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Monetizing ecosystem services of perennial wild plant mixtures for bioenergy

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ABSTRACT

The transition to a sustainable biobased economy promises to free the economy from its dependence on finite fossil resources by replacing them with biomass derived primarily from agricultural production. However, this often threatens the ecosystem services on which its very existence depends, such as climate regulation, erosion mitigation, and biodiversity conservation. A major challenge is that biomass provision is usually the only ecosystem service directly priced in markets. While there are several studies estimating the monetary value of a wider range of ecosystem services for common food and biomass crops, there is limited information for novel bioenergy cropping systems such as perennial wild plant mixtures (WPM). Therefore, this study assesses the monetary value of key ecosystem services of WPM, i.e. nursery services, recreational value, moderation of extreme events, climate regulation, nutrient cycling, erosion prevention, and the provision of biomass. In addition, three contrasting land use scenarios; parking lot, silage maize (*Zea mays* L.) cultivation for biogas production; and pristine forest; were used for comparison. While parking lot (0.15 €/ha*yr.) and pristine forest (1691.57 €/ha*yr.) yielded the minimum and maximum values, WPM cultivation (624.82 €/ha*yr.) performed surprisingly well compared to silage maize (653.61 €/ha*yr.). Thus, monetization of ecosystem services other than biomass provision made silage maize and WPM cultivation economically comparable by almost fully compensating for the lower biomass provision of WPM. Consequently, using such information to better reward farmers for more social-ecologically sound bioenergy cropping systems could help policymakers improve agricultural sustainability in the long run.

1. Introduction

According to the IPCC special report on global warming of 1.5 °C (IPCC, 2018), both electricity (e.g. solar-based) and biofuels (e.g. agricultural-based) are important drivers of transportation decarbonization. Overall, agricultural production must increase to satisfy the increasing demands of food, feed, fiber, and fuel for the growing global population, changing diets and the transformation towards a sustainable bioeconomy (Calicioglu et al., 2019; Fritsche et al., 2020; Galanakis et al., 2022; Tripathi et al., 2019). At the same time the expansion of agricultural areas should be avoided as land-use is one major driver of climate change and ecosystem vulnerability (Pörtner et al., 2022). This food-energy-environment trilemma is projected to worsen as more biomass is required for biofuels, which can comprise solid, liquid, or gaseous biomass fuels (Araújo et al., 2017; Tilman et al., 2009). Therefore, if dedicated biomass crops are used as biofuel feedstock, they must have a high yield potential as well as extra environmental advantages (Carlsson et al., 2017; Gelfand et al., 2013; Mishra et al., 2019; Valentine et al., 2012). Consequently, a variety of economic, environmental, and social factors must be addressed and met for increasing the social-ecological sustainably of biomass-based value webs (Panoutsou et al., 2022; Vargas-Carpintero et al., 2022; Von Cossel et al., 2020; Wagner et al., 2022, 2019).

Intercropping or mixed cropping systems are widely considered as a viable means of addressing the these challenges (Altieri et al., 2017; Robinson and Sutherland, 2002; Tilman et al., 2014; Weißhuhn et al., 2017). This is because species mixtures can create more diversified and robust agricultural production systems by utilizing a larger genetic basis

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(Altieri et al., 2017; Sanderson et al., 2007; Weigelt et al., 2009). For example, this is true for wildflower strips in silage maize cultivation, whereby both the technical feasibility (von Redwitz et al., 2019) and the true environmental costs (Wagner et al., 2022) must be carefully considered depending on the farm. In addition, it also matters whether the cropping systems are annual or perennial. According to Weißhuhn et al. (2017), perennial mixed cropping systems (or "polycultures") are the ones that significantly help to improve the sustainability of agricultural systems, in particular by providing more supporting ecosystem services (ES) than annual cropping systems while also providing biomass (Weißhuhn et al., 2017). This results in beneficial land use changes (bLUC) through the optimization of the multifunctionality of the agricultural production system (Englund et al., 2020). Novel perennial mixed cropping systems that meet this profile are, for example, perennial wild plant mixtures (WPM) for biogas production (Krimmer et al., 2021; Paltrinieri and Schmidt, 2020; Schmidt et al., 2018; Vollrath et al., 2012; Von Cossel, 2020; von Cossel and Lewandowski, 2016). The WPM comprise more than 25 annual, biennial, and perennial mostly wild plant species for the generation of bioenergy and several environmental and social benefits such as biodiversity support and landscape beauty (Vollrath et al., 2016, 2012). However, the economic performance is also relevant, and WPM cultivation for bioenergy purposes is notably less profitable than silage maize when only biomass yield level, biomass yield stability and biomass quality are considered (Baum, 2019; Friedrichs, 2013; Von Cossel, 2020). Consequently, not only the provisioning services but also the regulating, habitat and cultural services of bioenergy cropping systems such as WPM should be considered to achieve a more holistic sustainable agriculture, otherwise potential bLUC effects may be overlooked.

In this regard, the concept of ES has gained scientific traction in recent years (Costanza et al., 2017; Potschin and Haines-Young, 2016). A special emphasis has been placed on provisioning ES, primarily in managed ecosystems but also, to a lesser extent, in unmanaged ecosystems (Potschin et al., 2016) because these ES are at the core of direct human interest and activity, namely ensuring nutrition and material supply (Bethwell et al., 2021). Further, the notion of ES has been regarded as useful for assisting policy- and decision-making that promotes sustainability, from boosting stakeholder knowledge to changing decisions (Geneletti et al., 2018) while also contributing to sustainability, i.e. increasing human well-being while also conserving biodiversity and nature (Fang et al., 2018; Robert et al., 2005).

Analyzing tradeoffs and synergies between ES is critical due to time-, scale-, and land use-depending interactions (Le Provost et al., 2022; Li et al., 2017). However, it has a promising field of application in agriculture as a method for ensuring the delivery of various benefits from ecosystems and landscapes to society (Crossman and Bryan, 2009; Geneletti et al., 2018; Mastrangelo et al., 2014; Von Cossel et al., 2020). Nonetheless, farms are primarily compensated through the sale of agricultural goods (provisioning service: providing biomass yield, stability, and quality). Other ES, such as regulating services or environmental costs, either remain unpaid (Von Cossel et al., 2020; Wagner et al., 2022) or require specific contracts obligating farmers to perform the respective services (Ezzine-de-Blas et al., 2016). Sherrington et al. (2008) recommended subsidies as an effective approach to assist perennial crop market growth in order to motivate farmers to cultivate diverse cropping mixtures and enhance economic performance (Sherrington et al., 2008). In contrast, many other studies see little fundamental point in such voluntary agri-environment-climate measures because they have limited impact despite being widely used (Bredemeier et al., 2022). Instead eco-labeling was proposed to increase consumers' understanding and thus lead to a sustainable change in buying behavior (Morone et al., 2021). In some states in Germany, WPM cultivation is subsidized at a flat rate of 250–500 €/ha*yr.

To develop such labels and support programs, it is important to express the value of ES in monetary units to raise awareness and convey to policymakers the importance of ecosystems and biodiversity (de Groot et al., 2012). Information on monetary values allows for more effective use of limited money by determining where protection and restoration make most sense from an economic perspective and where they can be achieved at the lowest cost (Crossman and Bryan, 2009). It can also help determine how much compensation should be given for the loss of ES in liability regimes (Morone et al., 2021; Payne and Sand, 2011). However, most valuation approaches focus on ES of biomes at global scale (Costanza et al., 1997; de Groot et al., 2022; de Groot et al., 2012) or ES of common crops and land use types at field scale (Geneletti et al., 2018; Von Cossel et al., 2020). Therefore, this study assesses the monetary value of ES of WPM at field scale based on a schematic case study located in southwest Germany. This is aimed at exploring the importance and benefits of monetizing all ES of a novel bioenergy cropping system such as WPM instead of only accounting for the provision of biomass for bioenergy purposes. The first part of this study sets the criteria required for approaches to more holistically describe and account for the wide variety of ES that are provided by WPM. In the second part, a schematic case study is used in a first attempt to examine how the monetary value of the main ES provided by WPM compares to other contrasting land use scenarios: silage maize (*Zea mays* L.) cultivation for bioenergy generation; a parking lot; and a pristine forest.

2. Material and methods

2.1. Design of a schematic case study

A schematic case study was conducted to evaluate the monetary value of WPM ES and compare it with three scenarios (all within southwest Germany) within one vegetation period: a pristine temperate forest; a field with maize cultivation; and a parking lot with a sealed asphalt surface (Fig. 1). The scenario of a pristine temperate forest was chosen to have a reference ecosystem with a close to ideal provision of ES (except for the low provision of food or materials) on the normalized scales of 1 to 10 for every assessed ES. In contrast the parking lot with a sealed asphalt surface represents a human-made land use form with no apparent provision of ES.

2.2. Literature review

To summarize existing methods for quantifying ES in bioenergy cropping systems such as WPM and assessing their benefits and limitations, a literature review was carried out with Scopus using the Boolean operator "AND" between the search terms (Table 1) in July 2021. The searches were conducted within article title, abstract and keywords. The emphasis of the research was on agroecosystems and how to operationalize ES. The search term "monetization" was deliberately chosen to exclude those documents that used a different, non-monetary indicator to evaluate the ES. The references included in the reference lists of the documents found were also taken into account. The identified methods were divided into economic, socio-cultural and biophysical methods.

2.3. Visualization of monetization results

The monetization methods for indicator-based valuations (e.g. the biophysical, economic and socio-cultural valuation methods) of the different land use scenarios are described in the respective method description in the supplemental material (S1-S4). Subsequently to the assessment and monetization of the ES, the results of different land use scenarios were normalized on a scale from 1 to 10 to be easily comparable (in each category the highest value is set equal to 10, and all other values are given in relation to it). With these normalized scales flower diagrams for each cropping system were generated to illustrate the provided ES in a compact and clear form that makes the results easy to compare.

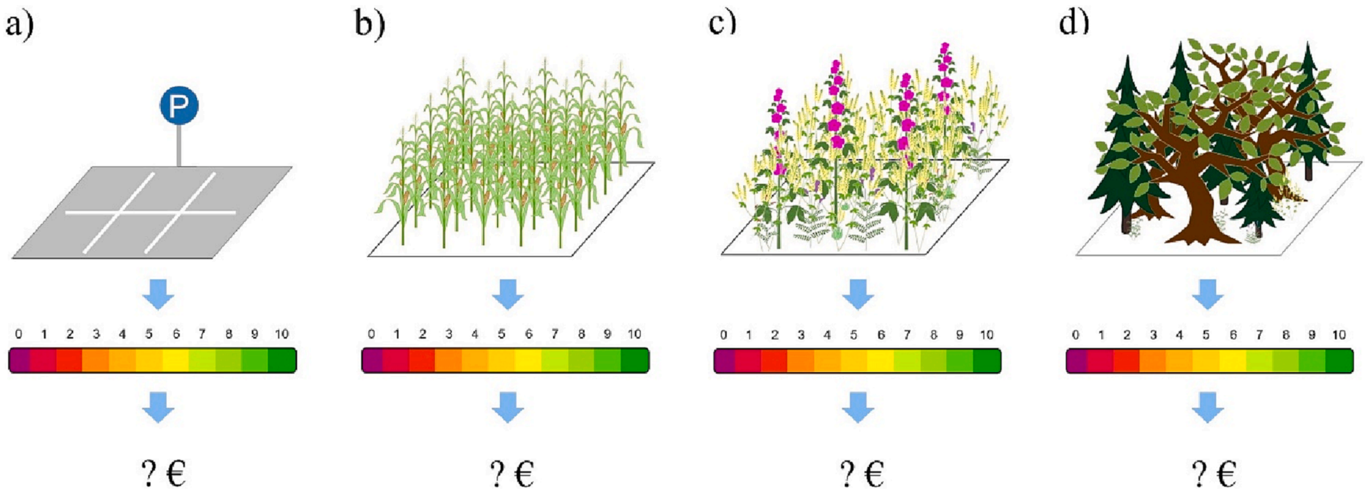

Fig. 1. Schematic overview of the valuation procedure developed for the exemplary schematic case study in southwest Germany. In the top row, the four scenarios are represented schematically in the following sequence from left to right: a) parking lot, b) silage maize (*Zea mays* L.), c) wild plant mixture, and d) pristine temperate forest. These four scenarios are then evaluated and assigned a normalized value on a scale reaching from 1 to 10, symbolized by the colored scale in the middle row. In the last step, the value reached on the scale is transformed into a monetary value.

Table 1
Search engines and keywords used for the literature review and the respective result numbers per keyword and search engine.

Key words	Scopus	Google Scholar
Ecosystem monetization	145	23,900
Ecosystem services categorization	84	52,400
Biodiversity monetization	29	10,300
Ecosystem service monetization methods	22	23,500
Ecosystem service monetization concepts	19	21,800
Economic ecosystem services monetization methods	13	23,200
Ecosystem service monetization methods scale	6	22,300
Socio-cultural ecosystem service monetization methods	1	5,090
Ecosystem service monetization methods field	1	22,300
Ecosystem service monetization methods field scale	1	20,300
Biophysical ecosystem service monetization methods	0	5,030
Ecosystem service monetization methods agriculture	0	19,400

3. Results and discussion

3.1. Principles for monetizing ecosystem services of the land use scenarios in the schematic case study

The assessment and subsequent monetization of ES of different cropping systems at field scale is a challenge due to the variety and complexity of ES. A suitable concept should assess the ES as precisely as possible, as comparably as possible and in a site-contextualized way, all while being easy to apply. During this research it became evident that first and foremost farmers need to be encouraged to take part in a monetary remuneration system for providing ES and possibly implement novel bioenergy cropping systems such as WPM that provide a variety of ES. In this sense, the evaluation method used here should contribute to a more holistic reward system for environmentally and biodiversity friendly agricultural practices. In Germany, current rewarding systems (subsidies) are associated with an overload of bureaucracy, ecologically and economically ineffective measures, unnecessary hurdles and deficiencies when applied in agricultural practice (Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (BMU), 2021). Therefore, the valuation method used here was based on the following principles: accessibility, comparability, adaptability, scalability, and time-efficiency (full descriptions are provided in supplemental material, S5).

Furthermore, the following ES were considered due to their relevance for farming systems (Von Cossel et al., 2020): biodiversity, recreational value, nutrient cycling, erosion prevention, climate regulation, moderation of disturbance and the provisioning of biomass.

These ES were selected based on the applicability of the respective valuation method in WPM cultivation and data availability, while considering the principles stated above. Consequently, the concept used here comprises seven valuation methods or individual ES with their respective indicators: floristic richness (nursery (habitat) services), choice modelling (recreational value), flood prevention (moderation of extreme events), social cost of carbon (climate regulation), nitrogen balance (nutrient cycling), soil coverage (erosion prevention), and both yield and quality of biomass (provision of biomass).

In order to compare the different approaches taken by other research on the monetization of ES, their methods were classified using the categories defined by Brander et al. (2018). Since the major goal of this literature review is to evaluate the monetary value of WPM-related ES on a field scale, the method of Bethwell et al. (2021) was included. The present study proposes an integrated set of indicators at the level of agro-ecosystems. In the realm of agro-ecosystems, Bethwell et al. (2021) expands the term “ES” with the concept that they are not “pure” ES in and of themselves, but that the flow/ production of provisioning ES in human-modified agricultural land use systems is clearly reliant on natural and specifically anthropogenic system inputs (Jones et al., 2016; Power, 2016).

The quality of information for land use and agro-ecosystem management policy and planning (site-specific management of complex agricultural landscapes and related governance systems) may be improved by a holistic collection of integrative indicators (Bethwell et al., 2021). The relevant indicators for these characteristics are in accordance with the standards outlined in the preceding section. Some of the components were used in the case study application.

What these two studies (Bethwell et al., 2021, Brander et al., 2018) lack to some degree is the operationalization and the assessment of tradeoffs and synergies between ES and how that affects agricultural practices, e.g. farmers are primarily compensated through the sale of agricultural goods, while other ES, such as regulatory services, remain unpaid. This gap is taken up by Geneletti et al. (2018) who assessed tradeoffs within the multifunctionality across agricultural landscapes. This holds great potential to support policy and decision-making and further promote multifunctionality in agriculture as a strategy for ensuring the delivery of various benefits from ecosystems and landscapes to the society.

3.2. Valuation methods

This section provides an overview of the results of the seven valuation methods (Fig. 2) used for monetizing the ES of the four land use scenarios.

3.2.1. Nursery (habitat) services via floristic richness

For the four scenarios, a summary of monetary values for each service per biome (values in Int.$/(ha*yr), 2007 pricing levels) from de Groot et al. (2012) was used as a reference.

De Groot et al. (2012) calculated the monetary values for genetic diversity in temperate forests to be 862 $ and 1214 $ for grasslands. According to Faber-Langendoen and Josse (2010), temperate grassland, meadow, and shrubland show an average species richness of 67 species. The monetary worth per species was computed using the monetary values calculated by de Groot et al. (2012). Based on that a value of 18.12 $ was discovered for one species on grassland. The value was translated straight to the maize field, which is dominated by a single species: maize (Faber-Langendoen and Josse, 2010). For the wild-plant field, a yearly average of eight species was estimated per hectare. Multiplied by the monetary worth of 1 species, the WPM field reaches $144.96. The currency was converted from Int.$ to € based on the exchange rate 1:0.84 (1 Sep 2021, 14:53 UTC).

3.2.2. Recreational value via choice modelling

A public survey was conducted using the methodology of Brander et al. (2018) to ask beneficiaries about their preferences for hypothetical changes in ES supply connected to landscape aesthetics. Individuals were specifically asked to negotiate ES with other commodities for which they are willing to pay. The participants (friends and relatives of the authors, n = 11) were asked if they would be willing to spend a certain amount of money per year to live next to a pristine forest, a wild-flower field, a maize field, or a parking lot with sealed soil. There were options to pay 1000, 750, 500, 250, 100, 10, 1, or 0 Euros. Based on the individual answers an average was calculated leading to an ES value of 636.36 € for the pristine forest, 668.18 € for the wild-flower field, 24.73 € for the maize-field and finally 0.91 € for the sealed-soil area.

3.2.3. Moderation of extreme events via avoidance costs

The severe flooding event in Germany in July 2021 (Welle, 2021) is a recent example for not only the threat which lies in uncontested climate change, but also the negative effects that human encroachment on rivers and soils by straightening rivers, canalizing brooks, disturbing natural retention areas and sealing of soils can have (HochwasserKompetenzCentrum e.V., 2017). Flood damage can be avoided or at least mitigated by increasing the water infiltration capacity of the soil (Umweltbundesamt, 2011). The approach for the valuation method of avoidance costs is based on the concept presented in the TEEB report (The Economics of Ecosystems and Biodiversity TEEB, 2013).

As a socio-economic, direct indicator (which means that the value reflects the sustainable level of use) the estimated avoidance costs (the loss in absence of the regulating service) is used for the valuation (The Economics of Ecosystems and Biodiversity TEEB, 2013). As an indicator for the capability of different land use system (respective cropping system), the infiltration capacity, measured in infiltrated liter in the soil from a total of 100 L poured on one square meter ($l/(100\,l{*}m^2)$), for each of the four different scenarios from the case study was set as a base. The infiltration capacity for the entirely sealed parking lot is 0 $l/(100\,l{*}m^2)$, for the maize field about 40 $l/(100\,l{*}m^2)$, for the WPM about 50 $l/(100\,l{*}m^2)$ and for the pristine temperate forest about 60 $l/(100\,l{*}m^2)$.

The numbers where derived from comparable sites, on which flooding experiments where conducted in a study by the German Federal Environmental Agency (Umweltbundesamt, 2011). For the monetary calculation the average yearly, estimated cost caused by flooding in Germany expressed in monetary value was taken. Hattermann et al. (2016) found the average flood damage in Germany to be at about 500,000,000 € per year. This amount then was divided by the agricultural land surface of Germany which is around 16,700,000 ha (Statista, 2021). The reason for taking only the agricultural land and not the whole surface area of Germany was that the intention of this work is to

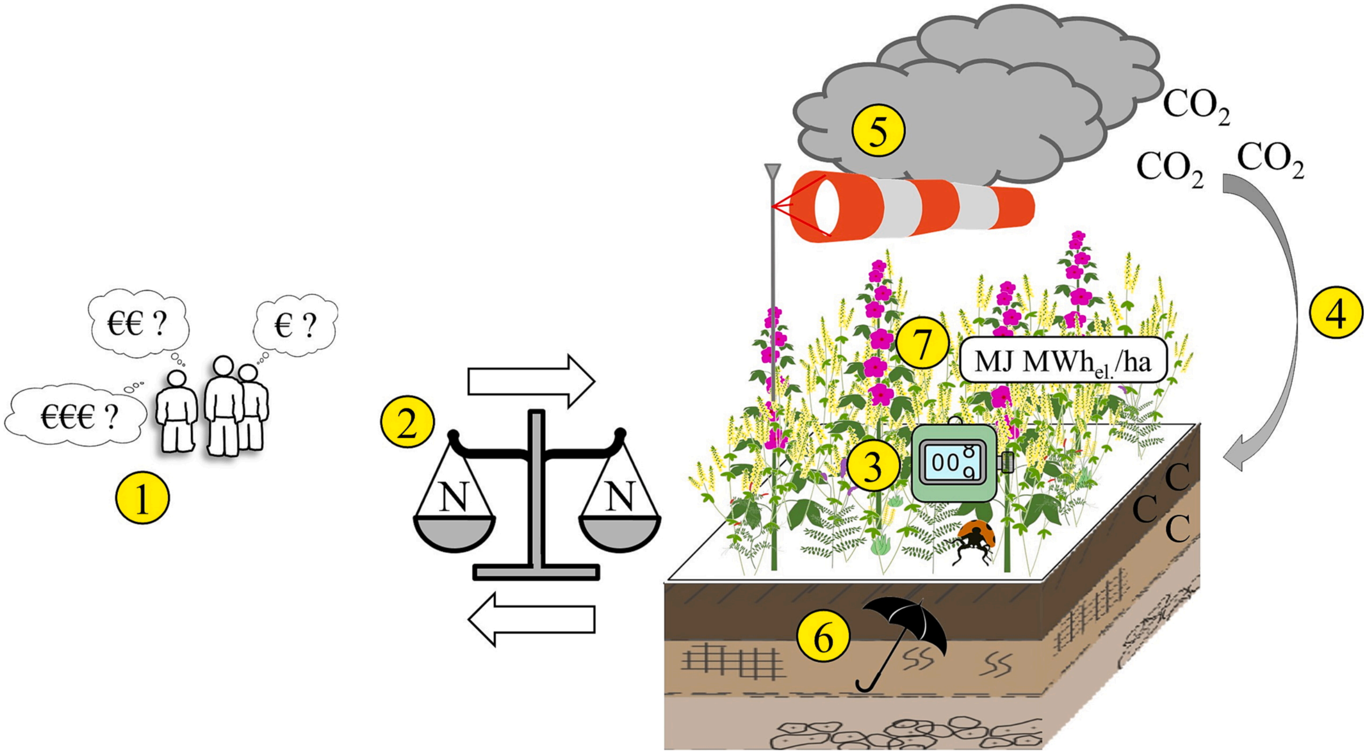

Fig. 2. Schematic visualization of the valuation methods applied in the case study: (1) choice modelling, (2) nitrogen balance, (3) floristic and faunistic richness, (4) social cost of carbon, (5) avoidance costs, (6) soil cover/protection, and (7) biomass provision.

calculate a possible remuneration at field scale, e. g. per hectare, explicitly for the agricultural sector. In addition, the goal was to analyze what every farmer can contribute to avoid this damage, which does not only occur on the agricultural land, but also in the remaining land surface of Germany. This includes for example the settlement area, which is not a part of the agricultural area, but from where the water can flow to the settlement from the field. Following the monetary calculation explained above and setting the infiltration rate as a base to normalize the values to be applied as a factor on a scale from 1 to 10, the results are for the parking lot 0 €/ha, for the maize field 17.96 €/ha, for the WPM 20.96 €/ha and for the pristine temperate forest 29.94 €/ha.

3.2.4. Climate regulation via social cost of carbon

Impacts of climate change due to carbon emissions, which e. g. lead to an increase in atmospheric CO_2-concentrations, can be translated to social costs due to the negative effects of global warming. The method applied to account for these costs was adapted from von Cossel et al. (2020). Soils have the feature to either sequester carbon from the atmosphere or release carbon into the atmosphere, in dependence of the management of the soil (Paustian et al., 1997).

As an indicator for the social cost of carbon (Ricke et al., 2018) the sequestered CO_2/ha (t CO_2/ha) for each land use type of the scenarios was applied. For the parking lot this number was 0.0 t CO_2 ha^{-1}, as the sealed surface hinders the interaction of soil and atmosphere. For the maize field the number was −2.2 t CO_2/ha, which means that the soil cultivated with maize releases CO_2 into the atmosphere (Umweltbundesamt, 2008). For the WPM the number was 3.52 t CO_2/ha fixed in the soil. This number was transferred from the carbon sequestration of miscanthus. For WPM, 60% of the carbon sequestration of miscanthus was used as an approximation (Von Cossel et al., 2020). For the pristine temperate forest a number of 12.0 t CO_2 ha^{-1} was applied (Bundesanstalt für Ernährung und Landwirtschaft (BLE), 2021).

These numbers were then normalized on a scale of 1 to 10 and then multiplied with the price per ton of CO_2 (CO_2-emission certificate) currently traded on the stock market, which lies as high as approximately 62 € at status quo (European Energy Exchange (EEX), 2021). The calculation yields 0 €/ha for the parking lot, also 0 €/ha for the maize field (actually −136 €/ha), because CO_2 is released during the cultivation instead of sequestering it. However, negative values were not assigned because CO_2 was absorbed by plants from the atmosphere during the vegetation phase. For the WPM 217 €/ha are rewarded and for the pristine forest 738 €/ha.

3.2.5. Erosion prevention via soil cover

Soil cover is an effective measure against water erosion. Thus, cropping systems with a higher soil coverage provide more effective prevention against erosion. Grasslands which have a soil cover of close to 100% prevent water erosion completely (Jankauskas and Jankauskiene, 2003). The value of grassland erosion prevention is valued at 37.49 €/ha (converted to € from 44 $/ha) (Jankauskas and Jankauskiene, 2003). With soil cover estimates of specific cropping systems, it is possible to calculate the respective value of the given erosion by multiplying the soil cover percentage by the value of grassland erosion prevention (37.49 €/ha) that completely prevents erosion (100%). The maize soil cover is 30% (Lehmphul, 2015). Thus, maize has a soil erosion prevention value of 11.25 €/ha. For the WPM cultivations, a soil cover percentage of 80% was estimated, which results in an erosion prevention value of 29.99 €/ha. At first glance the forest does not seem to have a soil cover of 100% but the large root systems of the trees in combination with the mycorrhizal community have a tight grip on the soil from below (Becerra et al., 2019). Therefore, a pristine temperate natural forest with trees and shrubs of different ages and a diverse mycorrhizal community is estimated to have a soil cover of 100% and a resulting erosion prevention value of 37.49 €/ha. The parking lot does not have any soil that can erode and thus cannot exhibit erosion prevention (0%).

3.2.6. Nutrient cycling via nitrogen balance

The nitrogen balance was chosen to assess the nutrient cycling and respective nutrient leaching of different cropping systems (McLellan et al., 2018). During the cultivation the nitrogen input in the form of fertilizers (organic/inorganic) is measured in kg/ha. After the harvest the nitrogen leaving the field with the harvest is estimated in kg/ha with crop specific nitrogen content data. For perennial cropping systems the relocation of nitrogen into the roots during the winter months is considered as well. All other possible inputs and outputs are disregarded for now but should be considered in future further developments of the concept. Monetary values are derived from the calculated nitrogen balances with the damage costs per kg nitrogen that leaches into the environment. The costs per kg nitrogen varies significantly in different studies. Matzdorf et al. (2010) calculated 0.30 to 1.30 €/kg nitrogen and an average of 0.80 €/kg. The European Nitrogen Assessment calculated costs of 5–20 €/kg (Brink et al., 2011). Calculations were performed with 0.80 €/kg nitrogen. Germany wants to reduce nitrogen surpluses to 70 kg/ha in 2030 (Lehmphul, 2015). This value was taken as a threshold: every avoided kilogram below the threshold gets rewarded with 0.80 €. The calculation resulted in a reward of 56 €/ha (70 kg/ha*0.80 €/ha) for the pristine temperate natural forest with a nitrogen balance of 0 kg/ha. The schematic WPM cultivation has a nitrogen surplus of 6.4 kg/ha and a corresponding reward of 50,88 €/ha ((70 kg/ha-6.4 kg/ha)*0.80 €/ha). The schematic maize cultivation has a larger nitrogen surplus with 26.8 kg/ha, resulting in a smaller reward of 34.56 €/ha. The sealed parking lot does not have a nitrogen cycle and thus is excluded from the reward.

3.2.7. Provision of biomass via yield and quality of biomass

The provision of biomass was monetized only for the cultivation of maize and WPM, since no biomass is produced in the parking lot, and no biomass is used in the pristine temperate forest. Basically, the price of ensiled biomass to be used for biogas production is subject to many factors that can vary greatly by location and time, such as wheat price, fertilizer price, biomass quality, and biomass yield level. In order not to overestimate the profit potential of WPM, a rather low average annual dry matter yield level of 10 t/ha was assumed according to Friedrichs (2013), although 14 t/ha and more are also possible. The reason for this is that WPM are still a relatively new cultivation system that farmers tend to test on less favorable sites, and yield losses are also likely due to a lack of experience. For maize, on the other hand, an above-average dry matter yield level of 21.6 t/ha was assumed in order to be able to represent how WPM compare to maize at high biomass yield difference in the monetary evaluation of the total ES of the cropping systems. The biomass quality of WPM was ranked lower than maize according to an independent report by Friedrichs (2013), in that silage from WPM was priced at only 79% of the price of silage from maize. Biomass yield differences between before and after ensiling were not considered here.

3.3. Visualization of the results

For visualization, the normalized values of the seven ES indicators for each of the four land use scenarios are depicted in flower diagrams (Fig. 3a-d). Each flower diagram provides a visualization of tradeoffs and synergies between ES and biodiversity within the researched area and allow for comparison of the study areas' performance. The ES provided by the research locations are represented using €/ha values.

To begin with the maize monoculture (Fig. 3a), it can be observed that the biomass supply covers most of its ES, whilst most of the other categories only exhibit minimal to no ES. The tradeoff between provisioning services in the form of biomass vs habitat and cultural services is particularly visible here.

In contrast, the flower diagram (Fig. 3b) of WPM field shows a well-balanced appearance. Except for biomass provisioning, the values of all categories are higher compared with maize. The larger surface covering results in an increased nitrogen balance. Additionally, since WPM

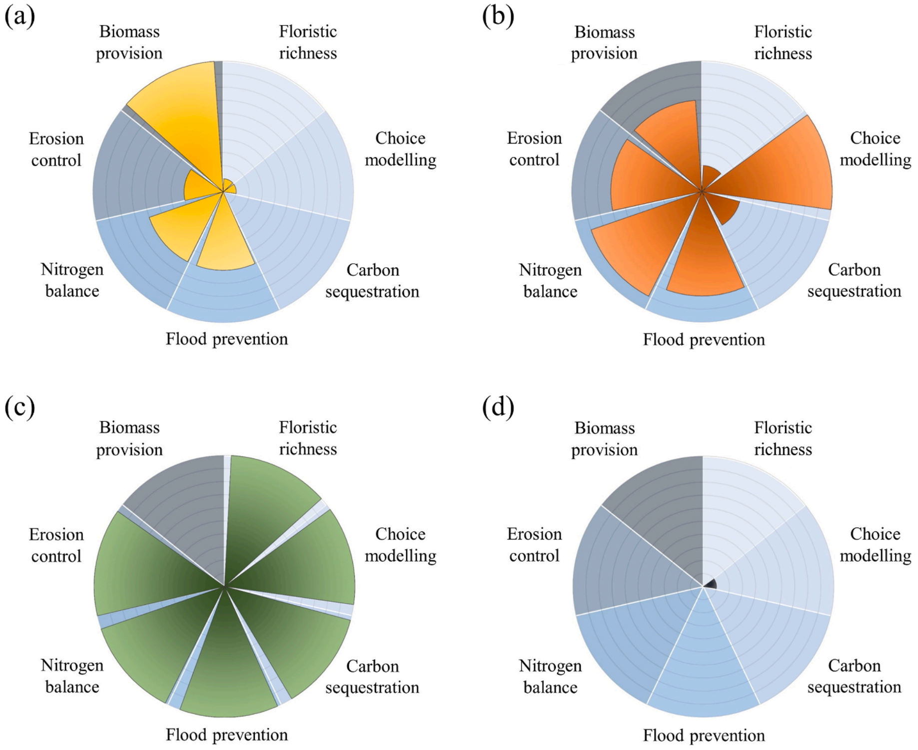

Fig. 3. Flower diagrams depicting the normalized values of the seven ecosystem service indicators in €/ha chosen for (a) silage maize, (b) wild plant mixtures, (c) temperate forest, and (d) parking lot.

mainly consist of perennial crops, erosion management is enhanced. Flood protection is enhanced since the infiltration rate is greater. Additionally, the WPM store carbon, whilst maize production releases more carbon in form of CO_2 than it sequesters. Also, peoples' stated preferences indicated a significant preference for living next to a WPM field rather than a maize field. The highest values in all categories (except biomass provisioning) can be found for the temperate forest (Fig. 3c). This emphasizes the importance of natural habitats, since even a more diverse cropping method, such as the perennial WPM, has reduced ES when compared to a natural ecosystem, as shown here (Fig. 3a, c). However, this clearly visualizes the tradeoff between provisioning and cultural as well as habitat services. Visible in the sealed soil flower diagram (Fig. 3d), there are no ES at all, apart from one individual who stated the preference to living near a parking lot in the choice modelling category.

The aggregate monetized values of all ESs must be added together for each scenario, along with the gain from biomass provisioning and the monetized values for the other ESs. This closes the profit gap that existed before considering the ES other than provisioning, with an overall profit of 653.60 €/ha for the maize field and 642.80 €/ha for the WPM (Table 2). The high total sum of 1691.57 €/ha for the pristine temperate forest particularly demonstrates the value of untouched ecosystems and the importance of considering indirect land use change when expanding bioenergy cropping in agroecosystems (Tamburini et al., 2020).

Table 2
Results of the case study with the ES involved, the methods applied and the corresponding calculated annual average monetary remuneration (in €/ha).

Ecosystem services (ES)	Valuation methods	Scenario 1: Parking lot	Scenario 2: Maize	Scenario 3: Wild plant mixture	Scenario 4: Pristine temperate forest
- Gene pool protection - Genetic resources - Biological control - Pollination - Nursery service	- Floristic richness - Value transfer	0.00	15.22	121.76	724.08
- Aesthetic information - Recreation	- Choice modelling	0.15	4.12	111.36	106.06
- Prevention of disturbance - Erosion prevention-Water flow regulation	- Avoidance costs - Value transfer	0.00	17.96	20.96	29.94
- Climate regulation - Air quality regulation	- Social cost of carbon - Value transfer	0.00	0.00	217.00	738.00
- Erosion prevention	- Soil cover - Value transfer	0.00	11.25	29.99	37.49
- Soil fertility maintenance - Nutrient cycling	- Nitrogen balance - Value transfer	0.00	34.56	50.84	56.00
Sum of ecosystem service rewards		0.15	83.11	551.91	1691.57
Profit from biomass sales		–	570.50	208.94	–
Total sum (rewards + w/o profit)		0.15	653.61	624.82	1691.57

4. Limitations of this study

The monetization of ES is essential in evaluating their importance to mankind, but especially in agriculture the valuation of ES in monetary terms serves as a pre-condition for enabling more diverse cropping systems like WPM and making them financially more viable for farmers (Brander et al., 2018). However, the transferability of ES values from common land use scenarios to WPM cultivation is difficult. For instance, several studies present ES values for very specific production systems (Geneletti et al., 2018; Bethwell et al., 2021; Von Cossel et al., 2020). For transfer to WPM cultivation, such ES values and / or the values used in the calculation might require adaptation and adjustment to meet the new context (Ezzine-de-Blas et al., 2016). A 'benefit transfer' has thus always to be handled with caution (The Economics of Ecosystems and Biodiversity TEEB, 2013), and only be applied when multiple parameters defining the context are similar (e.g. climate zone, income and price levels, slope, soil etc.). It has therefore to be noted that the values and figures used in this study (e.g. Fig. 3 a-d, Table 2) have a rather high level of uncertainty, because numbers were taken from studies with substantial differences in the local conditions or the particular types of land use. Therefore, the calculated monetary values for the remuneration of the examined ES in the schematic case study (Table e2) must be considered as conceptual. Site-specific contextualization seems to be a widely accepted approach in ES evaluation (Ezzine-de-Blas et al., 2016; Harrison et al., 2018). However, there are many different terms and different approaches for similar methods and indicators (Harrison et al., 2018; Spangenberg and Settele, 2010). These inconsistencies and the missing standardization may be barriers to the implementation and broader application of monetization ES of WPM on field scale in research and in practice. Therefore, the limitations of the methods used in the calculations will be discussed as follows.

4.1. Avoidance costs

The valuation method of avoidance costs by flooding applied in the case study has the advantage of being easy to calculate, yet it deserves a critical appraisal in the sense that not every part of Germany is equally prone to flooding, this means homogeneity is assumed as was also done in Von Cossel et al. (2020). The amount of yearly average damage costs is thus generalized by dividing it by the total agricultural land. But the inherent risk of flooding for a specific piece of land follows a heterogeneous pattern, as the topography across Germany reveals a high variability. Considering the amount of money awarded for providing ES that lower flood risk, future developments like ongoing climate change (Pörtner et al., 2022) will cause the remuneration amount to increase, so the monetary value for damage costs must be adjusted continually.

4.2. Floristic richness

When calculating the floristic richness, not relying on averages but actual research about species richness for each scenario would make the results significantly more precise (Von Cossel et al., 2020). Therefore, the results of monetizing ES of this category only express a principal approximation.

4.3. Choice modelling

For the evaluation of the cultural services (e.g., landscape aesthetics), the number of participants is crucial due to the wide range of potential opinions of the people (Aulia et al., 2020). Therefore, a public survey with a significantly higher number of participants than eleven would be more representative for the choice modelling section of the present study. This would have yielded a more realistic approximation of actual willingness to pay and thus the derivation of a more representative monetary value for nonuse assets, particularly for cultural services. However, if the monetization approach were to be implemented on a state level, this monetization approach could contribute highly to the determination of regional monetary values of novel bioenergy cropping systems such as WPM at field scale and therefore aid local and national policies concerning agricultural decisions and practices.

4.4. Soil cover

The monetization of erosion prevention with the soil cover indicator is simple but needs a reliable reference value. Soil cover is just one of many parameters influencing the erosion at a specific site. A major parameter is the slope of a field, which is not considered with the soil cover indicator. The disregard for time is another weak point for the monetization approach for erosion prevention carried out in this study. This is because soil cover changes and increases over the growing periods as well as over the years with dynamic bioenergy cropping systems such as WPM (von Cossel and Lewandowski, 2016). With the consideration of soil cover variation over time, the soil cover measurements could become unmanageable. Thus, this method needs to be further developed and standardized average soil coverages of dynamic bioenergy cropping systems such as WPM need to be determined, also considering their reintegration into crop rotations after a certain time (von Cossel, 2022).

4.5. Nitrogen balance

The nitrogen balance approach used here is very simple and exemplary. In the further development of monetizing nutrient cycling-based ES of WPM, other possible nitrogen inputs and outputs should be included such as the atmospheric deposition of nitrogen or biological fixation of atmospheric nitrogen via rhizobacteria (Liu and Ludewig, 2019). In practice, this ES can be calculated using data available from government regulations. Like soil cover, the time scale was not taken into account here. Perennial bioenergy cropping systems like WPM are likely to have higher annual yields after the first cultivation year (Janusch et al., 2021; Von Cossel, 2020) and the share of legumes (usually in symbiosis with nitrogen-fixing rhizobacteria) may change over time (von Cossel and Lewandowski, 2016). In addition, the amount of fertilizer applied can also be decreased over time when cultivating WPM (Von Cossel, 2020). These two aspects suggest that the nitrogen balance and the subsequent ES rewards of the WPM cropping system are likely to improve if the time scale is properly integrated into the nitrogen balance valuation method. Following Lehmphul (2015), a nitrogen surplus of 70 kg/ha was chosen as the reference point. In the future this threshold could be used as a leverage point to promote efforts reducing the nitrogen surpluses by lowering the threshold.

4.6. Visualization of the results via normalization

In terms of the flower diagrams (Fig. 3a-d) and the methodology used, normalization allows for the visualization of synergies and tradeoffs, as well as the overall expression of various ES for each study site. Following Geneletti et al. (2018), normalization generally entails converting the 'raw' value of the ES indicators, expressed in their respective units (e.g., €/h). In this case, the normalization was simply performed with respect to the maximum indicator values across the four study areas. This aspect is critical to discuss with stakeholders and to test different normalization approaches, because there may be more appropriate normalization approaches for bioenergy cropping systems depending, for example, on what kind of marginal land is used for their cultivation and where it is located (Von Cossel et al., 2019a). Similarly, the choice of monetization methods is an important step in the ES assessment of WPM because it allows for the analysis of tradeoffs and synergies. Furthermore, future studies should include a sensitivity analysis to investigate the relationship between agricultural practices of WPM cultivation and their environmental impacts, as well as an evaluation of the true costs and benefits of the cropping system (Wagner et al., 2022). Finally, due to the specific application, the limited number of study sites does not allow for the development of models to generalize and improve understanding of the direct and indirect causes of ES variations. Another important point to emphasize in the application of the proposed concept for monetizing the ES of novel bioenergy cropping systems such as WPM is that tradeoffs and synergies can be hidden or highlighted depending on the monetization methods, and ES category used (Geneletti et al., 2018). Moreover, even though revealed preference techniques are preferred because they represent actual behavior, their application to ES is limited. Stated preference techniques, on the other hand, are more adaptable in their application and rely on survey or trial responses (Brander et al., 2018).

In general, the concept of WPM ES monetization introduced in this study displayed various drawbacks throughout the application in the schematic case study. Often indicators are easy to measure but the monetization is not directly possible and requires additional reference values derived with other monetization methods (Geneletti et al., 2018). The valuation approach carried out here does not cover all ES provided by WPM because of the required balance between applicability and accuracy of the valuation approach. Thus, the valuation and weighing of the different ES provided by novel bioenergy cropping systems such as WPM must be further refined and developed to produce valid data that can be used in an ES reward scheme. Additional challenges are expected to arise when applying the concept in a real setting, even more so in a large-scale application with thousands of farmers participating. For example, some methods in the concept require measurements for each distinct cultivation site, which is not feasible in a broader application setting. A solution could be the introduction of standardized estimates, lowering the number of required separate measurements and thus the labor required for the concept application. However, standardized estimates will also reduce the accuracy of the valuation. Comparability and validity are only given if the ES of many different cropping systems are quantified and if the time factor is considered and integrated. Another point for research is the integration of the regional context into the concept (e.g slope of cultivation site/field, crop rotation management, soil quality etc.).

However, the focus of this study was on an initial attempt to evaluate the ES portfolio of the novel perennial bioenergy cropping system WPM. Despite all ambiguities mentioned above, the results verify the level of governmental subsidies for WPM cultivation (250–500 €/ha*yr.), in Germany. The approach used here can be further developed in follow-up projects and possibly include more ES of WPM to the concept in the future while maintaining the applicability.

5. Outlook and remaining research questions

The developing and expanding bioeconomy has the aspiration to provide sufficient food, feed, biobased products and bioenergy while at the same time complying with the planetary boundaries approach and following the concept of the triple-bottom-line comprised of social equity, economic viability and ecological sustainability (Lewandowski, 2018). The monetization of ES in agroecosystems holds a potential to contribute to this aspiration in the sense that it supports a transition towards holistic pricing of traded goods and services, account for externalities (i.e. public goods, environmental impact levels etc.) and presents a roadmap towards combining the income of farmers with the necessity to maintain and possibly regenerate ES functions (Von Cossel et al., 2020). Implemented in a reasonable manner, the monetization of ES provided by WPM could contribute to solve the trilemma of material production (biomass for bioenergy purposes) and other ES (e.g. nursery services, climate regulation, erosion prevention etc.) competing for the scarce resource of land (Tilman et al., 2009). In this context, it would be very important to further develop more holistic approaches to integrate the values of other ES than biomass provisioning into a market economy which as far as now, still exhibits deficiencies in accounting adequately for the real worth of ES (de Groot et al., 2022; Von Cossel et al., 2020).

Concerning the concept used in the context of the exemplary schematic case study on WPM, this can be complemented with further cropping systems and regional settings, so the validity and magnitude is increased. The fine-tuning should be undertaken by inter- and transdisciplinary expert teams (e.g. agronomists, ecologists, policy makers and bioeconomists), as the process of developing a system for the monetization of ES (or the multifunctionality) provided by contrasting land use scenarios involves a multitude of disciplines, as for instance natural, social, and economic sciences (Geneletti et al., 2018; Morizet-Davis et al., 2023). The outcome can then be used, for example, by policymakers to inform decisions on policy issues regarding tradeoffs between economics and ecology, such as between maize and WPM cultivation for biogas production. Decision makers could thus be provided with an effective and comprehensible tool to adequately consider ES (Geneletti et al., 2018).

Talking about political decisions concerning WPM and the role of participation and particular interests, it is suggested that stakeholders cooperate rather than compete. This should help achieve the common goal of maintaining an environment in which the functionality of ES in more socio-ecologically sustainable bioenergy cropping systems (Von Cossel et al., 2019b) such as WPM is assured, especially for future generations. This implies that if farmers were rewarded for all ES provided, they would incur no losses while growing WPMs compared with common biogas crop (e.g. maize) cultivation. Both nature and the society would benefit as long as WPM are grown in accordance with best management practices (Vollrath et al., 2012; Von Cossel, 2020). Strategies like these could be first steps in reducing farmers' reluctance to cultivate WPM due to the potential risks (lower biomass yield and quality, uncertain establishment success, etc.) (Morone et al., 2021; Von Cossel, 2020) and additional duties with regard to subsidy-related regulations (Janusch et al., 2021). Another option would be to compensate WPM growers for the environmental services the crop-mixture provides to society, as the crop's perennial nature provides various ES such as erosion prevention (Cosentino et al., 2015) and greenhouse gas mitigation (Vollrath et al., 2012). However, as mentioned above, it would remain questionable whether the desired positive effects of WPM cultivation actually occur, so that the true benefits outweigh the true costs (Wagner et al., 2022). For example, contracts could include obligations to monitor cultivation success, which in turn could discourage farmers from cultivating WPM at all.

However, in addition to the recommendations described above, it should be further investigated whether the know-how gained in the process of monetizing ES of bioenergy cropping systems such as WPM and maize should be implemented in real-life remuneration schemes or should exclusively serve as an information base for decision-makers. Further, it must be clarified whether ecosystems, with their complexity, non-static properties, and dependence on many influences (Le Provost et al., 2022), can be adequately captured in metric scales and subsequently expressed in monetary terms - for the purpose of maintaining the functionality of the ES provided (Spangenberg and Settele, 2010; Unmüßig, 2019).

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2023.101529.

References

Altieri, M.A., Nicholls, C.I., Montalba, R., 2017. Technological Approaches to Sustainable Agriculture at a Crossroads: An Agroecological Perspective. Sustainability 9, 349. https://doi.org/10.3390/su9030349.

Araújo, K., Mahajan, D., Kerr, R., da Silva, M., 2017. Global Biofuels at the Crossroads: An Overview of Technical, Policy, and Investment Complexities in the Sustainability of Biofuel Development. Agriculture 7, 32. https://doi.org/10.3390/agriculture7040032.

Aulia, A.F., Sandhu, H., Millington, A.C., 2020. Quantifying the Economic Value of Ecosystem Services in Oil Palm Dominated Landscapes in Riau Province in Sumatra. Indonesia. Land 9, 194. https://doi.org/10.3390/land9060194.

Baum, G., 2019. Betriebswirtschaftliche Betrachtung der Wildpflanzennutzung für Biogasbetriebe. https://baden-wuerttemberg.nabu.de/imperia/md/content/badenwuerttemberg/vortraege/baum_betriebswirtschaftl_wildpflanzen_f__r_biogas_ver__ffentlichung.pdf (accessed 22.4.23).

Becerra, A.G., Diván, A., Renison, D., 2019. Bare soil cover and arbuscular mycorrhizal community in the first montane forest restoration in Central Argentina. Restoration Ecology 27, 804–812. 10.1111/rec.12937.

Bethwell, C., Burkhard, B., Daedlow, K., Sattler, C., Reckling, M., Zander, P., 2021. Towards an enhanced indication of provisioning ecosystemservices in agro-ecosystems. Environ. Monit. Assess. 193, 269. https://doi.org/10.1007/s10661-020-08816-y.

Brander, L., Van Beukering, P.J.H., Balzan, M., Broekx, S., Liekens, I., Marta-Pedroso, C., Szkop, Z., Vause, J., Maes, J., Santos-Martin, F., Potschin-Young, M., Burkhard, B., Balzan, B., Broekx, M., Liekens, S., Szkop, C., 2018. Report on Economic Mapping and Assessment Methods for Ecosystem Services Deliverable D3.2 - EU Horizon 2020 ESMERALDA Project, Grant agreement No. 642007.

Bredemeier, B., Herrmann, S., Sattler, C., Prager, K., van Bussel, L.G.J., Rex, J., 2022. Insights into innovative contract design to improve the integration of biodiversity and ecosystem services in agricultural management. Ecosyst. Serv. 55, 101430 https://doi.org/10.1016/j.ecoser.2022.101430.

Brink, C., van Grinsven, H., Jacobsen, B.H., Rabl, A., Gren, I.-M., Holland, M., Klimont, Z., Hicks, K., Brouwer, R., Dickens, R., Willems, J., Termansen, M., Velthof, G., Alkemade, R., van Oorschot, M., Webb, J., 2011. In: Costs and benefits of nitrogen in the environment. The European Nitrogen Assessment. Cambridge University Press, Cambridge, pp. 513–540. https://doi.org/10.1017/CBO9780511976988.025.

The Economics of Ecosystems and Biodiversity (TEEB), 2013. Guidance Manual for TEEB Country Studies. Geneva: United Nations Environment Programme. https://www.teebweb.org/wp-content/uploads/2013/01/TEEB_Guidance-Manual-Outline_130122-F.pdf (accessed 22.4.23).

Bundesanstalt für Ernährung und Landwirtschaft (BLE), 2021. Wie viel CO2 binden Wälder? https://www.landwirtschaft.de/landwirtschaft-verstehen/haetten-sies-gewusst/pflanzenbau/wie-viel-co2-binden-waelder (accessed 22.4.23).

Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (BMU), 2021. Umweltleistungen der Landwirte honorieren - Bundesministerin Schulze legt auf dem BMU-Agrarkongress konkrete Vorschläge zur Umsetzung der EU-Agrarreform vor.

Calicioglu, O., Flammini, A., Bracco, S., Bellù, L., Sims, R., 2019. The Future Challenges of Food and Agriculture: An Integrated Analysis of Trends and Solutions. Sustainability 11, 222. https://doi.org/10.3390/su11010222.

Carlsson, G., Mårtensson, L.-M., Prade, T., Svensson, S.-E., Jensen, E.S., 2017. Perennial species mixtures for multifunctional production of biomass on marginal land. GCB Bioenergy 9, 191–201. https://doi.org/10.1111/gcbb.12373.

Cosentino, S., Copani, V., Scalici, G., Scordia, D., Testa, G., 2015. Soil Erosion Mitigation by Perennial Species Under Mediterranean Environment. Bioenergy Res. https://doi.org/10.1007/s12155-015-9690-2.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260. https://doi.org/10.1038/387253a0.

Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: How far have we come and how far do we still need to go? Ecosyst. Serv. 28, 1–16. https://doi.org/10.1016/j.ecoser.2017.09.008.

Crossman, N.D., Bryan, B.A., 2009. Identifying cost-effective hotspots for restoring natural capital and enhancing landscape multifunctionality. Ecol. Econ. 68, 654–668. https://doi.org/10.1016/j.ecolecon.2008.05.003.

de Groot, R., Moolenaar, S., de Vente, J., De Leijster, V., Ramos, M.E., Robles, A.B., Schoonhoven, Y., Verweij, P., 2022. Framework for integrated Ecosystem Services assessment of the costs and benefits of large scale landscape restoration illustrated with a case study in Mediterranean Spain. Ecosyst. Serv. 53, 101383 https://doi.org/10.1016/j.ecoser.2021.101383.

de Groot, R.S. de, Brander, L., Ploeg, S. van der, Costanza, R., Bernard, F., Braat, L.C., Christie, M., Crossman, N., Ghermandi, A., Hein, L.G., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L.C., Brink, P. ten, Beukering, P.J.H. van, 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosystem Services 1, 50–61. 10.1016/j.ecoser.2012.07.005.

Englund, O., Dimitriou, I., Dale, V.H., Kline, K.L., Mola-Yudego, B., Murphy, F., English, B., McGrath, J., Busch, G., Negri, M.C., Brown, M., Goss, K., Jackson, S., Parish, E.S., Cacho, J., Zumpf, C., Quinn, J., Mishra, S.K., 2020. Multifunctional perennial production systems for bioenergy: performance and progress. WIREs Energy Environ. 9, e375.

European Energy Exchange, 2021. European Emission Allowances (EUA). European Energy Exchange AG Leipzig, Germany.

Ezzine-de-Blas, D., Wunder, S., Ruiz-Pérez, M., Moreno-Sanchez, R. del P., 2016. Global Patterns in the Implementation of Payments for Environmental Services. PLoS One 11, e0149847.

Faber-Langendoen, D., Josse, C., 2010. World Grasslands and Biodiversity Patterns. NatureServe, Arlington, VA. + Appendices.

Fang, X., Zhou, B.-B., Tu, X., Ma, Q., Wu, J., 2018. What Kind of a Science is Sustainability Science? An Evidence-Based Reexamination. Sustainability 10, 1478. https://doi.org/10.3390/su10051478.

Friedrichs, J.C., 2013. Wirtschaftlichkeit des Anbaus von Wildpflanzenmischungen zur Energiegewinnung - Kalkulation der erforderlichen Förderung zur Etablierung von Wildpflanzenmischungen (Opinion of experts). Rosdorf, Germany.

Fritsche, U., Brunori, G., Chiaramonti, D., Galanakis, C.M., Hellweg, S., Matthews, R., Panoutsou, C., 2020. Future Transitions for the Bioeconomy towards Sustainable Development and a Climate-Neutral Economy—Knowledge Synthesis Final Report. Publications Office of the European Union, Luxembourg, p. 89.

Galanakis, C.M., Brunori, G., Chiaramonti, D., Matthews, R., Panoutsou, C., Fritsche, U. R., 2022. Bioeconomy and green recovery in a post-COVID-19 era. Sci. Total Environ. 808, 152180 https://doi.org/10.1016/j.scitotenv.2021.152180.

Gelfand, I., Sahajpal, R., Zhang, X., Izaurralde, R.C., Gross, K.L., Robertson, G.P., 2013. Sustainable bioenergy production from marginal lands in the US Midwest. Nature 493, 514–517. https://doi.org/10.1038/nature11811.

Geneletti, D., Scolozzi, R., Adem Esmail, B., 2018. Assessing ecosystem services and biodiversity tradeoffs across agricultural landscapes in a mountain region. Int. J. Biodiversity Sci., Ecosyst. Serv. Manage. 14, 189–209. https://doi.org/10.1080/21513732.2018.1526214.

Harrison, P.A., Dunford, R., Barton, D.N., Kelemen, E., Martín-López, B., Norton, L., Termansen, M., Saarikoski, H., Hendriks, K., Gómez-Baggethun, E., Czúcz, B., García-Llorente, M., Howard, D., Jacobs, S., Karlsen, M., Kopperoinen, L., Madsen, A., Rusch, G., van Eupen, M., Verweij, P., Smith, R., Tuomasjukka, D., Zulian, G., 2018. Selecting methods for ecosystem service assessment: A decision tree approach. Ecosystem Services, SI: Synthesizing OpenNESS 29, 481–498. https://doi.org/10.1016/j.ecoser.2017.09.016.

Hattermann, F.F., Huang, S., Burghoff, O., Hoffmann, P., Kundzewicz, Z.W., 2016. Brief Communication: An update of the article "Modelling flood damages under climate change conditions – a case study for Germany" Nat. Hazards Earth Syst. Sci. 16, 1617–1622. https://doi.org/10.5194/nhess-16-1617-2016.

HochwasserKompetenzCentrum e.V.,2017. Hochwasser und StarkregenGefahren – Risiken – Vorsorge und Schutz. https://hkc-online.de/Downloads/HKC-_Hochwasser_Starkregen_Gefahren_Risiken_Vorsorge_und_Schutz.pdf (accessed 22.4.23).

IPCC, 2018. URL https://www.ipcc.ch/sr15/download/ (accessed 8.10.21).

Jankauskas, B., Jankauskiene, G., 2003. Erosion-preventive crop rotations for landscape ecological stability in upland regions of Lithuania. Agr Ecosyst Environ 95, 129–142. https://doi.org/10.1016/S0167-8809(02)00100-7.

Janusch, C., Lewin, E.F., Battaglia, M.L., Rezaei-Chiyaneh, E., Von Cossel, M., 2021. Flower-power in the bioenergy sector – A review on second generation biofuel from perennial wild plant mixtures. Renew. Sustain. Energy Rev. 147, 111257 https://doi.org/10.1016/j.rser.2021.111257.

Jones, L., Norton, L., Austin, Z., Browne, A.L., Donovan, D., Emmett, B.A., Grabowski, Z. J., Howard, D.C., Jones, J.P.G., Kenter, J.O., Manley, W., Morris, C., Robinson, D.A., Short, C., Siriwardena, G.M., Stevens, C.J., Storkey, J., Waters, R.D., Willis, G.F., 2016. Stocks and flows of natural and human-derived capital in ecosystem services. Land Use Policy 52, 151–162. https://doi.org/10.1016/j.landusepol.2015.12.014.

Krimmer, E., Marzini, K., Heidinger, I., 2021. Wild plant mixtures for biogas: promoting biodiversity in a production-integrated manner - practical trials for ecological enhancement of the landscape. Naturschutz Landschaftsplan. 2 https://doi.org/10.1399/NuL.2021.02.01.

Le Provost, G., Schenk, N.V., Penone, C., Thiele, J., Westphal, C., Allan, E., Ayasse, M., Blüthgen, N., Boeddinghaus, R.S., Boesing, A.L., Bolliger, R., Busch, V., Fischer, M., Gossner, M.M., Hölzel, N., Jung, K., Kandeler, E., Klaus, V.H., Kleinebecker, T., Leimer, S., Marhan, S., Morris, K., Müller, S., Neff, F., Neyret, M., Oelmann, Y., Perović, D.J., Peter, S., Prati, D., Rillig, M.C., Saiz, H., Schäfer, D., Scherer-Lorenzen, M., Schloter, M., Schöning, I., Schrumpf, M., Steckel, J., Steffan-Dewenter, I., Tschapka, M., Vogt, J., Weiner, C., Weisser, W., Wells, K., Werner, M., Wilcke, W., Manning, P., 2022. The supply of multiple ecosystem services requires biodiversity across spatial scales. Nat. Ecol. Evol. 1–14 https://doi.org/10.1038/s41559-022-01918-5.

Lehmphul, K., 2015. Reactive nitrogen in Germany. Umweltbundesamt. https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/reactive_nitrogen_in_germany_0.pdf (accessed 22.4.23).

Lewandowski, I. (Ed.), 2018. Bioeconomy: Shaping the Transition to a Sustainable, Biobased Economy, 1st ed. 2018. ed. Springer International Publishing : Imprint: Springer, Cham. 10.1007/978-3-319-68152-8.

Li, Y., Zhang, L., Qiu, J., Yan, J., Wan, L., Wang, P., Hu, N., Cheng, W., Fu, B., 2017. Spatially explicit quantification of the interactions among ecosystem services. Landsc. Ecol. 32, 1181–1199. https://doi.org/10.1007/s10980-017-0527-6.

Liu, Y., Ludewig, U., 2019. Nitrogen-dependent bacterial community shifts in root, rhizome and rhizosphere of nutrient-efficient Miscanthus x giganteus from long-term field trials. GCB Bioenergy 11, 1334–1347. https://doi.org/10.1111/gcbb.12634.

Mastrangelo, M.E., Weyland, F., Villarino, S.H., Barral, M.P., Nahuelhual, L., Laterra, P., 2014. Concepts and methods for landscape multifunctionality and a unifying framework based on ecosystem services. Landsc. Ecol. 29, 345–358. https://doi.org/10.1007/s10980-013-9959-9.

McLellan, E.L., Cassman, K.G., Eagle, A.J., Woodbury, P.B., Sela, S., Tonitto, C., Marjerison, R.D., van Es, H.M., 2018. The Nitrogen Balancing Act: Tracking the Environmental Performance of Food Production. Bioscience 68, 194–203. https://doi.org/10.1093/biosci/bix164.

Mishra, S.K., Negri, M.C., Kozak, J., Cacho, J.F., Quinn, J., Secchi, S., Ssegane, H., 2019. Valuation of ecosystem services in alternative bioenergy landscape scenarios. GCB Bioenergy 11, 748–762. https://doi.org/10.1111/gcbb.12602.

Morizet-Davis, J., Marting Vidaurre, N.A., Reinmuth, E., Rezaei-Chiyaneh, E., Schlecht, V., Schmidt, S., Singh, K., Vargas-Carpintero, R., Wagner, M., Von Cossel, M., 2023. Ecosystem services at the farm level – Overview, synergies, trade-offs and stakeholder analysis. Global Chall. https://doi.org/10.1002/gch2.202200225 (in press).

Morone, P., Caferra, R., D'Adamo, I., Falcone, P.M., Imbert, E., Morone, A., 2021. Consumer willingness to pay for bio-based products: Do certifications matter? Int. J. Prod. Econ. 240, 108248 https://doi.org/10.1016/j.ijpe.2021.108248.

Paltrinieri, S., Schmidt, J., 2020. Wildpflanzen statt Mais für Biogas - Was beeinflusst die Akzeptanz dieser biodiversitätsfördernden Anbaualternative? Naturschutz Landschaftsplan. 52.

Panoutsou, C., Giarola, S., Ibrahim, D., Verzandvoort, S., Elbersen, B., Sandford, C., Malins, C., Politi, M., Vourliotakis, G., Zita, V.E., Vásáry, V., Alexopoulou, E., Salimbeni, A., Chiaramonti, D., 2022. Opportunities for Low Indirect Land Use Biomass for Biofuels in Europe. Appl. Sci. 12, 4623. https://doi.org/10.3390/app12094623.

Paustian, K., Andrén, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Noordwijk, M., Woomer, P.L., 1997. Agricultural soils as a sink to mitigate CO 2 emissions. Soil Use Manag. 13, 230–244. https://doi.org/10.1111/j.1475-2743.1997.tb00594.x.

Payne, C., Sand, P., 2011. Gulf War Reparations and the UN Compensation Commission: Environmental Liability. Oxford University Press.

Pörtner, H.-O., Roberts, D.C., Adams, H., Adler, C., Aldunce, P., Ali, E., Begum, R.A., Betts, R., Kerr, R.B., Biesbroek, R., 2022. Climate change 2022: impacts, adaptation, and vulnerability. contribution of working group ii to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, UK and New York.

Potschin, M., Haines-Young, R., 2016. Defining and Measuring Ecosystem Services, in: Potschin, M., Haines-Young, R., Fish, R., Turner, R.K. (Eds.), Routledge Handbook of Ecosystem Services. Routledge, New York, NY : Routledge, 2016., pp. 25–44. 10.4324/9781315775302-4.

Potschin, M., Haines-Young, R., Fish, R., Turner, R.K. (Eds.), 2016. Routledge Handbook of Ecosystem Services. Routledge, London. 10.4324/9781315775302.

Power, A.G., 2016. Can Ecosystem Services Contribute to Food Security? Routledge Handbook of Ecosystem Services. Routledge.

Ricke, K., Drouet, L., Caldeira, K., Tavoni, M., 2018. Country-level social cost of carbon. Nature Clim. Change 8, 895–900. https://doi.org/10.1038/s41558-018-0282-y.

Robert, K.W., Parris, T.M., Leiserowitz, A.A., 2005. What is Sustainable Development? Goals, Indicators, Values, and Practice. Environ. Sci. Policy Sustain. Dev. 47, 8–21. https://doi.org/10.1080/00139157.2005.10524444.

Robinson, R.A., Sutherland, W.J., 2002. Post-war changes in arable farming and biodiversity in Great Britain. J. Appl. Ecol. 39, 157–176. https://doi.org/10.1046/j.1365-2664.2002.00695.x.

Sanderson, M.A., Goslee, S.C., Soder, K.J., Skinner, R.H., Tracy, B.F., Deak, A., 2007. Plant species diversity, ecosystem function, and pasture Management—A perspective. Can. J. Plant Sci. 87, 479–487. https://doi.org/10.4141/P06-135.

Schmidt, A., Lemaigre, S., Delfosse, P., von Francken-Welz, H., Emmerling, C., 2018. Biochemical methane potential (BMP) of six perennial energy crops cultivated at three different locations in W-Germany. Biomass Convers. Biorefin. 8, 873–888.

Sherrington, C., Bartley, J., Moran, D., 2008. Farm-level constraints on the domestic supply of perennial energy crops in the UK. Energy Policy 36, 2504–2512. https://doi.org/10.1016/j.enpol.2008.03.004.

Spangenberg, J.H., Settele, J., 2010. Precisely incorrect? Monetising the value of ecosystem services. Ecol. Complex. 7, 327–337. https://doi.org/10.1016/j.ecocom.2010.04.007.

Statista, 2021. Landwirtschaftliche Nutzfläche in Deutschland in den Jahren 1949 bis 2019 (in 1.000 Hektar).

Tamburini, E., Gaglio, M., Castaldelli, G., Fano, E.A., 2020. Is Bioenergy Truly Sustainable When Land-Use-Change (LUC) Emissions Are Accounted for? The Case-Study of Biogas from Agricultural Biomass in Emilia-Romagna Region. Italy. Sustainability 12, 3260. https://doi.org/10.3390/su12083260.

Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., Williams, R., 2009. Energy. Beneficial biofuels–the food, energy, and environment trilemma. Science 325, 270–271. https://doi.org/10.1126/science.1177970.

Tilman, D., Isbell, F., Cowles, J.M., 2014. Biodiversity and Ecosystem Functioning. Annu. Rev. Ecol. Evol. Syst. 45, 471–493. https://doi.org/10.1146/annurev-ecolsys-120213-091917.

Tripathi, A.D., Mishra, R., Maurya, K.K., Singh, R.B., Wilson, D.W., 2019. Chapter 1 - Estimates for World Population and Global Food Availability for Global Health. In: Singh, R.B., Watson, R.R., Takahashi, T. (Eds.), The Role of Functional Food Security in Global Health. Academic Press, pp. 3–24. https://doi.org/10.1016/B978-0-12-813148-0.00001-3.

Umweltbundesamt, 2008. Humusversorgung von Böden in Deutschland. https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/humusversorgung_von_boeden_in_deutschland.pdf (accessed 22.4.23).

Umweltbundesamt, 2011. Hochwasser - verstehen, erkennen handeln. https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/uba_hochwasser_barrierefrei_new.pdf (accessed 22.4.23).

Unmüßig, B., 2019. Wertschätzung Ja - Inwertsetzung und Monetarisierung von Natur – Nein Danke! [WWW Document]. Heinrich-Böll-Stiftung. URL https://www.boell.de/de/2019/09/23/inwertsetzung-und-monetarisierung-von-natur-nein-danke (accessed 9.1.21).

Valentine, J., Clifton-Brown, J., Hastings, A.F.S.J., Robson, P., Allison, G., Smith, P., 2012. Food vs. fuel: the use of land for lignocellulosic "next generation" energy crops that minimize competition with primary food production. Glob. Change Biol. Bioenergy. 4, 1–19. https://doi.org/10.1111/j.1757-1707.2011.01111.x.

Vargas-Carpintero, R., Hilger, T., Tiede, K., Callenius, C., Mössinger, J., Souza, R.F., Barroso Armas, J.C., Rasche, F., Lewandowski, I., 2022. A Collaborative, Systems Approach for the Development of Biomass-Based Value Webs: The Case of the Acrocomia Palm. Land 11, 1748. https://doi.org/10.3390/land11101748.

Vollrath, B., Werner, A., Degenbeck, M., Illies, I., Zeller, J., Marzini, K., 2012. Energetische Verwertung von kräuterreichen Ansaaten in der Agrarlandschaft und im Siedlungsbereich – eine ökologische und wirtschaftliche Alternative bei der Biogasproduktion. Bayerische Landesanstalt für Weinbau und Gartenbau. http://www.lwg.bayern.de/mam/cms06/landespflege/dateien/energie_aus_wildpflanzen_fnr_abschlussbericht_22005308_in.pdf (accessed 22.4.23).

Vollrath, B., Werner, A., Degenbeck, M., Marzini, K., 2016. Energetische Verwertung von kräuterreichen Ansaaten in der Agrarlandschaft - eine ökologische und wirtschaftliche Alternative bei der Biogasproduktion (Phase II) (Schlussbericht), Energie aus Wildpflanzen. Bayerische Landesanstalt für Weinbau und Gartenbau, Veitshöchheim. http://www.fnr-server.de/ftp/pdf/berichte/22038211.pdf (accessed 22.4.23).

Von Cossel, M., 2020. Renewable Energy from Wildflowers—Perennial Wild Plant Mixtures as a Social-Ecologically Sustainable Biomass Supply System. Advanced Sustainable Systems 4, 2000037. https://doi.org/10.1002/adsu.202000037.

Von Cossel, M., 2022. How to Reintroduce Arable Crops after Growing Perennial Wild Plant Species Such as Common Tansy (Tanacetum vulgare L.) for Biogas Production. Energies 15, 4380. https://doi.org/10.3390/en15124380.

Von Cossel, M., Winkler, B., Mangold, A., Lask, J., Wagner, M., Lewandowski, I., Elbersen, B., Eupen, M. van, Mantel, S., Kiesel, A., 2020. Bridging the Gap Between Biofuels and Biodiversity Through Monetizing Environmental Services of Miscanthus Cultivation. Earth's Future 8, e2020EF001478. 10.1029/2020EF001478.

Von Cossel, M., Lewandowski, I., 2016. Perennial wild plant mixtures for biomass production: Impact of species composition dynamics on yield performance over a five-year cultivation period in southwest Germany. Eur. J. Agron. 79, 74–89. https://doi.org/10.1016/j.eja.2016.05.006.

Von Cossel, M., Lewandowski, I., Elbersen, B., Staritsky, I., Van Eupen, M., Iqbal, Y., Mantel, S., Scordia, D., Testa, G., Cosentino, S.L., Maliarenko, O., Eleftheriadis, I., Zanetti, F., Monti, A., Lazdina, D., Neimane, S., Lamy, I., Ciadamiro, L., Sanz, M., Carrasco, J.E., Ciria, P., McCallum, I., Trindade, L.M., Van Loo, E.N., Elbersen, W., Fernando, A.L., Papazoglou, E.G., Alexopoulou, E., 2019a. Marginal agricultural land low-input systems for biomass production. Energies 12, 3123. https://doi.org/10.3390/en12163123.

Von Cossel, M., Wagner, M., Lask, J., Magenau, E., Bauerle, A., Von Cossel, V., Warrach-Sagi, K., Elbersen, B., Staritsky, I., Van Eupen, M., Iqbal, Y., Jablonowski, N.D., Happe, S., Fernando, A.L., Scordia, D., Cosentino, S.L., Wulfmeyer, V., Lewandowski, I., Winkler, B., 2019b. Prospects of bioenergy cropping systems for a more social-ecologically sound bioeconomy. Agronomy 9, 605. https://doi.org/10.3390/agronomy9100605.

Von Redwitz, C., Glemnitz, M., Hoffmann, J., Brose, R., Verch, G., Barkusky, D., Saure, C., Berger, G., Bellingrath-Kimura, S., 2019. Microsegregation in Maize Cropping—a Chance to Improve Farmland Biodiversity. Gesunde Pflanzen 71, 87–102. https://doi.org/10.1007/s10343-019-00457-7.

Wagner, M., Mangold, A., Lask, J., Petig, E., Kiesel, A., Lewandowski, I., 2019. Economic and environmental performance of miscanthus cultivated on marginal land for biogas production. GCB Bioenergy 11, 34–49. https://doi.org/10.1111/gcbb.12567.

Wagner, M., Winkler, B., Lask, J., Weik, J., Kiesel, A., Koch, M., Clifton-Brown, J., von Cossel, M., 2022. The True Costs and Benefits of Miscanthus Cultivation. Agronomy 12, 3071. https://doi.org/10.3390/agronomy12123071.

Weigelt, A., Weisser, W.W., Buchmann, N., Scherer-Lorenzen, M., 2009. Biodiversity for multifunctional grasslands 28. https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/156972/bg-6-1695-2009.pdf?sequence=2&isAllowed=y (accessed 22.4.23).

Weißhuhn, P., Reckling, M., Stachow, U., Wiggering, H., 2017. Supporting Agricultural Ecosystem Services through the Integration of Perennial Polycultures into Crop Rotations. 10.3390/su9122267.

Deutsche Welle, 2021. Hochwasser in Deutschland - Der Tag nach der Flutkatastrophe in Rheinland-Pfalz. Deutsche Welle. https://www.dw.com/de/der-tag-nach-der-flutkatastrophe-in-rheinland-pfalz/a-58294689 (accessed 22.4.23).