloom over a long period of time with very diverse flowering.	WPM provide a high diversity of ecosystem services (e.g., habitat provision through a wide range of (endemic) sources of food and nesting material, recreational value, provision of genetic resources through a wide range of sown and spontaneous wild plants) at higher levels than annual crops or perennial monocultures such as miscanthus and cup plant.[71,72,83] There are tradeoffs however in terms of biomass provision and feasibility (WPM still a relatively new cropping system compared to silage maize or miscanthus).[79]	The cultivation of WPM has a proven positive impact on the aesthetic appearance of the landscape.
Indicator	Land-use-change impacts (direct or indirect)	Bird numbers and species	
Potential contribution of the BA	In a study of Lask et al.,[82] it was shown that the replacement of maize by WPM as a biogas substrate leads to a negative indirect land-use change effect because WPM biomass yields are lower than those of maize and need to be compensated for by use of a larger land area.	WPM cultivation areas can provide valuable habitat for openland bird species if certain regulations are implemented (e.g., a minimum cultivation area width of 15 m).[78] In addition, with optimal arrangement of WPM croplands, existing habitats of openland bird species can be interconnected.	

(*Continued*)

Table A4. (Continued)

Public goods of WPM			
	Indicator category		
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes, and species	Ensure attractiveness of rural areas for residence and tourism with balanced social structure
Indicator	Use of agroecological practices (e.g., biological pest control and syntropic agriculture)	Number of insects and other invertebrates such as spiders, earthworms, and centipedes	
Potential contribution of the BA	WPM are grown without the use of pesticides.	Numerous types of food and nesting material provide important habitat for insects and other invertebrates other invertebrates such as spiders, earthworms and centipedes. In addition, the greater diversity of invertebrates in WPM stands could have positive effects on biocontrol of arable crops in adjacent fields.	
Indicator		Pollination	
Potential contribution of the BA		WPM provide various types of nectar and pollen.[77] These are available over a very long period of time and give pollinators (e.g., wild bees) the opportunity not only to survive but also to optimally provide for their offspring during flowerless periods of arable crops.[77] The latter constitute a major problem in modern agriculture, which is why this ecosystem function of WPM is considered to be particularly relevant for the resilience of agricultural systems.	
Indicator		Habitat quality based on common birds	
Potential contribution of the BA		WPM cultivation can provide high-quality habitat for many bird species. Preliminary studies have shown that numerous endangered bird species can thrive in WPM cultivation areas or on their borders (depending on the season and growth height of the WPM).[77]	
Indicator		Use of locally available, native species	
Potential contribution of the BA		WPMs offer a great opportunity to contribute to resilience as the fundamental concept of their cultivation is to use only those plant species that are native and, where appropriate, specific to the region.[68] Indeed, for some species such as common knapweed (*Centaures jacea* L.), there are different accessions according to region. The mixing of these accessions should be avoided.	

Table A5. Potential contribution of grassland to the bioeconomy through provision of private goods, structured by indicator categories adapted from Meuwissen et al.'s "*framework to assess the resilience of farming systems*".[4]

Private goods of grassland				
	Indicator category			
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions
Indicator	Total amount (Mg, dm^3) of major food products	Total amount (Mg, dm^3) of major non-food products and their properties (e.g., energy content, concentrations of valuable components)	Gross margin per hectare (for arable farms), gross margin per livestock unit (for livestock farms)	Number of workers employed on farms and related businesses including contract and part-time workers
Potential contribution of the BA	The main aim of grassland systems is to support animal production of milk and/or meat. Total EU milk production of around 20 million cows: 145 Mm^{-3} per year. Beef production: 6.8 Tg a^{-1} (https://ec.europa.eu/eurostat/de/). In the study of Smit et al.,[96] the relationship between grassland and milk productivity was R=0.57 ($p > 0.001$).	Availability depends on the demand of livestock production and opportunities for effective biomass harvesting through cutting (e.g., difficult on slopes). Potentially relevant components are protein, fiber (cellulose, lignin), energy for biogas or combustion and, in the case of silage, also lactic acid. Quality of grassland biomass depends mainly on cutting time and botanical composition. For example, the protein content can be 8–25% and the biogas yield 80–720 dm^{-3} kg^{-1} organic dry matter.[97]	Depends on the utilization of grassland biomass (e.g., ≈600–800 € per dairy cow).	Grassland with animal husbandry is labor-intensive and therefore the number of workers on grassland farms is relatively high.
Indicator	Yield (Mg ha^{-1}, dm^3 livestock unit^{-1}) of major food products	Yield (Mg ha^{-1}, dm^3 livestock unit^{-1}) of major non-food products	Forced exit rates of farms for economic reasons	Number of farm associations and learning platforms
Potential contribution of the BA	Approximately 4–16 m^{-3} milk ha^{-1}, depending on site conditions. In 2021, the average annual milk production per cow in Germany was ≈8.5 m^{-3}. Under favorable conditions, ruminants can produce up to about 600 kg of meat ha^{-1} a^{-1}, while on marginal areas the grassland biomass is only sufficient for maintenance needs of the animals.	Grassland biomass yields vary greatly depending on location, management intensity and year. On average, ≈6 Mg of dry matter ha^{-1} a^{-1} can be assumed for Europe.	Profitability of grassland farms is strongly dependent on milk and meat prices. This is especially problematic for small farms with high fixed costs. Additional products can improve the economic resilience of farms.	There are specialized grassland advisory organizations in all regions.
Indicator		Potential end uses of biomass and its components	On-farm processing (creation of additional income)	Provision of additional income opportunities
Potential contribution of the BA		Residues can be used for energy, as fertilizer, and for soil improvement.	Grassland biorefinery is at the pilot stage. On-farm plants for protein or fiber extraction are expected.	Novel grassland products (e.g., protein and fiber) can help diversify farm income and reduce dependence on dairy and meat companies for sales revenue.

(*Continued*)

Table A5. (Continued)

Private goods of grassland				
	Indicator category			
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions
Indicator		Supply of regional products	Inclusiveness of smallholder farmers (in terms of access to technology, markets, participation in value-adding activities)	Creation of "green" and sustainable job opportunities and business concepts
Potential contribution of the BA		Grassland biomass is not suitable for transport over long distances and is therefore utilized regionally.	Limited, due to mostly high costs for technology, which requires higher throughput.	More and more non-provisioning ecosystem services are supported by public funding. Grassland thus offers opportunities to combine biomass production with other activities such as landscape management, therefore creating new job opportunities.
Indicator		Substitution of fossil-based resources/products	Non-regional market dependence for sale of products	Better work organization (e.g., reduction of workload, avoidance of peaks)
Potential contribution of the BA		Bioplastics and bioenergy.	High.	Animals need daily care, opportunities for free time and vacations are thus limited.
Indicator		Proportion of biomass usable/convertible through processing	Non-regional market dependence for supply of inputs	
Potential contribution of the BA		1	Medium-low.	
Indicator		Synergies between existing agricultural activities and bioeconomy approach/technology, etc.	Keeping the added value of products on the farm	
Potential contribution of the BA		Grassland biomass no longer needed for livestock or of quality not suitable for feed can be used.	Possible with direct marketing in areas close to cities.	

Table A6. Potential contribution of grassland to the bioeconomy through provision of public goods, structured by indicator categories adapted from Meuwissen et al.'s "*framework to assess the resilience of farming systems*"[4] (GHG = greenhouse gas).

Public goods of grassland				
	Indicator category			
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes, and species	Ensure attractiveness of rural areas for residence and tourism with balanced social structure	Ensure animal health and welfare
Indicator	GHG emission intensity (per ha or per product)	Proportion of ecological focus and protected areas, including forests, set-aside land, national parks	Number of tourists visiting the area per year (excluding big cities)	Use of antibiotics
Potential contribution of the BA	Grassland is generally classified as a GHG sink. However, high fertilization intensity and especially inclusion of animal husbandry can render it a GHG source.	High-nature value (HNV) grassland in Germany: 5.2% of total agricultural area[101] → ≈15% of grassland area	Grassland regions are usually also attractive for tourists.	Only in case of disease (mastitis is common in dairy cows).
Indicator	Water withdrawal by agriculture as % of total withdrawal	Crop diversity, plant diversity	Extent of public access (e.g., footpaths and bridleways)	Percentage of animals free from stress/discomfort (e.g., based on behavioral indicators)
Potential contribution of the BA	European grassland has a high transpiration rate and therefore higher water consumption than arable crops, but lower than forest. Due to the shallower root system, less water is absorbed from deep soil layers.[256,257]	Depending on the location and management, ≈10–70 plant species can be found in grassland.	In pastures in particular, access is restricted by fences.	Grazing promotes animal welfare.
Indicator	Water retention	Bird numbers and species		
Potential contribution of the BA	Permanent grassland has high infiltrability and is therefore of great importance for water retention.	Depends on management and site.		
Indicator	Nutrient surplus	Number of insects and other invertebrates such as spiders, earthworms, and centipedes		
Potential contribution of the BA	Is essentially determined by the livestock stock units per area. Extensively used areas are usually not fertilized and are more likely to be affected by depletion.	Depends on management and site.		
Indicator	Capacity to avoid soil erosion	Habitat quality based on common birds		
Potential contribution of the BA	Year-round ground cover provides effective erosion control.	Grassland birds are affected indirectly by drainage of wetlands and intensification of land use and directly by agricultural activities.		

(*Continued*)

Table A6. (Continued)

Public goods of grassland				
	Indicator category			
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes, and species	Ensure attractiveness of rural areas for residence and tourism with balanced social structure	Ensure animal health and welfare
Indicator	Soil compaction	Use of locally available and native species		
Potential contribution of the BA	Heavy machinery and high livestock stocking rate can cause soil compaction.	Commercial seeds are only used for restoration in agriculturally improved grassland.		
Indicator	Frequency/number of social debates on water/air issues related to agriculture			
Potential contribution of the BA	Methane emissions from ruminants and gaseous ammonia losses from slurry storage and application are often addressed.			
Indicator	Contribution to landscape elements (landscape appearance, habitats and corridors)			
Potential contribution of the BA	Grassland has a significant impact on the landscape and is an important part of recreational landscapes. In particular, grazing is perceived positively as an aspect of animal welfare.			
Indicator	Land use change impacts (direct or indirect)			
Potential contribution of the BA	Grassland conversion is often prohibited to maintain ecosystem functions, especially water quality, soil C and biodiversity.[258]			
Indicator	Water protection (e.g., avoidance of eutrophication)			
Potential contribution of the BA	Low or unfertilized grassland has high potential for water protection. Pastures are less favorable than meadows due to nutrient spots.			

Table A7. Potential contribution of nutrient recycling to the bioeconomy through provision of private goods, structured by indicator categories adapted from Meuwissen et al.'s *"framework to assess the resilience of farming systems"*[4] (AD = anaerobic digestion, BBF = biobased fertilizer, BE = bioenergy, S/L = solid/liquid).

Private goods of nutrient recycling					
	Indicator category				
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions	Improve quality of life in urban areas
Indicator	Yield (Mg ha^{-1}, dm^3 livestock unit^{-1}) of major food products	Yield (Mg ha^{-1}, dm^3 livestock unit^{-1}) of major non-food products	Gross margin per hectare (for arable farms), gross margin per livestock unit (for livestock farms)	Number of workers employed on farms and related businesses including contract and part-time workers	Increased happiness and well-being
Potential contribution of the BA	Fertilization with separated biogas digestates results in yields comparable to those with mineral fertilizer; however, this depends on cropping system and site.[116] In general, fertilization with recycled nutrients aims at the same yields as with mineral fertilizers. Every fertilization approach has to be adapted to site and cropping system.	See "Yield (Mg ha^{-1}, dm^3 livestock unit^{-1}) of major food products".	Ideally same or higher gross margin, when BBF prices are lower than those of mineral fertilizers or when residues are applied as fertilizers.	Residue treatment and BBF production may require additional labor.	Yes, e.g., application of treated manure or BBFs cause less odor emissions. Yes, e.g., when "slurry tourism" is replaced by local treatment facility → less traffic/transport.
Indicator	Real price of food products for consumers	Production of renewable resources/energy in the agricultural system	Proportion of farm income coming from agricultural production (excluding subsidies and direct payments)	Number of farm associations and learning platforms	Contribution to self-sufficiency for raw materials or energy
Potential contribution of the BA	Still limited infrastructure for BBF production, thus more expensive for farmers.[259] Use of BBFs or residues may lead to higher food prices due to increased effort involved in application and uncertain fertilization effect.[260] In 2022, recycled nutrients/BBFs were cheaper than mineral fertilizer.	Subsequent AD of suitable wastes/residues can increase RE production.[117]	Ideally the same or higher.	Residue treatment can also be realized in collaboration with other farms, etc.	More in rural than in urban areas.
Indicator	Increased productivity of agricultural soils (for food production)	Supply of regional products	Forced exit rates of farms for economic reasons	Feeling proud to be a farmer in the region-cultural identity of rural inhabitants	
Potential contribution of the BA	BBFs and organic residues improve humus content, water and nutrient retention capacity of soils.[114,115]	Remains the same. In addition, BBFs can be produced locally.	Closed nutrient cycles can increase the resilience of farms.	Possible.	

(*Continued*)

Table A7. (Continued)

Private goods of nutrient recycling					
	Indicator category				
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions	Improve quality of life in urban areas
Indicator		Shortening of supply chains	On-farm processing (creation of additional income)	Provision of additional income opportunities	
Potential contribution of the BA		Yes, if BBFs are produced and applied locally. Yes, if local BBFs/residues are used instead of (imported) mineral fertilizers.	Possible, e.g., manure or digestate are already available on farms. Farm-based or manure-based biorefineries couple nutrient and energy recovery and have economic benefits for farmers,[120] e.g., AgroEnergie Hohenlohe (Agro Energie Hohenlohe GmbH & Co. KG, Kupferzell, Germany) and many more.	Potential additional income for farmers with nutrient surplus → sale of nutrients/fertilizers; depends on the residue treatment approach. Beyond agriculture, organic residues and recycled nutrients can be used to create products with higher profit margins, i.e., for hobby gardeners.[165]	
Indicator		Substitution of fossil-based resources/products	Level of self-sufficiency for raw materials/energy	Creation of "green" and sustainable job opportunities and business concepts	
Potential contribution of the BA		Recycled nutrients and BBFs can substitute mineral fertilizers whose production is highly energy consuming.[117]	The same or better (e.g., manure and other residues can be a source of both energy and digestates as alternatives to mineral fertilizers[1]).	Production of BBFs may require additional employees from outside the farm; in addition, there are other stakeholders along the whole value chain: technology provider, company to turn output into a product (BBF), sales and marketing of BBF. Development of new business models necessary to render the use of recycled nutrients profitable for the user.[261]	
Indicator		Synergies between existing agricultural activities and bioeconomy approach/technology, etc.	Inclusiveness of smallholder farmers (in terms of access to technology, markets, participation in value-adding activities)	Better work organization (e.g., reduction of workload, avoidance of peaks)	
Potential contribution of the BA		Yes, farm-based approaches available, e.g., AgroEnergie Hohenlohe (Agro Energie Hohenlohe GmbH & Co. KG, Kupferzell, Germany) and many more.	With S/L separation or drying, basic simple treatment approaches are available.[262]	Possible.	

(Continued)

Table A7. (Continued)

Private goods of nutrient recycling					
	Indicator category				
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions	Improve quality of life in urban areas
Indicator			Degree of income diversification	Increased happiness and well-being	
Potential contribution of the BA			Potential additional income for farmers with nutrient surplus → sale of nutrients/fertilizers; depends on the residue treatment approach. Organic residues and recycled nutrients can be used beyond agriculture, for instance by hobby gardeners with high profit margins.[165]	Possible.	
Indicator			Non-regional market dependence for sale of products	Safe health conditions for farmers (in terms of exposure to pesticides, dangerous chemicals, dust, noise, and odors)	
Potential contribution of the BA			Depends on residue treatment and outputs. Example: Recovered phosphorus (P) in transportable form can be sold to regions with P demand.[121]	Possibly improved by using treated residues or BBFs instead of synthetic products or raw manure (odor).	
Indicator			Non-regional market dependence for supply of inputs		
Potential contribution of the BA			Efficient integration of residues in cropping systems reduces dependence on imported fertilizers.[122]		
Indicator			Keeping the added value of products on the farm		
Potential contribution of the BA			Yes, when nutrients/fertilizers etc. are sold.		

Table A8. Potential contribution of nutrient recycling to the bioeconomy through provision of public goods, structured by indicator categories adapted from Meuwissen et al.'s "*framework to assess the resilience of farming systems*"[4] (BBF = biobased fertilizer, GHG = greenhouse gas, K = potassium, N = nitrogen, NUE = nutrient use efficiency, P = phosphorus).

Public goods of nutrient recycling			
	Indicator category		
	Maintain good condition of natural resources	Ensure attractiveness of rural areas for residence and tourism with balanced social structure	Improve efficiency of resource use
Indicator	GHG emission intensity (per ha or per product)	Rate of pluri-active farms	Productive utilization of un- or underutilized areas (urban, industrial, and agricultural)
Potential contribution of the BA	BBFs reduce GHG by an average of 78% for N and 41% for P.[124] High GHG emissions during storage and field application of raw manures[125] can be avoided when the materials are processed into BBFs. Certain production processes carry the risk of uncontrolled NH_3 losses, e.g., composting[126] or drying of digestates.[123] Replacing mineral fertilizers with BBFs reduces the environmental and climate impacts of N synthesis, and the P and K mining required for mineral fertilizer production.[127]	May increase when nutrient recovery/BBF production is applied in a farm-based approach.	Nutrient recycling may indirectly lead to improved use of industrial (BBF production) and agricultural (more targeted fertilization) areas.
Indicator	Water retention	Aesthetic value (cultural ecosystem service)	Land/water/nutrient use efficiency
Potential contribution of the BA	Organic matter application, e.g., in form of digestates, increases water retention capacity of soil, particularly on marginal sites.[115]	May be increased if residues are treated instead of stored → less manure heaps, etc.	Highly improved through efficient nutrient management: Struvite increases P use efficiency as it is a long-term P source and better matches crops' needs.[129] Slow mineralization of N in solid digestates results in lower N losses and thus higher NUE.[128]
Indicator	Nutrient surplus		Circularity - inclusion of options to make material or energy streams circular
Potential contribution of the BA	Nutrient surplus often in regions with high livestock density. Nutrient recycling and residue treatment can help reduce or redistribute the surplus.[121]		Nutrient recycling in agricultural production contributes to closing the loop between urban and rural areas. BBFs play a crucial role in improving circularity of nutrients.[120]

(*Continued*)

Table A8. (Continued)

Public goods of nutrient recycling			
	Indicator category		
	Maintain good condition of natural resources	Ensure attractiveness of rural areas for residence and tourism with balanced social structure	Improve efficiency of resource use
Indicator	Capacity to avoid soil erosion		Improved land use efficiency
Potential contribution of the BA	Increased organic matter (e.g., through solids) in soil decreases soil erosion potential.[263] Improved soil quality is a major driver of the use of organic inputs.[113]		Possible where recycled nutrients perform better than mineral fertilizer; single-nutrient fertilizers may enable more targeted fertilization.
Indicator	Soil compaction		Recycling rates in the production system
Potential contribution of the BA	Improved soil quality is a major driver of the use of organic inputs.[113]		Increased.
Indicator	Frequency/number of social debates on water/air issues related to agriculture		
Potential contribution of the BA	Ideally no longer necessary.		
Indicator	Water protection (e.g., avoidance of eutrophication)		
Potential contribution of the BA	Slow mineralization of N in solid digestates[128] and P in precipitated phosphate salts[129] prevent losses through leaching and run-off; P removal from manures/digestates help to avoid P overfertilization[111]; Recovery of separate nutrients from residues allow more targeted fertilization; Recycling prevents nutrients from being lost and becoming pollutants[264] → contribution to water protection.		
Indicator	Use of agroecological practices (e.g., biological pest control and syntropic agriculture)		
Potential contribution of the BA	Most residues and many BBFs are suitable for organic farming; Land management as in organic farming, e.g., incorporation recommended.		

Table A9. Potential contribution of agrivoltaics (APV) to the bioeconomy through provision of private goods, structured by indicator categories adapted from Meuwissen et al.'s "*framework to assess the resilience of farming systems*".[4]

Private goods of APV				
	Indicator category			
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions
Indicator	Total amount (Mg, dm^3) of major food products	Yield (Mg ha^{-1}, dm^3 livestock unit^{-1}) of major non-food products	Gross margin per hectare (for arable farms), gross margin per livestock unit (for livestock farms)	Number of workers employed on farms and related businesses including contract and part-time workers
Potential contribution of the BA	As 8.3% of the arable area is taken up by the APV plant installations,[133] the total amount of food produce will be reduced by the same amount.	APV plant in Heggelach: 246 MWh energy.[265]	Electricity generation will account for the largest proportion of gross margin per hectare[136] and will increase gross margin per ha compared to single crop production.	May increase, since cultivation of arable land in APV plants (slower working speed) and management of uncultivated areas require more working time.
Indicator	Yield (Mg ha^{-1}, dm^3 livestock unit^{-1}) of major food products	Production of renewable resources/energy in the agricultural system	Forced exit rates of farms for economic reasons	Provision of additional income opportunities
Potential contribution of the BA	Under APV, 10–30% lower yield in temperate regions, but in drought years potentially more stable yields.[135,266] E.g., yields for winter wheat, potato and celeriac were lower under APV in 2017 (average year) (−18.7%, −18.2%, and −18.9%) but higher in 2018 (dry, unfavorable year) (+2.7%, +11.0%, and 11.8%).[133,267]	Additional electricity production, e.g., APV plant in Heggelach: 246 MWh energy.[265]	Depends on ownership of APV plant. If the farmer is (partial) APV owner, less risk of forced exits, since secondary income for the farmer. If the farmer only performs the arable farming and does not profit directly from the APV plant (e.g., land leasing), the risk of forced exits may be higher, if arable farming costs increase (e.g., when APV plant provides only small benefits for crop production).	New job and income opportunities for maintaining APV plant (e.g., cleaning modules).
Indicator	Real price of food products for consumers	Supply of regional products	On-farm processing (creation of additional income)	Creation of "green" and sustainable job opportunities and business concepts
Potential contribution of the BA	Higher costs for crop production under APV as higher time demand (slower working speeds and inefficiencies).	Electricity can be used on farms and contribute to reducing energy poverty in rural areas.	Additional income if farmer is (co-)owner of the PV plant.[136]	New job and income opportunities for maintaining APV plant (e.g., cleaning modules).

(*Continued*)

Table A9. (Continued)

Private goods of APV				
	Indicator category			
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions
Indicator	Increased productivity of agricultural soils (for food production)	Substitution of fossil-based resources/products	Level of self-sufficiency for raw materials/energy	Increased happiness and well-being
Potential contribution of the BA	Potential yield stabilization in drought years and higher yields for crops that benefit from partial shading (e.g., berries) or protection (apple - hail protection).[133]	Substitution of conventional electricity by solar PV. The agrivoltaic system produces 98.5% less emissions and requires 98.7% less fossil energy in comparison to conventional meat (rabbit) and electricity production.[138]	Can decrease energy poverty in rural regions, especially, if APV plant is owned by the community or the farmer.	If farmer profits directly from the APV plant, happiness and well-being may increase. However, in scenarios where the farmer only experiences more difficult land management and only little benefits from the APV plant, there is a risk of decreased satisfaction.
Indicator		Synergies between existing agricultural activities and bioeconomy approach/technology, etc.	Inclusiveness of smallholder farmers (in terms of access to technology, markets, participation in value-adding activities)	Safe health conditions for farmers (in terms of exposure to pesticides, dangerous chemicals, dust, noise, and odors)
Potential contribution of the BA		Local energy supply; crop protection through PV infrastructure, e.g., against hail; potential reduction of drought stress.[133]	Small-scale APV systems including smallholder farmers are possible. However, in Europe, such installations are likely to be relatively large, which may entail the risk of excluding small-scale farmers or rendering only co-ownerships feasible.	Unclear (but low risk) especially in vertical APV systems. Less ventilation may increase risk of exposure to chemicals.
Indicator			Degree of income diversification	
Potential contribution of the BA			High degree, if APV plant is owned by the farmer. Income diversification may also include service provision for APV plants: e.g., mulching/managing the vegetation below the module/on uncultivated areas of the APV plants.[133]	
Indicator			Keeping the added value of products on the farm	
Potential contribution of the BA			Additional value creation only if farmers are directly involved in (profit directly from) the PV plant.[133]	

Table A10. Potential contribution of agrivoltaics (APV) to the bioeconomy through provision of public goods, structured by indicator categories adapted from Meuwissen et al.'s "*framework to assess the resilience of farming systems*"[4] (GWP = global warming potential, GHG = greenhouse gas).

Public goods of APV				
	Indicator category			
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes, and species	Ensure attractiveness of rural areas for residence and tourism with balanced social structure	Improve efficiency of resource use
Indicator	GHG emission intensity (per ha or per product)	Diversity of ecosystem service provision	Net migration	Productive utilisation of un- or underutilized areas (urban, industrial, and agricultural)
Potential contribution of the BA	Compared to the separate production of crops and electricity, the GWP of an APV system is considerably lower.[137] In Germany, the study by Wagner et al.[137] showed that the change from single-use agriculture to a dual-use APV system leads to overall significant environmental benefits, particularly in the categories climate change (40%), freshwater eutrophication (24%), and fossil resource use (23%).[137]	Uncultivated land underneath modules/around the pillars could be used as biodiversity areas, thus contributing to increased plant diversity, and providing additional ecosystem services.[266]	Lower migration risks, due to job creation and lower risk of energy poverty in rural areas.	Potential productive utilisation of underutilized areas, since these could be of high interest for APV systems.
Indicator	Water withdrawal by agriculture as % of total withdrawal	Number of insects and other invertebrates such as spiders, earthworms and centipedes	Number of tourists visiting the area per year (excluding big cities)	Land/water/nutrient use efficiency
Potential contribution of the BA	Reduced water withdrawal (14–29%) through reduced evaporation due to partial shading.[268]	Potentially higher if uncultivated areas offer diverse habitats. An entomological assessment and a vegetation survey of wild herbs showed no significant effect of APV and large variation depending on crop cultivated.[133]	May be negatively affected if APV systems occupy large areas in tourist regions.	Higher water use efficiency and decreased water consumption (14–29%) due to partial shading, especially in arid regions and during drought periods in humid regions.[268] Doubling of renewable-energy land productivity by combining agricultural production with solar energy generation.[134]
Indicator	Water retention	Use of locally available native species	Rate of pluri-active farms	Circularity-inclusion of options to make material or energy streams circular
Potential contribution of the BA	May increase water retention due to uncultivated strips within the arable field.	Potentially more room for native species on uncultivated land under modules/around pillars.	May increase if APV system is part of the farm business model.	Agricultural enterprises could generate electricity on farm to meet their own demand (in future potentially also for battery electric tractors) and thus increase circularity and energy independency.

(*Continued*)

Table A10. (Continued)

Public goods of APV				
	Indicator category			
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes, and species	Ensure attractiveness of rural areas for residence and tourism with balanced social structure	Improve efficiency of resource use
Indicator	Capacity to avoid soil erosion		Extent of public access (e.g., footpaths and bridleways)	Improved land use efficiency
Potential contribution of the BA	May decrease erosion in cases where the uncultivated strips underneath the modules are along slopes. However, increased erosion below run-off from PV modules.[133]		Public access in open landscape may be limited, since APV plants are often fenced to protect modules from theft.	Combined agricultural and electricity production leads to 56–86% improved land use efficiency.[265]
Indicator	Contribution to landscape elements (landscape appearance, habitats, and corridors)		Aesthetic value (cultural ecosystem service)	
Potential contribution of the BA	Uncultivated areas under the modules/around the pillars supporting the APV system can contribute to extensive landscape elements that support biodiversity.		Aesthetic value of landscapes may decrease if APV systems are installed on exponated areas or at high regional densities.	
Indicator	Land use change impacts (direct or indirect)			
Potential contribution of the BA	10–15% of arable land is directly affected by conversion into APV. Additionally, the remaining area may be affected by lower yields due to shading. This may result in lower area yields and could contribute to indirect land use change.			
Indicator	Use of agroecological practices (e.g., biological pest control and syntropic agriculture)			
Potential contribution of the BA	Uncultivated areas under the modules/around the pillars could contribute to an increase in beneficial insects and help reduce pesticide demand.			

Table A11. Potential contribution of urban agriculture to the bioeconomy through provision of private goods, structured by indicator categories adapted from Meuwissen et al.'s "*framework to assess the resilience of farming systems*".[4]

Private goods of urban agriculture					
	Indicator category				
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions	Improve quality of life in urban areas
Indicator	Total amount (Mg, dm^3) of major food products	Total amount (Mg, dm^3) of major non-food products and their properties (e.g., energy content, concentrations of valuable components)	Gross margin per hectare (for arable farms), gross margin per livestock unit (for livestock farms)	Provision of additional income opportunities	Awareness of need for sustainable food production
Potential contribution of the BA	According to the Worldwatch Institute 15–20% of the global food production takes place in urban and peri-urban areas.[44] Urban food production alone accounts for 1-5%.[143]	Oil, starch, fiber and sugar crops play only a minor role in urban agriculture.[152]	Urban community gardening, e.g., in Germany, aims to avoid costs,[46] while urban farming is usually based on a business model where gross margin/profit depends largely on cultivation method, specific crop and location. Economic viability of vertical farming is hardly achievable due to both high fixed and variable costs.[141,148,269]	See below.	Sustainable urban agriculture can become a key concept in the bioeconomy connecting consumers and producers. Food is either produced by the consumers themselves (urban gardening) or by professional producers in cities (vertical indoor farming). Consumers thus learn about seasonality, resource use, and labor requirement in agriculture.[151]
Indicator	Yield (Mg ha^{-1}, dm^3 livestock unit^{-1}) of major food products	Yield (Mg ha^{-1}, dm^3 livestock unit^{-1}) of major non-food products	Proportion of farm income coming from agricultural production (excluding subsidies and direct payments)	Creation of "green" and sustainable job opportunities and business concepts	More sustainable consumer behavior
Potential contribution of the BA	Urban agricultural yields are similar to or higher than conventional agriculture.[152] Vegetables: 4.6 kg m^{-2} cycle^{-1} (compared to conventional 1.90 kg m^{-2} cycle^{-1}); Fruits: 2.20 kg m^{-2} cycle^{-1} (conventional 1.40 kg m^{-2} cycle^{-1}); Cereals: 0.62 kg m^{-2} cycle^{-1} (conventional 0.40 kg m^{-2} cycle^{-1}); Roots and tubers: 3.8 kg m^{-2} cycle^{-1} (conventional 1.3 kg m^{-2} cycle^{-1}); Oil crops: 0.85 kg m^{-2} cycle^{-1} (conventional 0.34 kg m^{-2} cycle^{-1})	Yields in urban agriculture (compared to conventional agriculture): Fiber crops: 0.42 kg m^{-2} cycle^{-1} (conventional: 0.010 kg m^{-2} cycle^{-1}); Sugar crops: 5.30 kg m^{-2} cycle^{-1} (conventional: 6.90 kg m^{-2} cycle^{-1}).[152]	Urban farms often rely entirely on income from production. A few create additional revenues from visitor groups or educational activities.[269] Urban (community) gardens often serve multiple business models including direct marketing, participatory farming,[44] workshops/trainings, (inter-)cultural activities, nutrition and other therapeutic approaches.[46]	Revenues from soilless cultivation, including urban farming, are estimated to increase from ≈$6.9 billion in 2016 to ≈$12 billion by 2025. Investments in vertical farming rose from $60 million in 2015 to $414 million in 2018. Hence, there is great potential for green and sustainable job creation and thus new income opportunities.	Among urban gardeners in Germany, 26% stated to buy more organic food, while 35% and 42% buy more regionally and seasonally produced food, respectively. Even meat and sausage consumption is reduced by ≈10%.[46]

(*Continued*)

Table A11. (Continued)

Private goods of urban agriculture					
	Indicator category				
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions	Improve quality of life in urban areas
Indicator	Real price of food products for consumers	Potential end uses of biomass and its components	Forced exit rates of farms for economic reasons		Increased happiness and well-being
Potential contribution of the BA	To date, vertical farms are hardly economically viable. The high area productivity and resource-use efficiency and offset by high investment, energy and labor costs.[139,141,146] A modern vertical farm with controlled environment conditions are ≈\$15 million, compared to ≈\$2 80 000 for a controlled-environment greenhouse. With ≈\$33 kg^{-1} of vertically grown leafy greens, the price is ≈\$10 higher compared to leafy greens from an organic farm (\$23). Th high energy demand poses another barrier to the sustainability of vertical farm. For example, the energy demand and associated CO_2 emissions of lettuce from a vertical farm are two to five times higher than the same amount of conventionally farmed lettuce.[139,141,146]	Food, feed, fiber, fuel, fun, recreation, ecosystem services (plants as nature-based solutions, especially for green architecture: heat reduction, housing insulation, air quality improvement, biodiversity enhancement, water retention and storage (flood prevention), noise reduction, insulation, public health, recreation and social activities).[44,45,152] New, local biobased value chains for economic activities.[44–46]	The probability of forced exits is very high for vertical indoor farming. Baumont de Oliveira et al.[269] recently assessed the financial risk of vertical indoor farms and found (very) high risks in the categories 'production' (especially failure of environmental control and equipment), 'costs' (high energy, labor and technology cost variability), 'labor' (loss of expertise), and 'planning' (e.g., lease agreements change).[269]		Urban gardening was found to be among the top five leisure-time activities (out of 15) including recreation/leisure, biking and eating out and is thus considered to increase happiness and well-being.[40]
Indicator	Proportion of fruits and vegetables in total production	Production of renewable resources/energy in the agricultural system	On-farm processing (creation of additional income)		Creation of communities for social inclusion
Potential contribution of the BA	Vegetables are the most typical crop types cultivated in urban agriculture. Of minor importance are cereals, fruits, oil crops, roots and tubers, and fiber and sugar crops.[152]	Garden / biomass production activities often combined with renewable energy production. In particular solar energy applications are used in urban agriculture,[46,139,141] whereas biodigestion is sometimes combined with greenhouse and vertical farming (for nutrient recovery and water circulation).[44,141,179]	Some urban (community) gardens process their produce and serve dishes or preserve them for subsequent selling.		Social interaction and intercultural exchange are the two most important reasons for the establishment of urban community gardens in Germany, usually comprising diverse participants and thus supporting the mutual exchange of social values, knowledge, garden practices and lifestyles.[46]

(*Continued*)

Table A11. (Continued)

Private goods of urban agriculture					
	Indicator category				
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions	Improve quality of life in urban areas
Indicator	Increased productivity of agricultural soils (for food production)	Supply of regional products	Level of self-sufficiency for raw materials/energy		Integration of green elements
Potential contribution of the BA	Applies only to circular cultivation systems that recycle nutrients from organic residues and wastes through biodigestion,[141,179] or (vermi-) composting (e.g., terrabioponics,[46]).	Hyper-local production	Circular production systems have a high level of energy self-sufficiency,[179] while urban gardens and, in particular, urban farms rely on urban infrastructure as well as materials and energy.		Urban agriculture is about the integration of various green elements into urban areas including private and community gardens, greening of roofs and facades, greening of vacant areas, urban trees and forests as well as roof-top greenhouses, indoor farms and vertical farms.
Indicator		Shortening of supply chains	Inclusiveness of smallholder farmers (in terms of access to technology, markets, participation in value-adding activities)		Contribution to self-sufficiency for raw materials or energy
Potential contribution of the BA		Very short supply chains through urban production at place of consumption.	In developing countries, urban gardening has always been and still is required for food security. In those areas, it is often smallholder farmers who moved to cities who practice urban gardening.[182]		The European Commission highlights cities as circular bioeconomy hubs, emphasizing the need for re-using the large quantities of organic wastes as feedstock for various biobased products.[180]

(*Continued*)

Table A11. (Continued)

Private goods of urban agriculture					
	Indicator category				
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions	Improve quality of life in urban areas
Indicator		Substitution of fossil-based resources/products	Degree of income diversification		
Potential contribution of the BA		Reduction in biomass transport through local production.	(As above) Urban farms often rely entirely on income from production. A few create additional revenues from visitor groups or educational activities.[269] Urban (community) gardens often serve multiple business models including direct marketing, participatory farming,[44] workshops/trainings, (inter-)cultural activities, nutrition and other therapeutic approaches.[46]		
Indicator		Proportion of biomass usable/convertible through processing	Non-regional market dependence for sale of products		
Potential contribution of the BA		Depends on individual crops.	Very low. Produce is usually sold directly within the city.		
Indicator		Synergies between existing agricultural activities and bioeconomy approach/technology, etc.	Non-regional market dependence for supply of inputs		
Potential contribution of the BA		Urban areas act as bioeconomy hubs for resource circulation.[180] Urban agriculture encourages more sustainable consumer behavior and reduction of food waste.[46]	For urban community gardens, dependence can be considered very low, while high-tech vertical farms depend significantly on non-regional input supply especially for technical automation and control equipment as well as fertilizers.		

Table A12. Potential contribution of urban agriculture to the bioeconomy through provision of public goods, structured by indicator categories adapted from Meuwissen et al.'s "*framework to assess the resilience of farming systems*"[4] (CO_2 eq = carbon dioxide equivalents).

Public goods of urban agriculture				
	Indicator category			
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes, and species	Ensure attractiveness of rural areas for residence and tourism with balanced social structure	Improve efficiency of resource use
Indicator	GHG emission intensity (per ha or per product)	Proportion of ecological focus and protected areas, including forests, set-aside land, and national parks	Net migration	Productive utilization of un- or underutilised areas (urban, industrial, and agricultural)
Potential contribution of the BA	Non-commercial indoor cultivation systems often show higher impacts than commercial ones (0.55 and 0.44 kg CO_2 eq. kg^{-1} crop, respectively), there is large variation depending on the type of cultivation system and cultivated crops. For ground, open-air soil: 0.7 ± 1.1 kg CO_2 eq. kg^{-1} crop; for roof-top, open-air soil: 1.9 ± 2.1 kg CO_2 eq. kg^{-1} crop; for roof-top, open-air hydro 2.1 ± 1.7 kg CO_2 eq. kg^{-1} crop; for indoor hydroponics, ground-based: 3.3 ± 6.8 kg CO_2 eq. kg^{-1} crop; for indoor soil, ground-based: 4.0 ± 8.0 kg CO_2 eq. kg^{-1} crop; for roof-top indoor hydro: 5.9 ± 11.4 kg CO_2 eq. kg^{-1} crop.[270]	Urban gardens increase biodiversity.[44–46,155]	[141]	Urban agriculture focuses on the productive use of un- and underutilised spaces in urban areas, including vacant lots, backyards, facades, roofs, balconies, and buildings.[271]
Indicator	Water retention	Crop diversity, plant diversity	Number of tourists visiting the area per year (excluding big cities)	Land/water/nutrient use efficiency
Potential contribution of the BA	High potential for green roofs and green areas.[45,155] Rainwater retention in Rome is potentially sufficient for 949 garden plots (6 m^2) with vegetables (1 27 671 m^3).[272]	Very high crop diversity in urban gardens ([46,152,153]).	Urban community gardens can become tourist attractions. For example, the Berlin tourism office lists five community gardens as tourist attractions on their website.[273]	Land: see below (land use efficiency). Resource-use efficiency very much depends on the type of production system. The highest resource-use efficiencies can be achieved in indoor and vertical farming: Water-use efficiency: up to 95% less water than conventional agriculture. Nutrient-use efficiency: in soilless cultivation systems typically applied in indoor and vertical farming, the nutrient solution circulates within the system thus saving 55–85% fertilizer[274] and reducing the eutrophication potential of water bodies by 70–90%.[275]

(*Continued*)

Table A12. (Continued)

Public goods of urban agriculture				
	Indicator category			
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes, and species	Ensure attractiveness of rural areas for residence and tourism with balanced social structure	Improve efficiency of resource use
Indicator	Nutrient surplus	Diversity of ecosystem service provision	Percentage of women among farmers, contract workers and part-time workers	Circularity-inclusion of options to make material or energy streams circular
Potential contribution of the BA	Applies only to circular cultivation systems that recycle nutrients from organic residues and wastes through biodigestion ([141,179]), (vermi-)composting (e.g., terrabioponics[46]), or pyrolysis.[270]	Urban gardens, green architecture, urban green areas, and urban trees provide a wide variety of ecosystems services including: heat reduction, housing insulation, air quality improvement, biodiversity enhancement, water retention and storage (flood prevention), noise reduction, insulation, public health, recreation, and social activities.[44,45,152]	In Germany, about two-thirds of urban gardeners are female.[46]	The European Commission (EC) highlights cities as circular bioeconomy hubs, emphasizing the need for re-using the large quantities of organic wastes as feedstock for various biobased products (EC, 2018). Stoknes[179] showed that it is possible to cultivate vegetables on nutrient recovery from organic wastes.
Indicator	Contribution to landscape elements (landscape appearance, habitats, and corridors)	Bird numbers and species	Average age of farmers and part-time workers	Improved land use efficiency
Potential contribution of the BA	Urban gardening creates green hotspots for social and ecologic life.[44–46,155]	65 bird species observed in urban gardens in Tel-Aviv.[276]	Urban gardeners are a very diverse group of people spanning all ages, genders, origins, as well as income and educational levels.[46]	Urban agriculture yields are often expressed in terms of productivity compared to conventional agriculture. For example, Aerofarms (Newark, US) produce nearly 1 Gg of greens annually, claiming to be 390-times more productive than conventional open-field agriculture on a square-meter basis, while using 95% less water and no pesticides[144]; Sky Greens (Singapore) reports to be 10-times more productive than monolayer farming (skygreens.com), producing ≈10% of Singapore's vegetables.[146] A 30-storey vertical farm with a ground area of 5 acres (≈2 ha) could supply food for up to 10 000 people.[147] German Aerospace Centre estimated that a 1936 m^2 (44 m x 44 m) vertical farm with 37 floors (167.5 m height) has the potential to produce as much food as 216 ha of agricultural land.[148] Considering the global average cropland footprint of 2000 m^2 (0.2 ha) per person and year,[149] this exemplary vertical farm could roughly supply food for 1080 people annually - on the cropland footprint of one person.

(Continued)

Table A12. (Continued)

Public goods of urban agriculture				
	Indicator category			
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes, and species	Ensure attractiveness of rural areas for residence and tourism with balanced social structure	Improve efficiency of resource use
Indicator	Land use change impacts (direct or indirect)	Number of insects and other invertebrates such as spiders, earthworms, and centipedes	Extent of public access (e.g., footpaths and bridleways)	Recycling rates in the production system
Potential contribution of the BA	Urban food production can reduce pressure on agricultural lands[44,45]; Potential to unseal urban spaces.	Urban gardens attract various species of bees (especially, honeybees and bumblebees),[153] ladybirds,[277] butterflies, and predatory wasps.[278]	Urban gardens are typically public places. Urban farms can sometimes be visited.	Circular food production systems (e.g., terrabioponics) can rely entirely on nutrients recycled from organic household wastes.[46,141,179]
Indicator	Water protection (e.g., avoidance of eutrophication)	Pollination	Aesthetic value (cultural ecosystem service)	
Potential contribution of the BA	No negative effects on water bodies, when recirculating hydroponic cultivation systems are used (vertical indoor farming). Soil-based cultivation (home/community gardens) can lead to eutrophication depending on cultivation and management practices, e.g., overuse of fertilizers/pesticides.	Urban gardens increase pollinator abundance, with bees and bumblebees the dominant species in urban gardens.[153]	Urban community have a very high aesthetic value for urban environments. The BMBF project 'Gartenleistungen' made a holistic assessment of the values provided by several urban community gardens in Germany. The first urban community garden 'Inselgrün' (600 m^2) in Stuttgart has a cultural value (recreation, social meeting point) of 2 80 000 €, while the garden project 'Himmelbeet' (1700 m^2) in Berlin provides a value of 1.5 million € for its neighbors and citizens (Gartenleistungen 2022).	

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Table A12. (Continued)

Public goods of urban agriculture				
	Indicator category			
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes, and species	Ensure attractiveness of rural areas for residence and tourism with balanced social structure	Improve efficiency of resource use
Indicator	Use of agroecological practices (e.g., biological pest control and syntropic agriculture)	Habitat quality based on common birds		
Potential contribution of the BA	Urban gardeners in Germany favor soil-based cultivation with organic practices.[46] Biological pest control is suitable for (roof-top) greenhouse and indoor cultivation. Indoor farming with controlled environments works completely without pesticide use. Urban farming is typically monoculture cropping. Agroecological practices (e.g., mixed cropping) are often applied in urban (community) gardens.	Bird species richness depends on abundance of shrubs and bushes in or surrounding urban gardens.[276]		
Indicator		Use of locally available, native species		
Potential contribution of the BA		In Germany, the consumption of native fruit and vegetable varieties has increased by 25% since people have started to garden.[46] In total, 707 different plant species were observed in urban gardens in Los Angeles.[154]		

Table A13. Potential contribution of phototrophic cultivation of microalgae to the bioeconomy through provision of public goods, structured by indicator categories adapted from Meuwissen et al.'s "*framework to assess the resilience of farming systems*"[4] (FAO = Food and Agriculture Organization of the United Nations, DW = dry weight).

Private goods of phototrophic cultivation of microalgae					
	Indicator category				
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions	Improve quality of life in urban areas
Indicator	Total amount (Mg, dm^3) of major food products	Total amount (Mg, dm^3) of major non-food products and their properties (e.g., energy content, concentrations of valuable components)	Gross margin per hectare (for arable farms), gross margin per livestock unit (for livestock farms)	Number of workers employed on farms and related businesses including contract and part-time workers	Awareness of need for sustainable food production
Potential contribution of the BA	Since 1999, the global production volume of microalgae has increased from 1 Gg DW to 9 Gg DW, representing an estimated € 2.4 billion production value in 2011 with an expected annual growth rate of 10%. In comparison to the traditional agricultural industry, large-scale microalgae cultivation is still in its infancy.[279] It is estimated that ≈20–25% of the current world microalgae production and over 50% of the current world production of *Arthrospira* is sold for animal feed applications.[280,281] About 75% of the global microalgae production was used in the health food market as dietary supplements.[279] Official statistics on microalgae production volumes are virtually non-existent at European scale and data available from FAO or Eurostat are limited and fragmented. Some data have been collected on production volumes at European scale showing an approximate production of 182 Mg DW of microalgae and 142 Mg DW of cyanobacteria. *Chlorella* spp. and *Haematococcus pluvialis* are the microalgae most produced in terms of volumes, corresponding to more than 80% of the total values reported in the study of Araújo et al.[161]	See "Total amount (Mg, dm^3) of major food products".	Currently not ascertainable, as technology and markets are not mature and very diverse. Products are currently not competitive with established products such as high-protein feeds or high-fat foods (especially long-chain unsaturated fatty acids) due to high investment and production costs.	Depends on the cultivation system and the degree of automation. Here, it was calculated with approximately six employees per ha plant (depending on the daily amount of biomass harvested).	Yes. That is one important argument for the cultivation of microalgae. However, this goal cannot be achieved due to the high energy demand, especially of the photobioreactors, depending on the definition of sustainability.

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Table A13. (Continued)

Private goods of phototrophic cultivation of microalgae					
	Indicator category				
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions	Improve quality of life in urban areas
Indicator	Yield (Mg ha^{-1}, dm^3 livestock $unit^{-1}$) of major food products	Yield (Mg ha^{-1}, dm^3 livestock $unit^{-1}$) of major non-food products	On-farm processing (creation of additional income)	Number of farm associations and learning platforms	More sustainable consumer behavior
Potential contribution of the BA	Open raceway ponds: Ø 39 Mg DW ha^{-1} a^{-1}; Vertical tubular photobioreactor: Ø 70 Mg DW ha^{-1} a^{-1}; Flat-panel photobioreactor: Ø 87 Mg DW ha^{-1} a^{-1}.	Open raceway ponds: Ø 39 Mg DW ha^{-1} a^{-1} Vertical tubular photobioreactor: Ø 70 Mg DW ha^{-1} a^{-1} Flat panel photobioreactor: Ø 87 Mg DW ha^{-1} a^{-1}.	Yes. Surveys in the FuTuReS project revealed a willingness to establish cooperatives for community investment. This does not require fertile land. Enclosed spaces, such as vacant stables or basements, can be used (with artificial lighting) or cultivation facilities can be built in greenhouses. One example in Germany is the Deutsche Algen Genossenschaft eG (https://www.deutsche-algen.de/).	Training and further education opportunities on the topic of microalgae at Algenfarm Klötze GmbH & Co. KG (https://www.algomed.de/erlebnispfa algen/). Cooperatives: Deutsche Algen Genossenschaft eG (https://www.deutsche-algen.de/).	Acceptance of microalgae by consumers may be limited due to lack of process-related information. "*Educating consumers on the ecological benefits of microalgae cultivation, together with an increased presence of microalgae cultivation technologies in the media, could increase the impact of the environmental benefits on the evaluation of microalgae's future potential, especially in light of the climate change debate.*".[282]
Indicator	Real price of food products for consumers	Potential end uses of biomass and its components	Level of self-sufficiency for raw materials / energy	Provision of additional income opportunities	Creation of communities for social inclusion
Potential contribution of the BA	Market prices for products based on *Chlorella* sp. and *Arthrospira* vary between 25–50 € kg^{-1} DW and 30–70 € kg^{-1} DW.[161]	Microalgae production currently on the market tend to be in the "low-volume, high-value" category, such as extracts for use as cosmetic, food supplements and additives. Products such as biofuel, food, or feed tend to be allocated in the "high-volume, low-value" category. Due to high investment and production costs, the production of microalgae for such applications is not economically sustainable and microalgae-derived products are thus not competitive with established products on the market.[159]	With nutrient recovery (N, P) from biogas fermentation, use of waste gases from methane combustion (no purification steps required), electricity and water connection, cultivation, and processing of microalgae biomass is possible on any farm.	Currently only with high-value products.	There are different blogs and recipe sites that deal with the processing of microalgae in the daily diet (for example https://www.pureraw.de/News).

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Table A13. (Continued)

Private goods of phototrophic cultivation of microalgae					
	Indicator category				
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions	Improve quality of life in urban areas
Indicator	Increased productivity of agricultural soils (for food production)	Supply of regional products	Inclusiveness of smallholder farmers (in terms of access to technology, markets, participation in value-adding activities)	Creation of “green” and sustainable job opportunities and business concepts	Integration of green elements
Potential contribution of the BA	Microalgae biomass can enhance soil structure and water retention. Furthermore, microalgae-based biomass can be used as biofertilizer. They can improve nutrient supply or availability for plants through, among other things, nitrogen (N_2)-fixation and P-solubilization in the soil.[283]	Cultivation of microalgae in photobioreactors can be performed anywhere with access to energy, water, nutrients and CO_2.[159]	Possible through the formation of cooperatives (Deutsche Algen Genossenschaft eG, https://www.deutsche-algen.de/).	Hiring biologists or process engineers is desirable but not necessary with appropriate training of farmers.	Renewable energy, recirculation of nutrient-rich waste streams from biogas plants.
Indicator		Substitution of fossil-based resources/products	Degree of income diversification		Contribution to self-sufficiency for raw materials or energy
Potential contribution of the BA		Research into the use of microalgae-based biofuels and biopolymers has been ongoing for decades. Due to the advantage of avoiding agricultural land, the production of microalgal biomass does not compete with the cultivation of food and feed. However, current production costs for low-value, high-volume microalgae-based extracts are too high to compete with established products on the market.[161]	Depends on the degree of biomass utilization. In the case of cascaded extraction of different products (proteins, dietary fiber, lipids, and pigments) using mild extraction methods with low losses, the degree of diversification is high. In the case of extraction of one product only (e.g., lipids) it is relatively low.		Production of protein-rich feed or biofuels are possible, but economically unsustainable.

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Table A13. (Continued)

Private goods of phototrophic cultivation of microalgae					
	Indicator category				
	Deliver healthy and affordable food products	Deliver other biobased resources for the processing sector	Ensure a reasonable livelihood for people involved in agricultural production	Improve quality of life in farming areas by providing employment and decent working conditions	Improve quality of life in urban areas
Indicator		Proportion of biomass usable/convertible through processing	Non-regional market dependence for sale of products		
Potential contribution of the BA		Through the potential fermentation of residues after the best possible extraction of all products (biorefinery), up to 100% of the biomass can be used. However, the potential cannot be fully exploited due to the extraction methods currently applied and the focus on high-value products, whose total share of the biomass is in the low double-digit percentage range.	No dependence if the extracts (proteins, lipids) are used to a high degree where produced. Dependencies exist when selling high-value extracts such as pigments for the pharmaceutical and cosmetics industries.		
Indicator		Synergies between existing agricultural activities and bioeconomy approach/technology, etc.	Non-regional market dependence for supply of inputs		
Potential contribution of the BA		Fermentation of microalgae-based biomass in biogas plants -> use of renewable energy from biogas combustion and recirculation of nutrients -> use of purified exhaust gases for cultivation.[159]	Since special minerals (e.g., iron citrates) are required in small annual quantities, non-regional input supply dependency exists.		
Indicator			Keeping the added value of products on the farm		
Potential contribution of the BA			Yes.		

Table A14. Potential contribution of phototrophic cultivation of microalgae to the bioeconomy through provision of private goods, structured by indicator categories adapted from Meuwissen et al.'s "*framework to assess the resilience of farming systems*"[4] (CO_2 eq = carbon dioxide equivalents, DW = dry weight).

Public goods of phototrophic cultivation of microalgae				
	Indicator category			
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes and species	Ensure attractiveness of rural areas for residence and tourism with balanced social structure	Improve efficiency of resource use
Indicator	GHG emission intensity (per ha or per product)	Diversity of ecosystem service provision	Percentage of women among farmers, contract workers and part-time workers	Productive utilization of un- or underutilized areas (urban, industrial, and agricultural)
Potential contribution of the BA	Open raceway ponds: Ø 2.59 kg CO_2 eq kg DW^{-1}; Vertical tubular photobioreactor: Ø 2.04 kg CO_2 eq kg DW^{-1}; Flat-panel photobioreactor: Ø 2.93 kg CO_2 eq kg DW^{-1}; Flat-panel photobioreactor (with artificial light): ≈82 kg CO_2 eq kg DW^{-1}; Flat-panel photobioreactor (with sun light): ≈62 kg CO_2 eq kg DW^{-1}.	Water treatment, CO_2 sequestration, and nutrient recycling.[159]	Based on the results of European Commission,[284] 81% of the jobs within the industry are full-time. The percentage of women in the algae sector (microalgae and macroalgae) = 38%.	Possible and recommended.
Indicator	Water withdrawal by agriculture as % of total withdrawal		Average age of farmers and part-time workers	Land/water/nutrient use efficiency
Potential contribution of the BA	No knowledge. High potential for water recycling.		Based on the results of European Commission,[284] 55% of the people working in micro- and macroalgae industry are younger than 41.	The water and land demand/yield ratio of microalgae cultivation is significantly lower than for traditional agricultural crops.[285] The nitrogen demand of microalgae cultures does not differ significantly from that of meat or soy production in relation to the protein content of the biomass. While high-value plant nitrogen sources such as soy and fish meal are predominantly used to feed animals, lower-value nutrient sources such as ammonium, nitrate, nitrite and urea can be used in the production of plant proteins. These can be obtained from wastewater streams (e.g., liquid manure or digestate), among other sources. The consumption of phosphorus in microalgae cultivation is almost twice as high as in conventional protein sources, with the exception of fish farming in aquacultures. The amount of DNA in microalgae is higher than in other plant or animal cells due to their compactness. Consequently, there is a higher demand for phosphorus during cell division. This is a major disadvantage of microalgae cultivation due to scarce phosphorus resources. However, the recovery of phosphates from wastewater and digestate is also possible in microalgae cultivation. The use of heavy metal phosphate salts (some of which are radioactive) should generally be avoided due to the chelating properties (uptake and accumulation of heavy metals) of microalgae. The use of wastewater for nutrient supply has already been described in the literature and included in life cycle assessment (LCA) studies as a way to reduce costs and improve sustainability.[286,287] However, its use is questionable when applied to food and feed production. Reasons include increased contamination risks and the lack of a regulatory framework to date.[287]

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Table A14. (Continued)

Public goods of phototrophic cultivation of microalgae				
	Indicator category			
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes and species	Ensure attractiveness of rural areas for residence and tourism with balanced social structure	Improve efficiency of resource use
Indicator	Water retention		Extent of public access (e.g., footpaths and bridleways)	Circularity-inclusion of options to make material or energy streams circular
Potential contribution of the BA	High, due to closed systems and recycling. However, the water footprint when not recycled (in which case the water normally enters the wastewater system) is: Open raceway ponds: Ø 1.36 m^3 kg DW^{-1}; Vertical tubular photobioreactor: Ø 0.57 m^3 kg DW^{-1}; Flat-panel photobioreactor: Ø 0.10 m^3 kg DW^{-1}; Flat-panel photobioreactor (with artificial light): ≈0.14 m^3 kg DW^{-1}; Flat panel photobioreactor (with sun light): ≈0.18 m^3 kg DW^{-1}.		Training and further education opportunities on the topic of microalgae at Algenfarm Klötze GmbH & Co. KG (https://www.algomed.de algen/).	Possible recirculation of nutrient-rich (N,P) waste streams from biogas plants, recirculation of medium after dewatering of microalgae biomass (within the process).
Indicator	Nutrient surplus		Broadband coverage	Improved land use efficiency
Potential contribution of the BA	No nutrient surplus due to closed systems and controlled cultivation conditions.		Depends on the degree of automation of the plant. However, when using CO_2, permanent control of the ambient air of the plants is necessary to protect employees. Therefore, broadband coverage is necessary for remote monitoring and possibly remote control.	Depends on the product. The cultivation of microlayers requires significantly less land compared to conventional protein from animal sources. For example, soybean cultivation requires ten to twenty times the area of microalgae. In addition, cultivation of microalgae does not require arable land (more important are connected infrastructures for CO_2, energy and water supply).
Indicator	Capacity to avoid soil erosion		Aesthetic value (cultural ecosystem service)	Recycling rates in the production system
Potential contribution of the BA	High. No agricultural land required.		When establishing facilities in greenhouses, the discussion on building greenhouses in rural areas should be considered (similar to the cultivation of fruits and vegetables). When establishing inside existing buildings (basements, disused animal sheds) or on roofs, there is no impact on the landscape.	See "land/water/nutrient use efficiency" indicator.

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Table A14. (Continued)

Public goods of phototrophic cultivation of microalgae				
	Indicator category			
	Maintain good condition of natural resources	Protect biodiversity of habitats, genes and species	Ensure attractiveness of rural areas for residence and tourism with balanced social structure	Improve efficiency of resource use
Indicator	Soil compaction			
Potential contribution of the BA	Low to zero. No agricultural land required.			
Indicator	Contribution to landscape elements (landscape appearance, habitats, and corridors)			
Potential contribution of the BA	See “Aesthetic value” indicator.			
Indicator	Land use change impacts (direct or indirect)			
Potential contribution of the BA	Microalgae can be grown on marginal land and therefore offers an important and sustainable advantage in terms of food or feed production compared to established agriculture that requires agricultural land.[285,288] However, there are still many uncertainties regarding the actual emissions and the impact on land use change of industrial plants, among others.[289]			
Indicator	Water protection (e.g., avoidance of eutrophication)			
Potential contribution of the BA	By using microalgae whose biomass is further processed in terms of energy use, energy consumption and greenhouse gas emissions can be reduced in the bioremediation process. Furthermore, the oxygen produced by photosynthesis can increase the effectiveness of aerobic fermentation processes.[159]			
Indicator	Use of agroecological practices (e.g., biological pest control, syntropic agriculture)			
Potential contribution of the BA	The use of microalgae to reduce the negative impact of pesticides on the environment is the focus of research and is already considered a very suitable and promising technique for the future.[290]			

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

I.L. performed conceptualization (lead), investigation (equal), supervision (lead); writing – original draft (lead), and writing – review and editing (lead). M.v.C. performed conceptualization (supporting), methodology (supporting), resources (supporting), visualization (lead), writing – original draft (supporting), and writing– review and editing (equal). B.W. performed visualization (equal) and writing – review and editing (equal). A.B. performed visualization (equal) and writing – review and editing (equal). N.G. performed writing – review and editing (equal). A.K. performed writing – review and editing (equal). E.L. performed conceptualization (supporting) and writing – review and editing (equal). E.M. performed visualization (equal) and writing – review and editing (equal). N.A.M.V. performed methodology (equal) and writing – review and editing (equal). B.M. performed visualization (equal) and writing – review and editing (equal). V.S. performed conceptualization (equal) and writing – review and editing (equal). U.T. performed visualization (equal) and writing – review and editing (equal). M.T. performed visualization (supporting) and writing – review and editing (equal). R.V.-C. performed writing – review and editing (equal). S.W. performed visualization (equal) and writing – review and editing (equal). J.W. performed conceptualization (equal) and writing – review and editing (equal). E.R. performed methodology (equal), visualization (equal), and writing – review and editing (equal). All authors have read and approved the final manuscript.

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agricultural systems, bioeconomy, diversification, ecosystem services, private goods, public goods, resilience

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Evelyn Reinmuth works as a researcher at the department Biobased Resources in the Bioeconomy at the University of Hohenheim on integrated system modeling of bioeconomy approaches to approach the transition toward a sustainable circular bioeconomy. She is particularly interested in understanding how to obtain a high-quality biobased intermediates from agri-food side-streams for various industrial processes, given "food first". All modeling approaches will yield the identification of sustainable implementation strategies of deep tech innovations, skill-development needs, and partially also policy recommendations for existing frameworks.