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Key Points:

- Environmental services of the perennial lignocellulosic crop *Miscanthus* were monetized for marginal agricultural land in Germany
- Monetary value of *Miscanthus* cultivation accounts for 1,200–4,183 € a^{-1}, three times higher than the value of the raw material for biofuel
- Monetizing environmental services bridges the gap between biofuels and biodiversity by promoting the use of second generation biofuels

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(continued)

Bridging the Gap Between Biofuels and Biodiversity Through Monetizing Environmental Services of *Miscanthus* Cultivation

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Abstract Carbon neutrality in the transport sector is a key challenge for the growing bioeconomy as the share of biofuels has stagnated over the past decade. This can be attributed to basic economics and a lack of a robust market for these technologies. Consequently, more sustainable biomass supply concepts are required that reduce negative impacts on the environment and at the same time promote environmental services for sustainable agricultural cropping systems including erosion prevention, soil fertility improvement, greenhouse gas mitigation, and carbon sequestration. One promising concept is the cultivation of perennial biomass crops such as *Miscanthus* (*Miscanthus* Andersson) as biofuel feedstock. In this study, the multiple environmental services provided by *Miscanthus* are first explored and subsequently monetized. Then the integration of *Miscanthus* cultivation for biomass production into European agricultural systems is assessed. One hectare of *Miscanthus* provides society with environmental services to a value of 1,200 to 4,183 € a^{-1}. These services are even more pronounced when cultivation takes place on marginal agricultural land. The integration of *Miscanthus* into existing agricultural practices aids both conservation and further optimization of socio-economic welfare and landscape diversification. As these environmental services are more beneficial to the public than the *Miscanthus* farmers, subsidies are required to close the gap between biofuels and biodiversity that are calculated based on the provision of environmental services. Similar approaches to that developed in this study may be suitable for the implementation of other biomass cropping systems and therefore help foster the transition to a bioeconomy.

Plain Language Summary The transition to a nonfossil transport sector is one of the most difficult and at the same time crucial challenges of the growing bioeconomy. In order to provide enough sustainably sourced biomass for biofuel production, a vast range of requirements need to be fulfilled—first and foremost the use of marginal agricultural land under low-input conditions. Only in this way is it possible to avoid land use conflicts with food crop cultivation and biodiversity conservation. However, the utilization of marginal agricultural land often entails economic disadvantages for farmers. These financial losses should be compensated for by the public sector, as long as the cropping system provides environmental services such as groundwater protection, climate regulation, moderation of extreme weather events, and habitat functions. Monetizing the environmental services using concrete examples is still uncharted scientific territory; existing promotion concepts must be assessed as underdeveloped.

1. Introduction

Biofuel development is currently not on track (Le Feuvre, 2020). Production growth rates in the United States (1%) and Europe (0.5%) have fallen far behind the desired growth rates of 6% and 8%, respectively, set to reach the envisioned share of 10% biofuels in the transport sector by 2030 (International Energy Agency, 2019). The IPCC special report *Global warming of 1.5°C* (IPCC, 2018) points out that both electricity (e.g., solar-based) and biofuels (e.g., agriculture-based) are major drivers of the decarbonization of the transport sector.

Paulino et al. (2018) evaluated these two key technologies in a life-cycle assessment (LCA) against the two fossil-fuel-based alternatives compressed natural gas and diesel. Overall, electricity and biofuels lead to the highest reduction of climate change impacts at 43% and 46%, respectively. However, the LCA also

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revealed the disadvantages of biofuels and electricity. Electric vehicles lead to an increase in the impact categories human toxicity (about +75% cancer effects/about +200% noncancer effects), ionizing radiation human health (about +200%), freshwater eutrophication (about +400%), and water resource depletion (about +400%) (Paulino et al., 2018). Biofuels perform more favorably in all these categories but put pressure on ecosystems and associated functions in the following impact categories: acidification (about +90%), terrestrial and marine eutrophication (about +160% and +315%, respectively), and in particular land use (about +760%). Nevertheless, biofuels may still outperform fossil fuels in many impact categories other than climate change, provided that perennial C4 grasses are chosen to provide the biomass and are grown according to good agricultural practice (Kiesel, Wagner, & Lewandowski, 2017). Ultimately, biofuels perform least favorably compared to electric transportation in the impact categories related to the agricultural production of the biomass. Agriculture, forestry, and other types of land use create 23% of global human CO_2 emissions (IPCC, 2019). With more biomass being required for biofuels however, the food-agriculture-environment trilemma is likely to worsen (Araújo et al., 2017; Tilman et al., 2009). Agricultural land is limited and about 33% to 50% is already being degraded (Saturday, 2018; Wu et al., 2019). Agricultural production however is increasingly needed for food, feed, fiber, and fuel production for a developing bioeconomy, and also due to the growing world population and changing diets (Calicioglu et al., 2019; Tripathi et al., 2019). At the same time, the pressure of agricultural production is a major driver of the sixth global mass extinction (Barnosky et al., 2011; Ceballos et al., 2017; Ceballos & Ehrlich, 2018; Elshout et al., 2019; Isbell et al., 2017). Examining this trilemma (Tilman et al., 2009) from a value-chain perspective reveals options to turn it into multiple opportunities for the development of a sustainable bioeconomy (Lewandowski, 2016). One finding is that the production of biofuels should primarily rely on residues and organic wastes from agriculture and forestry, including the respective processing industries (Von Cossel, Wagner, et al., 2019). If dedicated biomass crops are utilized as feedstock for biofuel production, these need to provide a high yield potential and additional environmental benefits (Carlsson et al., 2017; Gelfand et al., 2013; Mishra et al., 2019; Valentine et al., 2012; Von Cossel, Lewandowski, et al., 2019; Von Cossel, Wagner, et al., 2019; Wagner et al., 2019). In addition, biomass crops should be grown on marginal agricultural land, where food production is compromised by adverse climatic, geographical, geological, or economic factors (Carlsson et al., 2017; Fernando et al., 2015, 2018; Galatsidas et al., 2018; Gelfand et al., 2013; Gopalakrishnan et al., 2011; Lask et al., 2019; Nabel et al., 2018; Von Cossel, Lewandowski, et al., 2019; Wagner et al., 2019; Xue et al., 2016). Perennial biomass crops have distinct advantages on above- and below-ground biodiversity (Bellamy et al., 2009; Williams & Feest, 2019), soil fertility, groundwater protection (Ferrarini et al., 2017; Mishra et al., 2019), climate change mitigation (Clifton-Brown et al., 2017; Emmerling & Pude, 2017; McCalmont et al., 2017), and carbon sequestration (Bui et al., 2018; Canadell & Schulze, 2014). Hence the production of perennial crops on marginal agricultural land carries the potential to restore degraded agricultural lands, which, at a later stage, can (again) become attractive for food production (Barbosa et al., 2015, 2018; Fiorentino et al., 2018; Pogrzeba et al., 2019). Finally, the fuel produced and the technology used need to be state of the art. Here one very promising solution is the production of isobutanol instead of ethanol (Boock et al., 2019).

Over the past decade, there has been increasing interest in the production of isobutanol (Boock et al., 2019; Brosse et al., 2012; Ezeji & Blaschek, 2010; Tollefson, 2008) because of its superior fuel properties compared to ethanol: (i) high energy density of 85% of standard petrol mix (ethanol 66%); (ii) blending with petrol is possible at any ratio; (iii) no corrosion of engines and pipelines due to its low absorption of water from air; and (iv) high octane levels, leading to less knocking in engines while increasing efficiency (Boock et al., 2019; Cai et al., 2018; Del Campo et al., 2017, 2018; Tollefson, 2008). Isobutanol is produced by pretreating herbaceous, cellulosic biomass with acids and enzymes. There are various pretreatment options available (Cai et al., 2018) that release monomeric sugars to be further utilized by microorganisms in biorefineries to produce isobutanol (Cai et al., 2018).

Currently, large-scale isobutanol production (Ezeji & Blaschek, 2010) is close to market entrance, because Gevo Inc. (USA) signed a construction license agreement with Praj Industries Ltd. (India) in 2019 to commercialize the production of renewable isobutanol. The transport fuel will be produced using various feedstocks from sugar production (sugarcane/sugar beet juice, syrup, molasses), annual crops like cassava, rice, wheat, sorghum, and agricultural residues including rice and wheat straw, corn stover, cotton stalks, and empty fruit bunches (BiofuelsDigest, 2019).

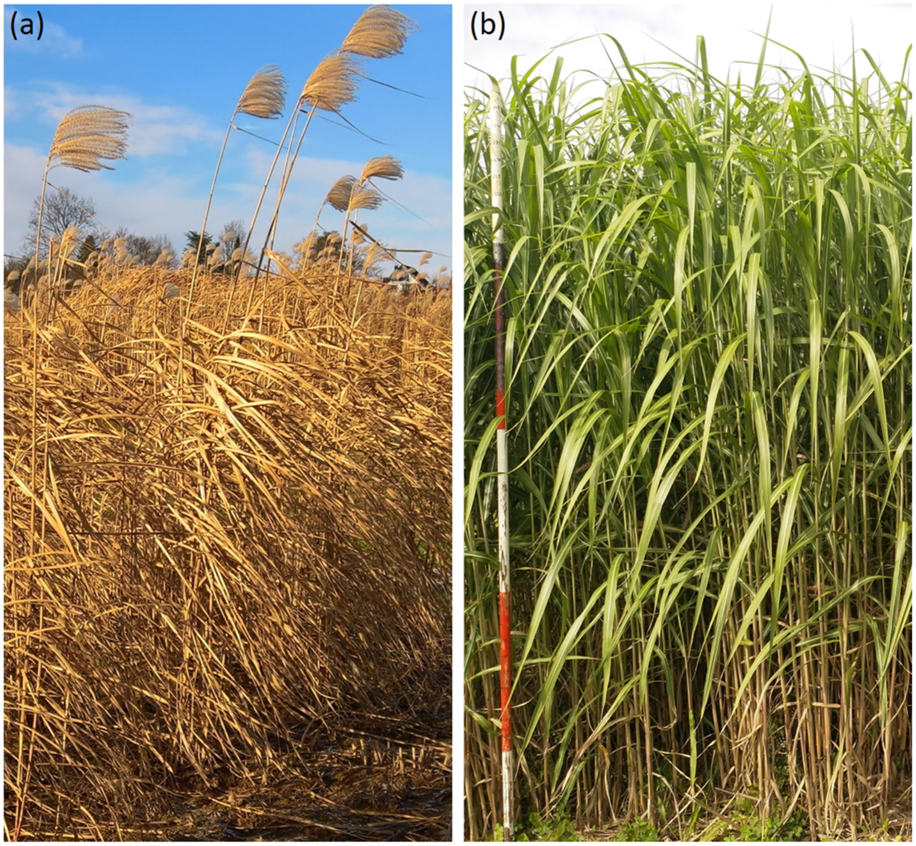

Figure 1. A 1.5-year-old (a) and a 5-year-old (b) field trial with *Miscanthus* × *giganteus* (Greef et Deuter) in southwest Germany. The pictures were taken in December 2017 (a) and August 2019, respectively.

This large feedstock base offers ample options for the production of isobutanol, but ensuring sustainable production requires multiple economic, environmental and social aspects to be considered (Von Cossel, Wagner, et al., 2019). Of particular importance is the avoidance of direct competition with food production. This renders cassava, rice, wheat, and sorghum somewhat unsuitable feedstocks (Tilman et al., 2009).

Today, *Miscanthus* (*Miscanthus* Andersson) is considered one of the most promising biomass crops for the development of a social-ecologically sound bioeconomy (European Commission, 2018c; FNR, 2018; Galatsidas et al., 2018; van der Weijde et al., 2017). *Miscanthus* originates from East Asia (Greef & Deuter, 1993) and grows under various environmental conditions in Europe and North America (Lewandowski et al., 2003). It is a perennial, rhizomatous C4 grass with a high biomass production potential of up to 40 Mg dry matter (DM) ha^{-1} a^{-1} in Europe (Anderson et al., 2011; Brosse et al., 2012), provided that adequate growth requirements (Ramirez-Almeyda et al., 2017) and cultivation techniques (Ramirez-Almeyda et al., 2017) are met. The perennial production cycle and crop management for *Miscanthus* were thoroughly described (Anderson et al., 2011; Brosse et al., 2012). *Miscanthus* biomass is suitable for a number of conversion and utilization routes: combustion (Iqbal & Lewandowski, 2016; Kiesel, Nunn, et al., 2017; Lewandowski et al., 2000; van der Weijde et al., 2017), bioethanol production (Cosentino et al., 2008; Koçar & Civaş, 2013; Scordia et al., 2013; Sørensen et al., 2008), and biorefining (GRACE, 2019), with combustion for energy and heat generation currently being the main utilization pathway (Iqbal et al., 2017). There are various genotypes of *Miscanthus* under investigation (Clifton-Brown & Lewandowski, 2002; Clifton-Brown et al., 2001, 2010; Greef & Deuter, 1993; Iqbal et al., 2017), with the hybrid *Miscanthus* × *giganteus* (Greef et Deuter) (Figure 1) being most commonly used (Anderson et al., 2011; Christian et al., 2008; Clifton-Brown et al., 2001, 2017; Iqbal & Lewandowski, 2016; Lewandowski et al., 2003).

The applications biogas production (Baute et al., 2018; Kiesel & Lewandowski, 2017; Mangold et al., 2019; Mangold et al., 2019; Ruf & Emmerling, 2017; Schmidt et al., 2018; Von Cossel et al., 2018; Wagner et al., 2019; Wahid et al., 2015) and animal bedding material (e.g., for chickens, horses, and cows) (Kasimati et al., 2015; Rauscher & Lewandowski, 2016; Renkema et al., 2016; Van Weyenberg et al., 2015) have also been recently put into practice (Van Weyenberg et al., 2015). However, the large potential of *Miscanthus* is not reflected in the small cultivation area of about 20,000 ha in Europe (Lewandowski, 2016). Reasons for this include a lack of knowledge of this new crop among farmers, accompanied by uncertainties about the financial returns of its cultivation due to the young, still evolving market and the currently higher revenues for other (annual) energy crops (Sherrington et al., 2008).

When considering the cultivation of *Miscanthus* on marginal agricultural land, its economic performance and the yield level are both crucial (Clifton-Brown et al., 2001; Gopalakrishnan et al., 2011; Ramirez-Almeyda et al., 2017). To be economically viable for biogas production, *Miscanthus* should yield at least 11 Mg DM ha^{-1} on marginal agricultural land (Wagner et al., 2019). Here it is particularly important to consider biophysical, climatic, geomorphologic, and economic marginality factors (Von Cossel, Lewandowski, et al., 2019). The later include, for instance, field-farm distances as well as the size and the shape of the cultivation areas (Winkler et al., 2020).

To encourage farmers to actually grow *Miscanthus* and improve economic performance, Sherrington et al. (2008) and Emmerling and Pude (2017) proposed subsidies as an appropriate measure to facilitate *Miscanthus* market development (Sherrington et al., 2008). A further option could be paying *Miscanthus* growers for the environmental services provided to society, as in particular the perennial nature of the grass provides various ecosystem services such as erosion mitigation (Cosentino et al., 2015), greenhouse gas mitigation (Clifton-Brown et al., 2007; Hastings et al., 2017; Kiesel, Wagner, et al. 2017; Wagner et al., 2019), soil fertility improvement (Bourgeois et al., 2015; Emmerling, 2014; Felten & Emmerling, 2011; Ruf et al., 2017), groundwater protection (Christian & Riche, 1998; Clifton-Brown & Lewandowski, 2000; Ferrarini et al., 2017; Lewandowski & Schmidt, 2006; McIsaac et al., 2010; Monti et al., 2019; VanLoocke et al., 2012), and carbon sequestration (Borzêcka-Walker et al., 2008; Dondini et al., 2009; Felten & Emmerling, 2012; Nakajima et al., 2018). For these reasons, *Miscanthus* was approved as a greening measure in Europe in January 2018 (European Commission, 2018b). This measure is a first step to lowering farmers' reluctance to cultivate *Miscanthus* on marginal agricultural land in face of the associated risks (lower yield, uncertain establishment success etc.). This is because farms are obliged by law to apply greening measures on at least 5% of their farmland and, as it produces a good biomass yield, *Miscanthus* (together with cup plant) is one of the few greening measures that can be beneficial for the farmer. As yet however, there is no remuneration model that takes into account the ecosystem services mentioned above, for example in the form of a "common goods bonus" (Grethe et al., 2018; Neumann et al., 2017). So far, no studies have analyzed how the monetary value (as the sum of direct market pricing, avoidance costs, factor valuation, contingent valuation, and benefit transfer) of the ecosystem services provided by *Miscanthus* cultivation can be assessed.

Thus, the aims of this study are (i) the exploration and monetization of environmental services (external benefits) of *Miscanthus* cultivation based on a literature review and (ii) an analysis of these services with respect to the benefits provided for specific types of marginal agricultural land in order to develop marginal agricultural land low-input systems (MALLIS) (Biala et al., 2007; Ramirez-Almeyda et al., 2017; Von Cossel, Lewandowski, et al., 2019) in Europe. This study provides a value-chain approach to the decarbonization of the transport sector in Europe by making *Miscanthus* cultivation more attractive for use as a biofuel feedstock and at the same time enhancing ecosystem functions.

2. Materials and Methods

First, the economic, ecologic, and social impacts of *Miscanthus* cultivation are explored and assessed employing "The Economics of Ecosystems and Biodiversity" (TEEB) approach, advocated by the United Nations Environmental Programme (UNEP) (TEEB, 2013). This approach allows an internalization of associated external costs, in particular adverse impacts on the environment, in agricultural biomass production as well as a quantification of benefits, primarily environmental services, in economic terms (TEEB, 2013). Following the TEEB approach, the ecosystem services provided by *Miscanthus* cultivation are valorized in monetary terms in order to highlight the value of ecosystem services with respect to agricultural policy development (TEEB, 2013).

The elicitation of services applicable to *Miscanthus* cultivation is based on the Common International Classification of Ecosystem Services (Haines-Young & Potschin-Young, 2018). When attempting to valorize ecosystem services in agricultural landscapes, it is important to distinguish between services provided by natural ecosystems and services provided by cultivated landscapes where humans use ecosystem services, for example, pollination and water for the production of resources, products, and services (De Groot et al., 2002). According to Matzdorf et al. (2010), landscape-level services provided by *Miscanthus* cultivation should be referred to as "environmental services," and this term is used in the following sections. These environmental services also include the conscious avoidance of permitted inputs and practices in order to reduce negative external effects, when the owner of the land area (in this case) is also the producer of the effects (Matzdorf et al., 2010). The cultivation of low-input perennial crops on agricultural lands has multiple environmental, social, and economic benefits, especially when compared to high-input annual crops (Kiesel, Wagner, et al., 2017; Wagner et al., 2019) such as maize (*Zea mays* L.), currently the main bioenergy crop in Germany (FNR, 2018).

The second step was the summarizing of recent developments in *Miscanthus* research and production in Europe using the literature database "Scopus" (Elsevier B.V., Amsterdam, Netherlands) and "Google Scholar" (Google Inc., CA, USA). From this, cultivation requirements, agricultural production steps and utilization options were derived.

Subsequently, suitable agricultural areas for *Miscanthus* production in Europe were identified, where it would not compete with food production due to biophysical constraints (Elbersen et al., 2018; Terres et al., 2014; Van Orshoven et al., 2012, 2014; Von Cossel, Lewandowski, et al., 2019). In this study, the major constraints were selected based on the findings of Von Cossel, Lewandowski, et al. (2019). The most suitable areas for *Miscanthus* cultivation on marginal areas were identified using the DSS tool of the EU-funded project MAGIC (MAGIC, 2019), providing a spatial distribution of the major types of marginal agricultural land in Europe (MAGIC DSS, 2019). For this conceptual study, the fictional case study area of Brandenburg (Germany) was chosen. The selection of this area was based on the following criteria: the large-scale aggregation of marginal areas (Figure 2) with sandy soil, low field capacity, and low precipitation (MAGIC DSS, 2019); its central geographic position in Europe; its favorable distribution infrastructure including railways as well as crude oil and product pipelines (Information Technology Associates, 2017); and because it is one of the major agricultural states in Germany (MLUL, 2018a). All these criteria qualify this area as a suitable location for the potential large-scale production of *Miscanthus* biomass and the economically feasible operation of an isobutanol biorefinery.

Finally, the environmental services of *Miscanthus* cultivation are discussed with respect to different design and implementation approaches of *Miscanthus*-based MALLIS for the feedstock production in the emerging isobutanol industry.

3. Valorization of Ecosystem Services Provided by *Miscanthus* Cultivation

The valorization of environmental and social services provided by the perennial crop *Miscanthus* based on the UNEP's TEEB approach (De Groot et al., 2012; De Groot et al., 2002) reveals an economic value of 1,200 to 4,183 € ha^{-1} a^{-1} for the case study area of Brandenburg (Figure 2). The range is due to both site-specific conditions and large variations in the selling price of *Miscanthus* biomass (65 to 95 € $Mg^{-1}DM^{-1}$) at assumed yield levels of 15 and 25 Mg DM ha^{-1} a^{-1}. Table 1 provides an overview of provisioning, regulating, maintaining and cultural services assessed in this study on an annual, per hectare basis. The following sections describe the valuation methods for the different services applicable to *Miscanthus*.

3.1. Provisioning Services

3.1.1. Provision of Raw Material

The currently most important ecosystem service provided by *Miscanthus* cultivation is the supply of biomass for multiple utilization options including isobutanol production, combustion, animal bedding, anaerobic digestion, and building materials (Anderson et al., 2011) as well as for ornamental use in floristry.

Miscanthus for isobutanol production is harvested using a maize chopper with subsequent baling in March at yield levels of 15 to 25 Mg dry matter (Winkler et al., 2020). The annual production costs for a 10-ha field

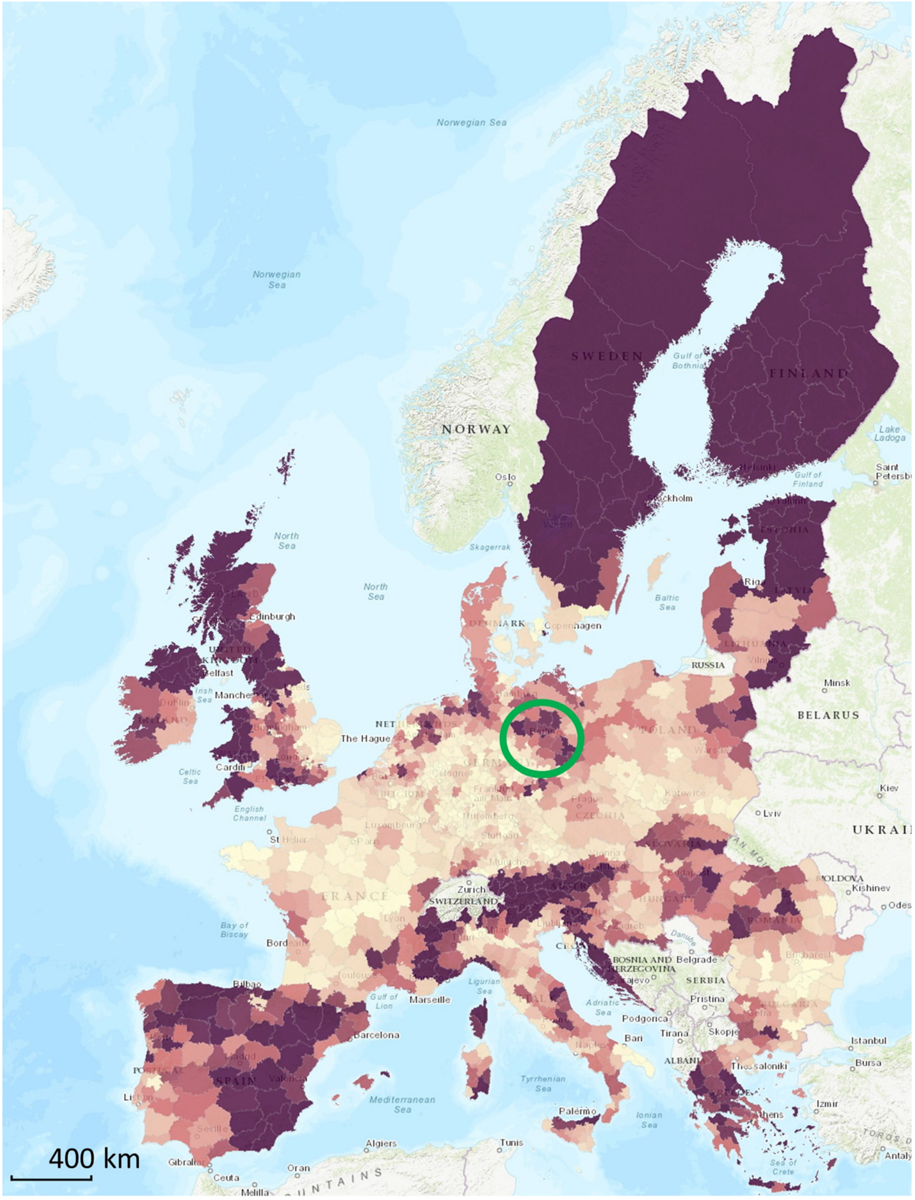

Figure 2. Spatial distribution of marginal agricultural land in Europe (EU-27) (adapted from DSS) 143. The darker the color, the higher the proportion of total agricultural land (not total land) of marginal agricultural land per region. The green circle shows the region of Brandenburg (Germany).

amount to 783 € (15 Mg yield level) and 1,080 € (25 Mg yield level). The selling price for the baled biomass is between 65 and 95 € Mg^{-1}. This results in attainable gross margins of between 192 € ha^{-1} a^{-1} (15 Mg DM ha^{-1} a^{-1}; selling price 65 € Mg^{-1} DM^{-1}) and 1,295 € ha^{-1} a^{-1} (25 Mg DM ha^{-1} a^{-1}; selling price 95 € Mg^{-1} DM^{-1}).

3.1.2. Provision of Genetic Resources

Miscanthus has a great genetic diversity, allowing the plant to be cultivated in a wide range of soils and climates. However, *Miscanthus* breeding is still in its infancy (Vermerris, 2008). The sterile hybrid *Miscanthus* × *giganteus* (Greef et Deuter) is currently the only genotype grown for commercial utilization. Consequently, there is untapped potential for further breeding of other genotypes of this high-yielding biomass crop with specific features adapted to local climatic and soil conditions.

At present however, there is very limited knowledge on the materials and products that biodiversity and the genetic resource base can provide to human society. As such, these services belong to the most difficult

Table 1

Assessed Annual Monetary Value of Ecosystem Services Provided by 1 ha Miscanthus (Various Genotypes of Similar Morphology) on Marginal Agricultural Land Areas in the Federal State of Brandenburg, Germany

Ecosystem service categories	Description	Valuation method[a]	Value (€ ha^{-1} a^{-1})	References
Provisioning services				
Raw material	Feedstock for isobutanol production	1	192 to 1,295	(Winkler et al., 2020)
Genetic resources	Crop genetic resources	4	18	(Brenner et al., 2000; Costanza et al., 1997)
Fresh water/groundwater	Provision of drinking water through sediment passage	1	0 to 111	(Bannik et al., 2008; BDEW, 2017; BfG, 2019; LBGR, 2019; MLUL, 2018a; Schmidt et al., 2003)
N_2 fixation	Substitution of N fertilizer	1	0 to 65	(Beale & Long, 1997; Keymer & Kent, 2014; Liu & Ludewig, 2019)
Ornamental resources	Flowers and leaves for decoration[b]	1	0 to 33	(Ausbildung.de, 2019; Der-renner.com, 2019)
Regulating services				
Air quality regulation	CO_2 conversion to O_2; O_3, SO_x	5	64	(Tianhong et al., 2010; Van der Ploeg & de Groot, 2010)
Climate regulation	CO_2 sequestration	1	217	(EEX, 2019; McCalmont et al., 2017)
	CO_2 substitution	1	514	(Brosse et al., 2012; Cai et al., 2018; EEX, 2019)
Waste treatment	Reduction of N leaching into environment	2	30	(Christian & Riche, 1998; Matzdorf et al., 2010; McIsaac et al., 2010)
Improvement of soil fertility	Yield increase of crops following *Miscanthus*	1	23	(Clifton-Brown et al., 2017; LOGISTEC, 2015; Markets Insider, 2019; PGRO, 2019)
Nutrient cycling	N, P, K recirculation in plant-soil system	1	65	(Agrarheute.com, 2019; Masters et al., 2016; Ruf et al., 2017)
Erosion prevention	Erosion decrease	2	0 to 43	(Van der Ploeg & de Groot, 2010)
Moderation of extreme events	Flood plain management[c]	1	0 to 771	(Grossmann et al., 2010; McCalmont et al., 2017; Rosolova et al., 2010)
Habitat services				
Pollination and biocontrol	Pollination of crops Biocontrol agents for crop pests and diseases	5	50	(Brenner Guillermo, 2007; Fernando et al., 2015)
Cultural services				
Aesthetic information	Close-to-nature flood plain planting	4	0 to 857	(Grossmann et al., 2010)
Recreation and tourism	Local recreation value of agricultural landscape	4	27	(Alvarez-Farizo, 1999; Bergstrom et al., 1985; Brenner Guillermo, 2007)
Estimated annual monetary value of environmental services provided by 1 ha *Miscanthus*			1,200 to 4,183	

Note: Values with ranges are very site-specific.

[a] Valuation methods: 1—direct market pricing, 2—avoidance costs, 3—factor valuation, 4—contingent valuation, 5—benefit transfer. [b] It is assumed that only 1% of the area is used for this service. [c] This service only applies to flood-prone areas and has to be subtracted for areas without the risk of flooding.

category for valorization (Brenner Guillermo, 2007). This also applies to the perennial grass *Miscanthus* with its high, but untapped genetic potential. Due to the lack of specific data, the average value of 17.81 € ha^{-1} a^{-1} (20 \$ ha^{-1} a^{-1}) for grasslands was assumed here, based on a contingent valuation (Costanza et al., 1997) used by Brenner-Guillermo (Brenner Guillermo, 2007) for grasslands in Spain.

3.1.3. Provision of Drinking Water

The soil below a low-input *Miscanthus* field has the ability to filter precipitation water, especially from the second year onwards when no pesticides are applied. Water filtration through soil removes substantial amounts of particles, pathogens, and organic and inorganic chemicals by sediment passage (Schmidt et al., 2003). This natural filtration has been utilized for drinking water for a long time in Germany, where 61.5% of drinking water is sourced from groundwater (BDEW, 2017). Sediment passage can substitute, simplify, or support other water treatment and purification steps and thus reduce drinking water filtration costs. For example, reduced dissolved organic carbon load rates increase the lifetime of carbon filters, thus saving replacement costs (Schmidt et al., 2003). Consequently, perennial, low-input crops such as *Miscanthus* appear a suitable soil cover to enhance water purification through sediment passage.

In the Brandenburg case study area, 86% of the soils have a high sand and loam content (MLUL, 2018a) and a high sorption capacity for heavy metals (LBGR, 2019). They are thus considered suitable soils for sediment passage.

The annual average precipitation in Brandenburg is about 560 mm (MLUL, 2018a) with the climatic water balance being only positive during winter, when 158 mm or 1,580 m^3 ha^{-1} infiltrate in the soil (BfG, 2019). About 40% of that water moves into surface water bodies and 60% into groundwater (Bannik et al., 2008). Consequently, 94 mm or 938.5 m^3 ha^{-1} flow into groundwater and are filtrated through the soil. Filtration accounts for 9.2% of the drinking water production costs (Bodensee-Wasserversorgung, 2019). As sediment passage is typically not the only type of filtration used for drinking water (Schmidt et al., 2003), a conservative assumption of a 10% reduction in filtration costs is taken for the valorization of this natural prefiltration. The end-consumer price of drinking water in Brandenburg of 1.43 € m^{-3} is used (Brawag.de, 2019). In this study, the provisioning service of drinking water filtration through *Miscanthus* cultivation is estimated as reducing water filtration costs by 0.118 € m^{-3} or 111.12 € ha^{-1} a^{-1}.

3.1.4. Provision of N_2 Fixation

In a study on N_2 fixation in the rhizosphere of *Miscanthus* roots, it was found that 16% of the N content in the whole plant of *Miscanthus* (1 year old plants) can be absorbed by N_2 fixation (Keymer & Kent, 2014). Even though this number probably depends strongly on site conditions and agricultural management (e.g., N fertilization) (Liu & Ludewig, 2019), it is assumed that 16% of *Miscanthus*' annual N demand can be covered by N_2 fixation, which would correspond to a partial substitution of synthetic N fertilizers. Since the N quantity within fully developed *Miscanthus* stands (with an average annual dry matter yield of 25 Mg ha^{-1}) is on average 31 g m^{-2} during the main vegetation phase (Beale & Long, 1997), this would result in an N fertilizer substitution of 50 kg ha^{-1} a^{-1}. And with a market price of urea of 341 € Mg^{-1} (46% N), 64.87 € ha^{-1} a^{-1} would be provided (Table 1). Due to the uncertainties of the location influences and the transferability of the value (16% N) to fully developed *Miscanthus*, a minimum value of zero is given here.

3.1.5. Provision of Ornamental Resources

A number of *Miscanthus* genotypes are popular ornamental plants for home gardens, landscaping and also in floristry, where the flowers and leaves are used in floral bouquets (Der-renner.com, 2019). For *Miscanthus* × *giganteus* (Greef et Deuter), this utilization option only applies to the use of leaves, because fully established *Miscanthus* × *giganteus* (Greef et Deuter) does not produce flowers under normal growth conditions (Bufe & Korevaar, 2018) (Figure 1b). The provision of leaves was valorized here based on the authors' own assessment of production costs. Leaves are harvested in autumn, with a bunch sold to end-customers for 2.90 € (Der-renner.com, 2019). A *Miscanthus* field planted with 10,000 plants per hectare results in a potential value of 522,000 € ha^{-1} with 18 productive years over a 20-year cultivation period. The total production and harvest costs, including establishment, would amount to 160,027 €. For floristic use, the leaves need to be harvested by hand. For hand harvest it was assumed that one person cuts the plants, one person sheaves them and a third person drives a tractor with a trailer. Assuming a total cutting and sheaving time of 5 min per *Miscanthus* plant, the total harvest would take 6 weeks. The average florist wage in Germany is currently about 1,800 € per month (Ausbildung.de, 2019). Personnel costs for harvest would consequently amount to about 8,100 €, while the cultivation costs for a farmer are 125.49 €.

The annual attainable gross margin would be 18,099 € ha^{-1}. Factoring in 10% losses during harvest, transport, storage and selling would reduce this to 16,289 € ha^{-1} a^{-1}. Such large amounts of *Miscanthus* need to be sold to wholesalers, who take have an approximate share of 80% of end-customer prices. Hence, the estimated theoretical value of the ornamental resource provision is 3,258 € ha^{-1} a^{-1}. However, it is very unlikely that it would be possible to use an entire hectare for this purpose, as the market is very limited. Therefore, it is assumed that per hectare only 1% is used for the provision of ornamental resources. Consequently, a more realistic value for this category is about 33 € ha^{-1} a^{-1}. It should also be considered that this figure very much depends on (i) the size of the distribution area and (ii) how much *Miscanthus* is cultivated in the region. For this reason, it remains unclear how much *Miscanthus* can be sold as an ornamental resource per distribution area. The example given here should therefore be interpreted with caution when upscaling *Miscanthus* cultivation.

3.2. Regulating and Maintaining Services

3.2.1. Air Quality Regulation

Plants are among the most important regulators of the atmospheric and oceanic gas balance and consequently air quality. This ecosystem service includes the CO_2/O_2 balance, the O_3 concentration and the regulation of SO_x levels (Brenner Guillermo, 2007). Tianhong et al. (2010) valorized the gas regulation service provided by cropland in general based on the benefit transfer method and gave a value of 63.69 € ha^{-1} a^{-1}. This value was applied here as a fair approximation of this regulating service.

3.2.2. Climate Regulation

The climate regulation service of 1 ha of *Miscanthus* is calculated based on the CO_2 sequestration in the soil and the CO_2 substitution potential, when using *Miscanthus* as a feedstock for isobutanol production with the aim of substituting fossil petrol.

3.2.2.1. CO_2 Sequestration

Carbon accumulates in the topsoil under *Miscanthus* through leaf fall and dead roots and rhizomes (Clifton-Brown et al., 2007). Leaf fall ranges from 29% to 42% of the total aboveground biomass (Lewandowski et al., 2000). The annual average C accumulation in soils under *Miscanthus* can range between 1.0 and 2.2 Mg C ha^{-1} a^{-1} (McCalmont et al., 2017). Hence, a substantial amount of carbon from the atmosphere is stored in the soil in the form of humus.

For the valorization of this service, the amount of carbon is multiplied by the current price of CO_2 emission certificates of 26.83 € Mg^{-1} $CO_2{}^{-1}$ (EEX, 2019). This gives a value of 216.63 € for the CO_2 stored in the soil each year. Note that this value would be considerably higher if the price of CO_2 emission certificates was set at the level of the consequential costs of one ton of CO_2, that is, approximately 180 € Mg^{-1} $CO_2{}^{-1}$ (UBA, 2018).

3.2.2.2. CO_2 Substitution

The production of isobutanol from *Miscanthus* creates less CO_2 (26 g CO_2-Eq. MJ^{-1}), than the production of fossil petrol (95 g CO_2-Eq. MJ^{-1}) (Cai et al., 2018). For unit conversion from g CO_2-Eq. MJ^{-1} to Mg CO_2-Eq. ha^{-1} a^{-1}, an average heating value of 18.5 MJ kg^{-1} for isobutanol and 43.45 MJ kg^{-1} for fossil petrol (Brosse et al., 2012), and an average *Miscanthus* dry matter yield of 15 Mg DM ha^{-1} a^{-1} is applied. This results in a CO_2 emission saving of 19.1 Mg CO_2-Eq. ha^{-1} a^{-1} for the substitution of fossil petrol by isobutanol.

Multiplying these savings by a CO_2 emission certificate price of 26.83 € Mg^{-1} $CO_2{}^{-1}$ (EEX, 2019) gives the CO_2 saving potential a monetary value of 513.73 € ha^{-1} a^{-1}.

3.2.3. Waste Treatment—Reduced Nutrient Leaching

The reduction of nutrient leaching into the environment is currently a subject of debate in Germany with respect to the implementation of measures to comply with the "EU nitrate directive" (The Nitrates Directive, 1991). This directive aims at preventing the pollution of surface water and groundwater by nitrate from agriculture. In the federal state of Brandenburg, about one third of the surface water bodies are moderately polluted with nitrate, with maize being the most frequently cultivated bioenergy crop in this area (MLUL, 2018a, 2018b).

N fertilization of maize is about 150 kg N ha^{-1} and cultivation period (Herrmann et al., 2014), whereas the N requirement of the perennial crop *Miscanthus* is only about one-third of that amount (52 kg N ha^{-1} a^{-1}).

Consequently, the N leaching potential of *Miscanthus* is considerably lower. McIsaac et al. (2010) found significantly lower nitrate leaching rates under *Miscanthus* (3.0 kg N ha^{-1} a^{-1}) than for a maize–soy bean rotation (40.4 kg N ha^{-1} a^{-1}) (McIsaac et al., 2010). Ammonium losses in *Miscanthus* are less than 1 kg NH_4-N ha^{-1} a^{-1} and thus negligible (Christian & Riche, 1998). This makes *Miscanthus* cultivation a potential measure for the protection of surface and groundwater bodies to comply with the EU nitrate directive.

The savings through the reduced N leaching into the environment are calculated to be in the range of 0.3 to 1.3 € kg^{-1} N^{-1} (Matzdorf et al., 2010). Taking the average value (0.8 € kg^{-1} N^{-1} leached) and the potentially avoided N emissions (37.4 kg ha^{-1} a^{-1}), when cultivating *Miscanthus* instead of maize and soybean results in an economic advantage of 29.92 € ha^{-1} a^{-1}. However, it should be noted that this value would be significantly higher for regions with a higher nitrate load, such as large parts of northern Germany (SMUL, 2019).

3.2.4. Soil Fertility Improvement

The shift towards low-demanding perennial crops with a cultivation period of 10 to 20 years allows the soil to recover from annual, often intensive cropping (Clifton-Brown et al., 2017). Perennial biomass crops such as *Miscanthus* have recently also been proven to function as wind barriers, increasing both the environmental and economic performance of pasture growth (Littlejohn et al., 2019).

Miscanthus cultivation increases soil organic carbon by 0.42 to 3.8 Mg C ha^{-1} a^{-1}, thus improving soil fertility (McCalmont et al., 2017). Regular carbon inputs and the perennial cultivation with almost no soil disturbance improve soil structure, increase water-holding capacity (up to 100 to 150 mm), enhance floral and faunal abundance and diversity, and also reduce water run-off and erosion (Emmerling & Pude, 2017; Kahle et al., 2001; McCalmont et al., 2017). Earthworm community enhancement for example increases bioturbation of the soil and the formation of macro pores, which in turn increase the water infiltration capacity of the soil (Felten & Emmerling, 2011).

These beneficial effects of *Miscanthus* cultivation result in a higher long-term soil fertility (Clifton-Brown et al., 2017), which can potentially increase yields of the follow-on crops. To date however, very few studies have assessed these effects. Dufossé et al. (2014) compared the grain yield of wheat planted after a 20-year *Miscanthus* cultivation and that grown on an adjacent control plot and found no effect: Both sites yielded 9.8 Mg DM ha^{-1}. By contrast, data from the EU project "LogistEC" funded under the 7th Framework Programme indicate yield increases in winter wheat (+45%) and winter bean (+34%) grown after *Miscanthus* removal, compared to a conventional crop rotation where these crops were cultivated after winter wheat and winter bean (LOGISTEC, 2015). Winter wheat yielded 7.4 Mg ha^{-1} after *Miscanthus* removal and 4.1 Mg ha^{-1} after a previous winter wheat season. The same pattern was observed in the subsequent year, where winter bean after winter wheat after *Miscanthus* resulted in a yield of 3.2 Mg ha^{-1}, whereas winter bean following two seasons of winter wheat yielded 2.1 Mg ha^{-1}. However, it should be noted that (i) the higher yield after *Miscanthus* was due to pest infestations in both the winter wheat and the winter bean in the conventional crop rotation, and (ii) cultivation of these two crops on fallow land achieved higher yields than after *Miscanthus* (LOGISTEC, 2015).

Nevertheless, *Miscanthus* cultivation has multiple beneficial effects on soil fertility, which are likely to result in higher yields of the follow-on (annual) crops than in conventional annual crop rotations. Due to the lack of data, the yield increases in winter wheat and winter bean are used here as an estimation for the valorization of soil fertility improvement.

The current market price of wheat is 184.25 € Mg^{-1} (Markets Insider, 2019) and 289.01 € Mg^{-1} for beans (PGRO, 2019). A yield increase of 45% in winter wheat would thus result in an additional revenue of 611.37 € ha^{-1}, while a 34% yield increase in winter bean would create 317.91 € ha^{-1}. For the allocation of this benefit to *Miscanthus* cultivation, the average of these two estimations is divided by 20 years, giving an estimation for the soil fertility improvement of 23.23 € ha^{-1} a^{-1}.

3.2.5. Nutrient Cycling

When harvested after winter, *Miscanthus* is characterized by an efficient water and nutrient utilization (Lewandowski & Schmidt, 2006; Ruf et al., 2017; Yu et al., 2013). Nutrients are relocated at senescence internally via phloem translocation to the rhizomes as well as externally through leaf fall, stubble residues, and harvest losses (Ruf et al., 2017). Considerable amounts of nutrients are recirculated within the cultivation system based on these two pathways.

Nutrient recirculation is an important factor for economic cultivation, as fertilizer rates are reduced. Nutrient recirculation within the cropping system reduces nutrient removal through biomass harvest, thus substantially lowering fertilizer input for the following growth cycle (Yu et al., 2013).

This “service” provided by the perennial nature of *Miscanthus* is valorized by multiplying the amount of relocated nitrogen, phosphorous, and potassium by the current prices for the respective fertilizers (as single nutrient fertilizers). Based on the study of Ruf et al. (2017), direct nutrient translocation to the rhizomes, leaf fall, stubble residues, and harvest losses amount to 65.37 kg N ha^{-1} a^{-1}, 10.31 kg P ha^{-1} a^{-1}, and 16.76 kg K ha^{-1} a^{-1}. The current prices for these plant nutrients are 341 € Mg^{-1} urea, 398 € Mg^{-1} P_2O_5, and 347 € Mg^{-1} K_2O (Agrarheute.com, 2019). Consequently, the nutrients recycled within the cropping systems have an economic value of 48.46 € ha^{-1} a^{-1} for nitrogen, 9.40 € ha^{-1} a^{-1} for phosphorous and 7.01 € ha^{-1} a^{-1} for potassium, which sum up to 64.87 € ha^{-1} a^{-1}.

In addition, indirect nutrient relocation through leaf fall, stubble residues and harvest losses enhance the nutrient contents of the soil-plant system, leading to an improvement in soil fertility (Kahle et al., 2001). A comparison with annual crops shows, for example, that *Miscanthus* removes 49.0% N, 17.4% P, and 31.9% K of the nutrient removed by soy bean and only 3.7% N, 1.8% P, and 1.8% K of the nutrients removed by maize (Masters et al., 2016). Nutrient recirculation within the cropping system is a considerable asset of *Miscanthus* in terms of fertilizer demand and potential nutrient leaching when compared to other major (energy) crops such as maize and soy bean (Masters et al., 2016), as well as in terms of nitrogen use efficiency when compared to reed canary grass and triticale (Lewandowski & Schmidt, 2006).

3.2.6. Erosion Prevention

Soil erosion has the highest impact on crop productivity. The associated water and nutrient losses account for 50% to 75% of the reduced productivity (Pimentel et al., 1995). The permanent soil coverage achieved by perennial crops like *Miscanthus* considerably reduces soil erosion (Jankauskas & Jankauskiene, 2003; Lewandowski, 2016). Jankauskas and Jankauskiene (2003) report that perennial grasses prevent water erosion completely. Strip cultivation with other annual crops, such as cereals and energy crops, can reduce water erosion by 80% up to a gradient of 14° (Dauber & Miyake, 2016; Jankauskas & Jankauskiene, 2003).

The soil erosion reduction through *Miscanthus* is valorized using the TEEB database. The soil erosion avoidance costs of permanent grasslands were assessed by the Belgian Ministry of Agriculture, Nature and Food Quality as having a value of 42.75 € ha^{-1} a^{-1} (Van der Ploeg & de Groot, 2010) and applied here as a fair approximation for the cultivation of *Miscanthus*. This figure is taken as an average value—it would be higher on areas more susceptible to erosion and lower on other less susceptible areas (Table 1)—since it is assumed that distribution of erosion susceptibility is generally very heterogeneous on farmlands.

3.2.7. Moderation of Extreme Events

In addition to the advantageous effects on soil fertility, soil structure improvement, and reduced soil erosion described above, *Miscanthus* cultivation can play an important role in the moderation of extreme weather events. These include droughts, heavy rainfall, and flooding, all of which are expected to increase in both frequency and intensity due to climate change (Samaniego et al., 2018; Teuling, 2018; Von Cossel, Wagner, et al., 2019). While *Miscanthus* is not the best choice for drought-affected sites (Ramirez-Almeyda et al., 2017; Von Cossel, Lewandowski, et al., 2019), it provides many advantages for sites prone to flooding (Barbosa et al., 2015). The improved soil structure through the perennial crop cultivation increases infiltration and storage capacity of the soil by 100 to 150 mm (McCalmont et al., 2017). Higher bioturbation rates through soil biota create higher porosity (Felten & Emmerling, 2011) with beneficial impacts on water infiltration rates and groundwater storage, and the dense crop stands have higher evapotranspiration rates (McCalmont et al., 2017).

Thus, low-input *Miscanthus* fields are a potential agricultural use option for river flood plains. The modeling approach of Rosolova et al. (2010) revealed that *Miscanthus* acts like a “green leaky dam” which slows down the water flow on and upstream of the field and also the flood propagation across the flood plain. Both decrease the flood levels in the area downstream of the field. The model showed the largest effect when the whole flood plain is covered with *Miscanthus* (Rosolova et al., 2010).

The economic value of *Miscanthus* for the moderation of floods is estimated here based on values taken from a case study assessing the economic effects of flood plain management options for the river Elbe in Brandenburg, Germany (Grossmann et al., 2010). One of flood management options ranked highest was the relocation of the dike to create 35,000 ha of flood plain. This option had an overall economic benefit 3.1 times higher than the annual costs of about 18 million €. Covering this area with *Miscanthus* would avoid flood damage to houses, roads, bridges etc. (5 million € a^{-1}), save dike maintenance costs (6 million € a^{-1}), and support other measures introduced to fulfill the EU Water Framework Directive. These include the reduction of nutrient loads by restricting agricultural inputs and improving the cleaning efficiency of sewage plants (16 million € a^{-1}).

Cultivating 35,000 ha of *Miscanthus* on the river Elbe flood plain would create total benefits of 27 million € annually, corresponding to 771.41 € ha^{-1} a^{-1}. This service of course does not apply to areas not prone to floods and is thus omitted for the lower value of the range of total estimated annual monetary value of environmental services provided by 1 ha of *Miscanthus* (Table 1).

3.3. Habitat Services—Pollination and Biocontrol

Although *Miscanthus* does not produce nectar, both young and adult *Miscanthus* stands provide nursery services for pollinators and biocontrol agents. In addition, *Miscanthus* stands form suitable habitats for many forms of wildlife due to the low management intensity (Clifton-Brown et al., 2010; Emmerling & Pude, 2017; Fritz et al., 2009). Over a long period of the year they can replace the function of field trees and shrubs for open land animals like European roe deer (*Capreolus capreolus* Linnaeus, 1758) and brown hare (*Lepus europaeus* Pallas, 1778) (Fritz et al., 2004, S. 200). Deciduous trees and shrubs planted around fields are important wildlife habitats. A study by Pywell et al. (2015) demonstrated that up to 8% of arable fields can be converted into wildlife-friendly habitats in this way, while maintaining or even increasing the yield level of wheat, oilseed rape, and beans. The higher crop productivity through ecological intensification was attributed to habitat creation for flying and epigeal predators of crop pests (e.g., grain aphids), thus enhancing biocontrol and also to the higher abundance of pollinators (esp. important for beans).

Miscanthus stands also provide more nesting space than annual crops like maize. In Germany, eight different bird species were recorded in *Miscanthus* fields including European greenfinch (*Chloris chloris* Linnaeus, 1758), Eurasian sparrow hawk (*Accipiter nisus* Linnaeus, 1758), common quail (*Coturnix coturnix* Linnaeus, 1758), common linnet (*Linaria cannabina* Linnaeus, 1758), and the common buzzard (*Buteo buteo* Linnaeus, 1758) (Bellamy et al., 2009; Fritz et al., 2004).

The abundance of spiders and beetles is also higher in *Miscanthus* stands than in maize and the perennial crop common reed (Fritz et al., 2004). Haughton et al. (2009) reported a higher abundance of butterflies, esp. Satyrinae (Boisduval, 1833), in field margins around *Miscanthus* and short rotation coppices than around arable crops. Soil biota also benefit from the extensive management of *Miscanthus* fields, with an enhanced diversity of earthworm communities and a more balanced species composition (Felten & Emmerling, 2011).

The biodiversity value of *Miscanthus* fields is considered comparable to that of forests, grasslands and annual crops (Fernando et al., 2015). Thus for the valorization of the habitat and nursery services provided by *Miscanthus*, the average of the values listed for these three biomes in the TEEB database is taken (Van der Ploeg & de Groot, 2010). In the database, these values are listed separately for biocontrol and pollination services (Brenner Guillermo, 2007): Temperate forests have the highest pollination value of 353.53 € ha^{-1} a^{-1}, followed by temperate grasslands at 28.28 € ha^{-1} a^{-1} and cultivated land at 17.68 € ha^{-1} a^{-1}. Biocontrol services for the biomes listed above are 4.42, 26.51, and 26.51 € ha^{-1} a^{-1}, respectively. The average of the values for temperate grasslands and cultivated land (49.49 € ha^{-1} a^{-1}) is regarded a fair approximation of the pollination and biocontrol services provided by a *Miscanthus* field.

3.4. Cultural Services

3.4.1. Aesthetic Information

Landscapes also possess inherent aesthetic functions with opportunities for reflection, spiritual and cognitive development as well as an aesthetic experience (Brenner Guillermo, 2007). The use if *Miscanthus* fields as a close-to-nature flood plain allows an approximation of the aesthetic information of *Miscanthus* in the landscape.

Planting this low-input perennial crop with its reed-like appearance in this area, interspersed with typical flood plain trees such as willow and poplar, would be a viable option for a plant community in the riparian buffer of the river Elbe. This 35,000-ha landscape along the river was valorized at a figure of 30 million € a^{-1}, based on a choice experiment assessing the population's willingness to pay for the maintenance of these areas (Grossmann et al., 2010). This results in a total value of 857.14 € ha^{-1} a^{-1} for the aesthetic information of the close-to-nature *Miscanthus*-poplar-willow flood plain. However, since this value is highly dependent on the location of the land, the species composition of the plant community (*Miscanthus*, willow, poplar), the prevailing social attitudes, and the importance of tourism in the region, we therefore also added a minimum value of 0 € for this parameter (Table 1).

3.4.2. Recreation and Tourism

Recreational aspects of landscapes are important for tourism. In Brandenburg, the German Federal Ministry for Rural Development, Environment and Agriculture currently supports the development of new tourist activities of stakeholders along the agricultural value chain, for example, gastronomic activities, direct marketing of local products, and the creation of new products with local identity (MLUL, 2019). In this respect, the recreational value of the agricultural landscape in this area is important for tourism.

Brenner Guillermo (2007) estimated the recreational value of cropland along the Catalan coast, an important tourist area, by drawing on reference values. In another study, Alvarez-Farizo (1999) assessed the willingness to pay for the agricultural conservation of environmentally sensitive areas to maintain landscape quality in Scotland (Alvarez-Farizo, 1999). Seventy percent of the survey participants agreed with government payments of 36 £ ha^{-1} a^{-1} to farmers for landscape conservation. A similar study was carried out by Bergstrom et al. (1985), who assessed the willingness to pay for the scenic and nostalgic value of prime agricultural land in the United States. Here the households were willing to pay 13 \$ ha^{-1} a^{-1} for the conservation of the agricultural land, instead of using the land for residential, industrial, or commercial purposes.

The average of these values from the latter two high-income countries is applied here as a fair approximation of the recreational value of agricultural landscapes for tourism. This results in a recreational tourism value of 26.69 € ha^{-1} a^{-1} of agriculturally used flood plains.

4. Recent Developments in *Miscanthus* Research and Production in Europe

The perennial C4 grass *Miscanthus*, with its 11 and 12 species, is native to Asia (in particular China, Japan, and Korea), Polynesia as well as South-East Africa (Anderson et al., 2011; Chung & Kim, 2012; Greef & Deuter, 1993). The sterile clone *Miscanthus* × *giganteus* (Greef et Deuter), a hybrid form of *M. sinensis* and *M. sacchariflorusis*, is the only genotype currently grown for commercial utilization in Europe and the United States (Kiesel & Lewandowski, 2017). Thanks to its robustness and adaptability (Ramirez-Almeyda et al., 2017), *Miscanthus* can achieve high dry matter yields in various locations within a number of climate zones (Brosse et al., 2012; Hastings et al., 2009; Tuck et al., 2006; Xue et al., 2016).

According to Ramirez-Almeyda et al. (2017), both dry matter yield and production costs of *Miscanthus* harvested in spring depend on the input level. As a perennial crop, *Miscanthus* generally requires less energy, material and labor than annual cropping systems, and is thus considered a low-input industrial crop (Von Cossel, Lewandowski, et al., 2019). However, a distinction must also be made between different input intensities for *Miscanthus* cultivation. In Europe, most locations require at least a medium input to achieve yields between 10–20 Mg DM ha^{-1} (Ramirez-Almeyda et al., 2017). A low input is only sufficient to produce a high yield in a few areas of Central Europe (Ramirez-Almeyda et al., 2017). In most cases high inputs are required to attain a yield of 25 Mg DM ha^{-1}. However, higher inputs often increase production costs up to 300 € Mg^{-1} DM^{-1} and reduce environmental benefits (Ramirez-Almeyda et al., 2017).

As land use competition with both food crops and biodiversity conservation need to be avoided in industrial cropping systems (Araújo et al., 2017; Caspeta et al., 2013; Fritsche et al., 2010; Tilman et al., 2009; Von Cossel, Lewandowski, et al., 2019; Wu et al., 2019; Wüstemann et al., 2015), marginal agricultural land should be taken into consideration for the location of *Miscanthus* cultivation (Von Cossel, Wagner, et al., 2019). "Marginal agricultural land" can be defined as the sum of "areas facing natural constraints" (Elbersen et al., 2017) which are available for agricultural utilization but unsuitable for food crop cultivation (Von Cossel, Lewandowski, et al., 2019). This implies that food crop cultivation is not economically feasible on this land as its overall performance is low. Indicators include, for example, low grain yield, grain quality, and environmental risks (Wu et al., 2019). The low performance of food crop cultivation on marginal agricultural lands can stem from one or more biophysical constraints (Terres et al., 2014; Van Orshoven et al., 2012, 2014). As a consequence, parts of these lands are subject to degradation or are in natural succession (Kalt et al., 2019). For this reason, it is important to consider on a case-by-case basis whether *Miscanthus* cultivation would be beneficial in social-ecological terms (Von Cossel, Wagner, et al., 2019). Literature sources cite the total area of marginal agricultural land distributed across Europe (EU-27) as between 446,000 km^2 and 646,833 km (Gerwin et al., 2018; MAGIC DSS, 2019; Von Cossel, Lewandowski, et al., 2019). The spatial distribution and regional densities of these marginal agricultural areas are given in Figure 2. These numbers reveal both the high economic and social-ecological relevance of an appropriate utilization of such areas (Galatsidas et al., 2018; Von Cossel, Lewandowski, et al., 2019; Von Cossel, Wagner, et al., 2019). For example, *Miscanthus* could be grown on approximately 12% (5.36 million ha) (Gerwin et al., 2018) to 73% (45 million ha) (MAGIC DSS, 2019) of European (EU-27) marginal agricultural land.

A comparison of the available constraint-specific thresholds (Terres et al., 2014; Van Orshoven et al., 2012, 2014) and growth requirements of *Miscanthus* (Ramirez-Almeyda et al., 2017; Von Cossel, Lewandowski, et al., 2019) shows that the crop could be suitable on several types of marginal agricultural land including sandy, saline and erosion prone sites (Alexopoulou et al., 2015; Cosentino et al., 2015; Nsanganwimana et al., 2014; Von Cossel, Lewandowski, et al., 2019). Additionally, *Miscanthus* could be suitable for a number of other less severe marginal sites (Von Cossel, Wagner, et al., 2019) and sites with multiple marginality constraints (Lewandowski et al., 2016; Ramirez-Almeyda et al., 2017; Terres et al., 2014; Van Orshoven et al., 2014; Von Cossel et al., 2018; Xue et al., 2016). Therefore, appropriate *Miscanthus* cultivation on European marginal areas can not only be of great economic advantage but also of great importance for environmental services, such as erosion mitigation and groundwater protection.

5. Discussion

This section first discusses the methods used in and results of the calculations, followed by possible social and ecological impacts of *Miscanthus* cultivation for isobutanol production. Finally, recommendations are derived.

5.1. Valorization of Environmental Services

The valorization of ecosystem services is important in order to understand the value ecosystems have for mankind (Abson et al., 2014; Haines-Young & Potschin-Young, 2018). Globally, ecosystem services can be valued at $ 140 trillion per year (Abson et al., 2014; Haines-Young & Potschin-Young, 2018), which is much higher than the 2018 global gross domestic product of about $ 85 trillion (Abson et al., 2014; Haines-Young & Potschin-Young, 2018). However, the services provided (e.g., clean water and air and pollination) and the negative impacts of agriculture on ecosystems that reduce the provision of these services are rarely valued on the market (FAO, 2015). Thus, there is often little awareness of them in public discourse and political debate. From 1997 to 2011, terrestrial land use change—mainly in form of deforestation of tropical forests and depletion of wetlands (including floodplains, swamps) to provide arable land—resulted in a loss of ecosystem services to the value of $ 20.2 trillion (Abson et al., 2014; Haines-Young & Potschin-Young, 2018). Consequently, the picture provided by assessments of agricultural system performance is far from complete. The predominant focus on crop yields does not appropriately address or assess the advantages and disadvantages of agricultural landscapes. The valorization of the external effects of agricultural crop production renders them more tangible and measurable in monetary terms. In this way, the conventional "production-only" assessment approach, which considers stocks, flows, outcomes, and impacts alone, can be made more holistic (TEEB, 2018).

The environmental services (referring to ecosystem services in agricultural landscapes according to Matzdorf et al., 2010) assessed here in an exemplary agricultural landscape amount to between 1,200 and 4,183 € ha^{-1} a^{-1} in total (Table 1). Of this, the provision of tangible products and services accounts for 210 to 1,522 € ha^{-1} a^{-1}, regulating services 913 to 1,727 € ha^{-1} a^{-1}, habitat services 50 € ha^{-1} a^{-1} and cultural services 27 to 884 € ha^{-1} a^{-1}. Consequently, non-use values (regulation, habitat and cultural services) can have a higher total value (990 to 2,661 € ha^{-1} a^{-1}) than the provision of biomass, drinking water, and genetic resources. Thus it is worth taking a closer look at regulating, habitat and cultural services in the assessment of agricultural production systems (Lead et al., 2010).

Similar service values for agricultural landscapes are reported from New Zealand. Here, a total annual environmental service value of 962 to 11,038 € ha^{-1} a^{-1} is attributed to conventionally managed agricultural fields and a higher value of 1,220 to 14,712 € ha^{-1} a^{-1} (Sandhu et al., 2008) to organically managed fields.

For the valorization of environmental services, *Miscanthus*-specific data were employed, wherever available. This was the case for the provisioning services (except genetic resources) and the services nutrient cycling, erosion prevention, soil fertility, and carbon sequestration. Where no specific data were available, comparable values were taken from the TEEB database as approximations of the services genetic resources, air quality regulation and nursery service. Where neither specific data nor comparable values were available, proxies and estimations were developed, drawing on existing data from contingent valuation and benefit transfer studies. This approach allowed an estimation of the service value of moderation of extreme events, aesthetic information, and recreation and tourism.

The valorization of provisioning services, also recognized in “production-only” approaches, is relatively straightforward and based on direct market pricing of tangible products. Here this refers to the harvestable biomass for the intended use, the ornamental use of leaves by florists, and the provision drinking water.

The provision of drinking water calculated as costs saved for water filtration through sediment passage is a highly important and tangible service for the public. The low-input crop *Miscanthus* with its well-established and active root system is suitable for ecological focus areas due to the low leaching and run-off into water bodies (Emmerling & Pude, 2017) This is one of the reasons why, in 2018, *Miscanthus* was added to the “greening” measures in the EU common agricultural policy (European Commission, 2018b). Christian and Riche (1998) recorded nitrate leaching rates under established *Miscanthus* stands comparable to the low levels of extensively managed grassland. This leads to improved groundwater quality (and environmental conservation). Mineral-N removal also takes place when *Miscanthus* is cultivated as bioenergy buffer strips. A 5-m-wide strip removed 63% and a 10-m-wide strip 80% of the incoming nitrate into the groundwater (Ferrarini et al., 2017). An increase in *Miscanthus* cultivation can thus help comply with the EU Water Framework Directive and at the same time reduce drinking water production costs (Bodensee-Wasserversorgung, 2019).

Some of the services assessed in valorization studies are often mutually exclusive. This is the case in this study for the provision of raw material (*Miscanthus* as feedstock for isobutanol) and ornamental use (harvest of leaves). It was assumed that only 1% of the leaves and flowers are actually harvested from a *Miscanthus* field, on the one hand due to the low market demand, on the other hand because leaf harvest and removal compromises nutrient cycling, soil fertility improvement, and CO_2 sequestration.

Other environmental services tend to be substitutional (in the sense of double accounting). Some degree of substitution is typical and tolerable in valorization studies, because ecosystems and biodiversity are subject to major nonlinearity and complex interactions (TEEB, 2018). Taking this into account requires a clear description of the service and the way it is actually assessed. In this study, the services recreation and tourism, aesthetic information, and moderation of extreme events appear to be interlinked and are thus substitutional. Recreational areas are usually in appealing landscapes favored by tourists for their high aesthetic information. The monetized services were distinguished in this study by allocating the willingness to pay for the conservation of agricultural landscapes to the recreation and tourism service to The residents' willingness to pay for the maintenance of a close-to-nature flood plain (instead of high dams channeling the river) was allocated to the landscape's aesthetic information. In addition, the service of extreme event moderation is estimated based on the costs of avoiding flood damage and of dike maintenance as well as savings from improved cleaning efficiency of sewage plants.

The valorization of environmental services in agro-ecosystems also takes into account the reduction and/or avoidance of negative external effects through farmers' decisions. Out of the 14 environmental services valorized here, only two (raw material, ornamental resource) would have been taken up by “production-only” economic assessments of *Miscanthus* production, automatically disregarding or “externalizing” additional values or services and thus negative impacts on the environment.

In addition, the environmental service “albedo-induced cooling effect” could not be monetized, as no data were available. A number of land use change scenarios have indicated that *Miscanthus* stands have a higher albedo effect during the vegetation period from May until the following March than, for example, the cereals wheat and barley (Cai et al., 2016; Jørgensen et al., 2014). In the period from harvest in March until canopy closure in May, the albedo effect of *Miscanthus* is still higher, because leaves that fall off during harvest cover the soil with a light mulch layer. Being brighter than bare soil, the mulch layer reduces soil warming and the subsequent terrestrial radiation into the atmosphere (Bernués et al., 2016; Jablonowski et al., 2017). Against the background of rising temperatures in a number of regions due to climate change, it is likely that the albedo-induced cooling effect of plant stands will be of increasing importance in future. Hence the albedo-induced cooling effect requires further research and, when data are available, should also be included in monetization studies.

Thus, the environmental services assessed include both distinct services and consciously avoided negative environmental effects, which need to be summed up to obtain the annual economic value of 1 ha of *Miscanthus*.

Provisioning, regulating, habitat, and cultural services are crucial for human welfare and some even for survival, such as air, drinking water, food, heating, and cooking fuel. Environmental services are characterized by somewhat complex interactions of biotic and abiotic factors that differ from place to place, thus creating different ecosystem successions (Lead et al., 2010). Valorization makes these services measurable and thus difficult to ignore in the public discourse on the sustainability of biofuels, agricultural value chains, and the growing biomass demand for the development of the bioeconomy. The holistic consideration of environmental services is of high importance, because agriculture's environmental footprint has increased exponentially over the past 25 years (FAO, 2016).

A survey conducted by Bernués et al. (2016) revealed that farmers working with and within agro-ecosystems are often well informed on and aware of environmental services. This applies in particular to knowledge on the regulating services like soil fertility, erosion prevention, air quality regulation, and gene pool protection, as well as their interactions and their relationship to agricultural practices. For the group of nonfarmers questioned in the survey, cultural services such as the aesthetic value of landscapes are of high importance, while the service “quality food” is equally important to both groups. Finally, the two groups are of the opinion that the provision of environmental services should receive more awareness in society and should also form the basis of agricultural subsidies (Bernués et al., 2016).

The environmental services valorized here are also applicable to other perennial crops, such as cup plant, Virginia mallow, switchgrass, giant reed, willow, and wild plant mixtures (Alexopoulou et al., 2015; Bufe & Korevaar, 2018; Fagnano et al., 2015; Fernando et al., 2016; Ferrarini et al., 2017; Jablonowski et al., 2017; Nabel et al., 2014; Stolarski et al., 2019; Von Cossel, Steberl, et al., 2019; Von Cossel & Lewandowski, 2016). Valorization of the various services however needs to be performed with crop-specific information and data, for example, for nutrient cycling, soil fertility improvement, CO_2 sequestration and erosion prevention. Some of these alternative perennial crops (cup plant, Virginia mallow, willow, and wild plant mixtures) fulfill an additional important environmental service that *Miscanthus* does not—the provision of nectar and pollen (Von Cossel, Wagner, et al., 2019). This service has become increasingly important due to rapidly decreasing pollinator abundances in agriculture (Hallmann et al., 2017; Isbell et al., 2017; Potts et al., 2016). Therefore, *Miscanthus* is less interesting from a biodiversity conservation perspective than cup plant (Bufe & Korevaar, 2018) or Virginia mallow. However, if harvested brown (in winter), *Miscanthus* can serve as habitat over a longer period of time and provided a range of open-land animals with protection from predators and the elements (Bellamy et al., 2009; Semere & Slater, 2007). This is not the case for cup plant which, as with maize, is harvested in autumn. For that reason, cup plant provides less habitat functions in winter than *Miscanthus*. The valorization of the multiple environmental services and the reduction of adverse environmental impacts provide information on the wider impacts of biomass production on an environmental, economic, and societal level and arguments for the integration of perennial biomass crops like *Miscanthus* into agricultural landscapes.

5.2. How to Best Integrate *Miscanthus* Into Agricultural Production in Order to Benefit From its Environmental Services

5.2.1. Diversification of the Agricultural Landscape

The long period of soil dormancy and the low use of pesticides and synthetic fertilizers in *Miscanthus* cultivation offers a number of ecological advantages (Heaton et al., 2008; Von Cossel, Lewandowski, et al., 2019), for both the cultivation site (agroecosystem) (Felten & Emmerling, 2011; Jørgensen et al., 2014; Williams & Feest, 2019) and adjacent ecosystems such as flowing or stagnant water bodies (Christian & Riche, 1998).

Miscanthus for isobutanol production is harvested on frozen topsoil in winter, allowing a more soil-friendly harvest compared to annual cropping systems (autumn harvest) (Von Cossel, Wagner, et al., 2019). The difference in harvest time diversifies conventional farm production systems and supports landscape heterogeneity (Huth et al., 2019). The large-scale maize cultivation for bioenergy, which in 2018 covered 7.5% of total crop land in Germany (FNR, 2019), creates a monotonous landscape that is negatively perceived in public opinion (Mockshell & Kamanda, 2017). A diversification through perennial crops with different growing cycles and harvest dates (e.g., in March for *Miscanthus*) could help to improve the image of bioenergy cropping systems (Borin et al., 2010; Daniel, 2001; Huth et al., 2019).

In addition, landscape heterogeneity is known to increase the resilience of agroecosystems (Tscharntke et al., 2012). In view of the severe climate change effects on agriculture expected in the near future (Pachauri et al., 2014; Samaniego et al., 2018; Teuling, 2018; Von Cossel, Wagner, et al., 2019), increasing the agroecosystem's resilience is highly relevant for adaptation strategies.

5.2.2. Strip Cultivation of *Miscanthus*

Site-specific strip cultivation of *Miscanthus* is a promising management strategy with economic and ecological advantages (Dauber & Miyake, 2016). The cultivation of *Miscanthus* on steep slopes or close to water bodies can help reduce the risk of both erosion and N leaching (Dauber & Miyake, 2016; Feldwisch, 2011). In addition, fields with awkward shapes could be economically optimized by realigning the field through planting *Miscanthus* in the odd corners (Clifton-Brown et al., 2017; Feldwisch, 2011). This field shape tuning could significantly improve the driving lane management and thus the costs of all measures that need to be performed in the vegetation periods of the annual crops grown on the main fields. The *Miscanthus* yield can compensate for the yield loss of the main crop.

Miscanthus integration, for example, in strips, creates habitats for insects and can connect surrounding habitats with each other (Dauber & Miyake, 2016). Additionally, the permanent strip vegetation on the field decreases erosion and evaporation (Dauber & Miyake, 2016). Furthermore, the average yields of the crops grown in between strip-cultivated *Miscanthus* can be significantly increased, as reported for a 2.5-m-high hedge-based strip cultivation system (Möndel, 2007).

These benefits decrease with field size, with habitat functions being provided in particular adjacent to or surrounding annual crop fields (Dauber & Miyake, 2016). Thus, large-scale *Miscanthus* production, for example, in the vicinity of an isobutanol biorefinery, has limited ecosystem service capacity. However, *Miscanthus* cultivation in strip cultivation only would extend the biorefinery's sourcing area and thus increase biomass transport requirements. Thus, in the overall concept of large-scale *Miscanthus* cultivation, strip cultivation should be seen as one important factor for the enhancement of environmental services in agricultural landscapes.

5.2.3. Social Implications of Crop Management

In temperate zones, the harvest of the main agricultural crops (often annual crops) takes place in the same time periods. These periods create various social burdens for the rural population (in particular children), including noise, traffic jams, dirt on roads, and dust in the air (Karr, 2012). Although these burdens also apply to *Miscanthus* harvest, the advantage is that it takes place in late winter. This is a less outdoor-oriented phase of social life, thus lowering direct exposure to the burdens mentioned above. However, a brown *Miscanthus* harvest also implies that leaves are shed during winter, long before the harvest, and depending on the main wind direction, can be blown across public or private properties (gardens, parks, roads etc.) and might need frequent removal. This can cause negative social impacts and pose a threat to *Miscanthus*' image. Therefore, when planning *Miscanthus* cultivation areas near villages, the main wind direction needs be considered to avoid negative effects for the local community. In this way, the benefits of its low management intensity and uncommon harvest date can be taken advantage of.

5.2.4. Income Creation

The creation of new income sources in rural areas has become highly relevant, since many regions have experienced migration and deprivation in the last decades (Jokisch, 2002; Kahane et al., 2013; Satterthwaite et al., 2010). This is linked to the lack of jobs in rural areas other than those in the primary sector. The development of the bioeconomy may be able to counteract this trend. Biorefinery concepts (European Commission, 2018a) are likely to be implemented in rural areas where the biomass is produced. This is because the transport of biomass (with its high water content) is usually more demanding than the transport of a refined product. The development of *Miscanthus*-based isobutanol biorefineries thus holds great potential for job creation and new income opportunities in rural areas.

6. Conclusions

The inclusion of environmental services in the design and assessment of agricultural systems offers a change of focus from a production-only to a more holistic perspective. In addition, this approach reveals the necessity for farmers to consciously reduce the adverse environmental and societal impacts of agriculture. The valorization of both the provision of these services and the reduction of negative impacts makes them explicitly tangible and accountable. Monetary values are the common denominator understood by all stakeholders in the political and societal discourse on the sustainability of agricultural biomass production.

Modern biofuel production from perennial biomass crops, such as *Miscanthus*, provides a promising option to stimulate a continued development of the currently stagnating biofuel sector in Europe. The environmental services provided by *Miscanthus* can improve soil fertility and thus the long-term crop productivity of marginal lands. Hence the cultivation of perennial biomass crops on marginal areas constitutes a substantial measure in the sustainable intensification of agriculture. Not only can considerable amounts of feedstock for biofuel be produced during the period of land restoration, but the process may also render the land economically viable (again) for food and feed production.

Putting this value-chain strategy into farming practice needs to be supported by political incentives. However, to date, farmers in Europe are not acknowledged for the provision of environmental services to society. This aspect needs to be addressed in the new EU Common Agricultural Policy (CAP) currently under development, which includes the development of the bioeconomy as one of its objectives. In this way, EU member states would benefit from more options in the design and implementation of national CAP Strategic Plans. This could stimulate the production and supply of sustainable biomass, a key challenge in the development of national bioeconomies. As already concluded by several other studies (Grethe et al., 2018; Neumann et al., 2017; Pe'er et al., 2014), this would be an important step forward towards sustainable agriculture. Another option would be a remuneration model in the form of a “common goods bonus” (Grethe et al., 2018; Neumann et al., 2017) that pays farmers for the provision of ecosystem services. This would compensate farmers for yield reductions and provide an incentive to adopt an environmental-service-based farming approach.

This conceptual study shows that the perennial biomass crop *Miscanthus* can provide the following services: air regulation, drinking water filtration, flood prevention, biodiversity, improved soil fertility, N_2 fixation, soil erosion reduction, and creation of more diverse landscapes with recreational value. Through the sustainable cultivation of perennial biomass for isobutanol biorefineries and the restoration of marginal land, environmental-service-based farming can help turn the food-agriculture-environment trilemma into a promising opportunity. In addition, it can contribute to the achievement of the 10% biofuel target by 2030 (International Energy Agency, 2019) to support the sustainability transition in the transportation sector.

Data Availability Statement

Data sets for this research are included in the references compiled in Table 1.

Conflict of Interest

The authors declare no competing interests.

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