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The True Costs and Benefits of Miscanthus Cultivation

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Abstract: Agroecosystems provide numerous ecosystem services (ESs) such as provisioning, regulating, habitat and cultural services. At the same time, the management of these agroecosystems can cause various negative impacts on the environment such as the generation of greenhouse gas emissions. However, the way humans manage agroecosystems often focuses only on the production of agricultural goods, which yield monetary benefits in the short term but do not include the positive and negative external effects on ESs. In order to enable a holistic assessment of the economic and environmental costs and benefits, the current study combines the production costs, the monetary value of the ESs provided and the monetization of the environmental impacts caused by the management of agroecosystems using the perennial crop miscanthus as an example. Depending on the scenario assessed, the cultivation of miscanthus leads to a net benefit of 140 to 3051 EUR ha^{-1} yr^{-1}. The monetary value of the ESs provided by the miscanthus cultivation thereby considerably outweighs the internal and external costs. The approach applied allows for a holistic assessment of the benefits and costs of agroecosystems and thus enables management decisions that are not only based on the biomass yield but include the various interactions with the environment.

Keywords: life-cycle assessment; ecosystem services; true cost accounting; monetization; bioeconomy; miscanthus

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1. Introduction

Ecosystems provide numerous benefits for humans, such as food and air to breathe, without which survival would not be possible [1–3]. Agroecosystems play a crucial role in the preservation of the provision of these services, as in Germany for example, more than 50% of the land area is used for agriculture [4]. The incorporation of perennial crops such as miscanthus (*Miscanthus* ANDERSSON) or cup plant (*Silphium perfoliatum* L.) into the predominately annual monoculture cropping systems offers the chance to increase the provision of various ecosystem services (ESs), including water purification, pollination and biological plant protection in addition to the provision of biomass [5–8]. Von Cossel et al. (2020b) [9] showed for miscanthus, a multipurpose industrial perennial crop for providing biomass for bioenergy and biobased products [10,11], that the monetary value of the ESs provided can be more than three times the profit a farmer earns for just selling the biomass.

However, the way humans manage ecosystems is often focused only on the production of agricultural goods, including biomass, and less attention is paid to the complexity of the long-term factors underlying ESs, especially with regard to their mutual interactions (synergies, trade-offs, etc.) [12]. For example, agricultural activities often lead to a decline in biodiversity despite the potential importance of biodiversity for the resilience of the agroecosystem [13]. In addition, the existence of many indirect ecosystem factors, some of which are still unknown in their importance for provisioning ESs, like faunal species diversity, is just taken for granted [13]. The main reason is that in the management of conventional cropping systems, usually only ESs with monetary benefits in the short term are considered, such as biomass provision [14]. On the other side, despite levels being usually lower than annual cropping systems, miscanthus cultivation can cause various negative impacts on the environment, such as the generation of greenhouse gas emissions (GHG) through the combustion of fossil fuels or nutrient leaching through the application of mineral and organic fertilizers [15]. These emissions cause considerable external costs, which at the moment are usually disregarded or not adequately taken into account [16]. In summary, the cultivation of agroecosystem may lead to various positive and negative external effects, which are currently not included in the management process.

So far, true-cost-accounting approaches usually only focus on costs without taking benefits into account. Therefore, this paper aims to apply a new expanded approach by taking a more holistic look at both benefits and costs (the sum of which would result in "true costs and benefits") of cropping systems using miscanthus (*Miscanthus* ANDERSSON) cultivation as an example for a perennial, industrial crop. This assessment combines the production costs, the monetary value of the ESs provided as well as the monetization of the environmental impacts caused by the cultivation and the harvest of the biomass. The combination of these analyses allows for a holistic assessment of the true economic and environmental value provided by cropping systems in monetary terms.

2. Materials and Methods

2.1. Goal and Scope

The goal of the current study is the holistic assessment of the economic and environmental costs and benefits of miscanthus cultivation for society. The current study focuses, therefore, on crop cultivation, harvest, and transport of the biomass to the farm gate. The costs and benefits occurring in the further downstream value chain are not assessed. In addition, social costs and benefits are not included in this study. The economic costs of miscanthus cultivation are assessed based on the production costs. The environmental benefits are represented via the monetized ESs provided by miscanthus, including the revenue of the biomass sale. The environmental costs of miscanthus cultivation are assessed by conducting a life-cycle assessment (LCA) and monetizing the identified environmental impacts. This allows us to internalize these previously external costs. However, there are various monetization approaches available that differ substantially in their monetization factors, for example, due to differences in the selected cost approach or the area of reference [17,18]. Therefore, the influence of the selected monetization approach is critically analyzed and discussed.

2.2. Production Costs

The production costs of miscanthus cultivation in Germany are based on Winkler et al. (2020) [19] and comprise average machine, material, energy and labor costs as well as interest. Winkler et al. (2020) [19] calculated the production costs for two different cultivation systems (conventional and organic), two yield levels, field sizes and farm-field distances, as well four utilization pathways differing in harvest regimes and methods. In the present study, a conservative approach was selected, setting the field-farm distance at 10 km and the field size at 1 ha with an annual average dry matter (DM) yield of 15 Mg ha^{-1}. The miscanthus harvest was considered annually via direct cutting and chipping on the field by a forage harvester in March, which is the standard harvest procedure for miscanthus in Germany, as combustion is still the most common form of use [20,21].

In the production costs calculated by Winkler et al. (2020) [19], land costs were not included. According to the German Federal Office for Agriculture and Food, the annual lease prices for agricultural land per hectare in the year 2020 amounted to 375 EUR (BLE 2021). For a holistic assessment, the costs of land have to be included in the production costs.

2.3. Monetization of Ecosystem Services

The ESs assessed, as well as their monetary value, are based on von Cossel et al. (2020b) [9] (Figure 1). The revenues generated by the biomass sale are based on Winkler et al. (2020) [19], assuming biomass prices between 65 to 95 EUR per Mg chopped miscanthus material and a biomass yield of 15 Mg DM ha^{-1} yr^{-1}. In von Cossel et al. (2020b) [9], the calculation of the environmental benefits provided by the sequestration of CO_2 in the soil is based on a CO_2 emission certificate price of 26.83 EUR per Mg CO_2. In order to be consistent with the monetization factors used for the LCA results, the approach of avoidance cost was applied, as presented in Trinomics (2020) [22]. Therefore, an environmental benefit of 102.50 EUR per Mg CO_2 sequestered in the soil is applied in the current study. The CO_2 emissions, which can be substituted by the miscanthus-based products [23,24], are not included because the current study only focuses on the cultivation of miscanthus and not on the entire miscanthus-based value chain. In addition, the monetary values of both *N_2 fixation* and *nutrient recycling* are excluded from the current study because these two ESs lead to a reduction in the amount of mineral fertilizer required [25,26] which is already included in the production costs. Furthermore, the ES *waste treatment—reduced nutrient leaching* is based on a reduction in nitrate leaching when comparing the cultivation of miscanthus and maize [9]. As the current study focuses on the assessment of the costs and benefits of one cultivation system and does not apply a comparison, this ES is not included.

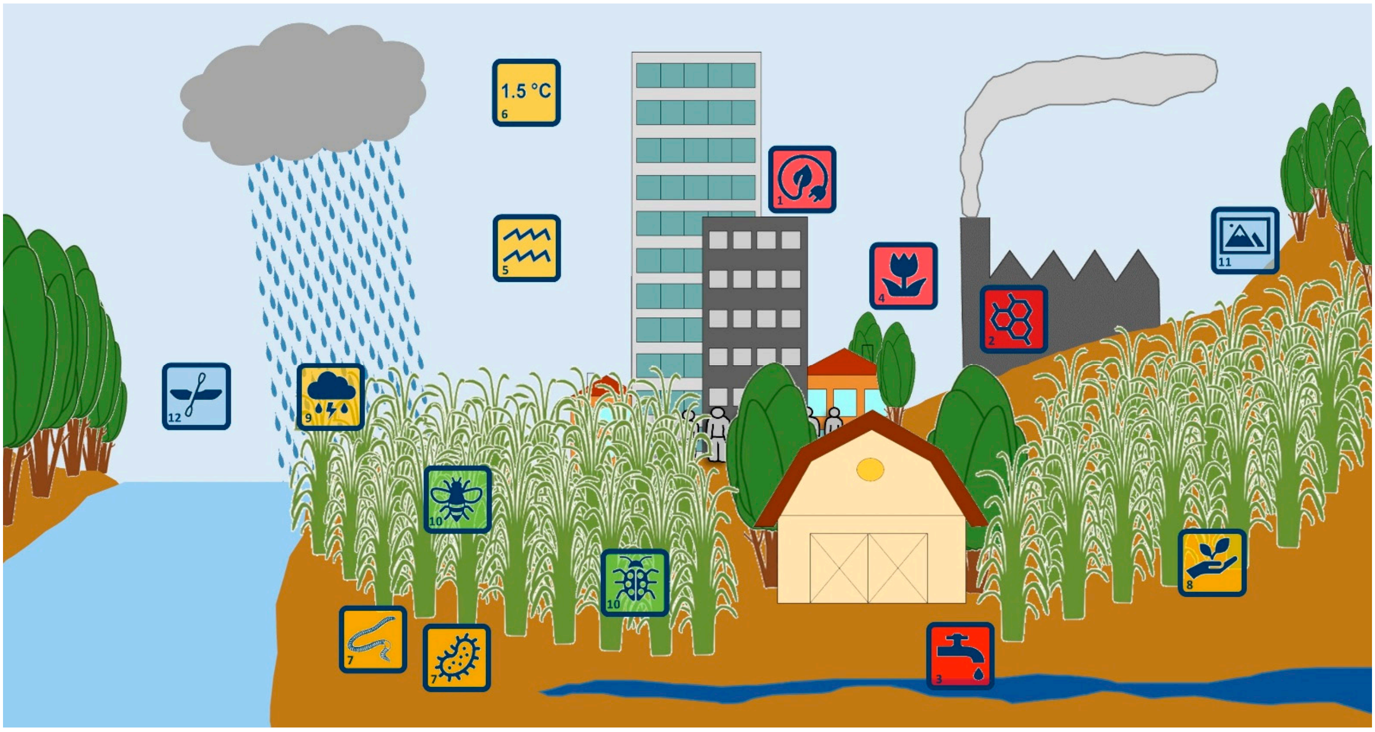

Figure 1. Overview of the main ecosystem services considered in this study in accordance with von Cossel et al. (2020b) [9]. Provisioning ecosystem services (in red): (1) raw material, (2) genetic resources, (3) fresh water/groundwater, (4) ornamental resources; Regulating ecosystem services (in orange): (5) air quality regulation, (6) climate regulation, (7) improvement of soil fertility, (8) erosion prevention, (9) moderation of extreme events; habitat ecosystem services (in green): (10) pollination and biocontrol; cultural ecosystem services (in blue): (11) aesthetic information and (12) recreation and tourism.

For several ESs, the monetary value in EUR h^{-1} yr^{-1} is given by von Cossel et al. (2020b) [9] as a range with minimum and maximum values. In the current study, the mean of these values is used to display the average benefit of the ESs provided. The influence of this assumption is analyzed in a scenario analysis, applying the minimum and maximum values.

2.4. Assessment and Monetization of the Environmental Impacts of Miscanthus Cultivation

In order to assess the environmental performance of the miscanthus cultivation a cradle-to-farm-gate LCA was conducted following the structure of the ISO standards 14040 and 14044 [27,28]. In the current study, the 16 impact categories and assessment methods were applied, which are included in the Product Environmental Footprint (PEF) methodology of the European Commission [29]. The selected functional unit (FU) is 1 ha under miscanthus cultivation with an average yield of 15 Mg DM ha^{-1} yr^{-1}. An area-based FU is chosen so that a consistent comparison is possible between production costs, benefits provided, in form of ESs, which are given on a hectare basis and the results of the LCA.

The data used for modeling the foreground system is based on the miscanthus cultivation system described in Winkler et al. (2020) [19], which also provides the basis for the calculation of the production costs (see Section 2.2). Summaries of the agricultural operations conducted during the cultivation period and the main in- and outputs are presented in Tables 1 and 2. Inputs that are only applied in the establishment or the harvest phase, such as pesticides or fertilizer, are converted to the entire cultivation period of 20 years. Nitrous oxide (N_2O), nitrate ($NO_3{}^-$) and phosphorus emissions due to the use of mineral fertilizers are modeled according to the recommendations of Pant and Zampori (2019) [29]. N_2O emissions from harvest residues were modeled according to IPCC (2019) [30]. The proportion of harvest residues in the form of leaves and stubbles is taken from Lask et al. (2021) [31]. Heavy metal emissions to agricultural soils caused by the application of fertilizers and pesticides are estimated based on Freiermuth (2006) [32]. It is assumed that 90% of the pesticides are released into agricultural soils, 9% into air and 1% to water [29]. Background data on emissions associated with the production of the input substrates such as fertilizers or pesticides are based on the ecoinvent database 3.8 using the cut-off system model [33]. In the current study, market datasets are used in order to include average transport impacts [33]. The software openLCA 1.10.3 is applied for the modeling and the calculation of the impacts using the integrated PEF method EF 3.0 (adapted).

Table 1. Agricultural operations during a 20-year miscanthus cultivation period (adapted from Winkler et al. (2020) [19]).

Agricultural Operation	Frequency per Cultivation Period
Plowing	2
Rotary harrowing	1
Planting	1
Mulching—first year	1
Herbicide spraying	2
Fertilizing	18
Harvesting	19

Table 2. Main inputs and outputs of miscanthus cultivation per year (adapted from Winkler et al. (2020) [19]).

Input/Output	Amount	Unit
N	47	kg ha^{-1} yr^{-1}
P	5	kg ha^{-1} yr^{-1}
K	82	kg ha^{-1} yr^{-1}
Herbicides	0.34	kg ha^{-1} yr^{-1}
Biomass dry matter yield	15	Mg ha^{-1} yr^{-1}

The monetization factors for the respective impact category are based on the central values stated in the report prepared by Trinomics (2020) [22] (see Table 3), as this is the only study that suggests a set of monetization factors which are explicitly meant to be used in combination with the PEF method applied in the current study [34]. In order to test the influence of the monetization factors, a sensitivity analysis was conducted, applying, in addition to central values, a low and high monetization value, as shown by Trinomics (2020) [22]. For terrestrial eutrophication, no satisfactory monetization approach is available at present, which could be applied to the PEF method at this early development stage [22,34]. Therefore, the external costs of this impact category are not included in the current study.

Table 3. Monetization factor for the impact categories assessed in EUR_{2018} per unit impact based on Trinomics (2020) [22].

Environmental Impact Category	Unit	Monetization Factor [EUR_{2018} per Unit Impact]
Acidification	mol H^+ eq.	0.344
Climate change	kg CO_2 eq.	0.1025
Ecotoxicity, freshwater	CTUe	0.0000382
Eutrophication, freshwater	kg P eq.	1.92
Eutrophication, marine	kg N eq.	3.21
Eutrophication, terrestrial	mol N eq.	-
Human toxicity, cancer	CTUh	902,616
Human toxicity, non-cancer	CTUh	163,447
Ionizing radiation	kBq U-235 eq.	0.0012
Land use	Pt	0.000175
Ozone depletion	kg CFC11 eq.	31.4
Particulate matter	disease inc.	784,126
Photochemical ozone formation	kg NMVOC eq.	1.19
Resource use, fossils	MJ	0.0013
Resource use, minerals and metals	kg Sb eq.	1.64
Water use	m^3 water eq.	0.00499

3. Results

The following sections describe the results of the analyses of (i) the monetary values provided by miscanthus cultivation and (ii) the environmental and economic costs of miscanthus cultivation.

3.1. Monetary Values of the ESs Provided by Miscanthus Cultivation

The estimated average monetary values of the ESs provided annually by cultivating miscanthus on 1 ha sum up to 3118 EUR (see Table 4). In the current study, the average monetary values for the ESs provided by miscanthus cultivation were applied, as explained in Section 2.3. In case the minimum monetary values of the ESs were used, that excluded location-specific ESs (e.g., flood plain management, erosion prevention, provision of drinking water through sediment passage), the ESs combined were worth 1985 EUR ha^{-1} yr^{-1}. Assuming the maximum monetary values of the ESs provided (including location-specific ESs) they would account for 4250 EUR ha^{-1} yr^{-1} [9].

Table 4. Single monetary values and total value of the ESs in EUR ha^{-1} yr^{-1} provided by miscanthus cultivation adapted from Winkler et al. (2020) [19] and von Cossel et al. (2020b) [9]. For those ESs in which ranges of variation are given in von Cossel et al. (2020b) [9], the arithmetic means were calculated. Some ESs (e.g., nutrient cycling, N_2 fixation) shown in von Cossel et al. (2020b) [9] were excluded in this study, as explained in Section 2.3.

ES Category	ES	Value (EUR ha^{-1} yr^{-1})
Provisioning services	Raw material	1200
	Genetic resources	18
	Fresh water/groundwater	56
	Ornamental resources	17
Regulating services	Air quality regulation	64
	Climate regulation	828
	Improvement of soil fertility	23
	Erosion prevention	22
	Moderation of extreme events	386
Habitat services	Pollination and biocontrol	50
Cultural services	Aesthetic information	429
	Recreation and tourism	27
Total	**-**	**3118**

3.2. *Environmental and Economic Costs of Miscanthus Production*

In the scenario described, the annual production costs amount to 1010 EUR ha^{-1}, including the lease price for agricultural land. Besides the land costs, the establishment of the miscanthus plantation in the first year of cultivation is one of the main cost drivers [19].

In Table 5, the LCA results of the miscanthus cultivation per ha in the analyzed impact categories are displayed.

Table 5. Environmental impact of miscanthus cultivation per environmental impact category and ha and year.

Environmental Impact Category	Impact Result	Unit
Acidification	22.98	mol H^+ eq.
Climate change	1248.01	kg CO_2 eq.
Ecotoxicity, freshwater	3.11×10^4	CTUe
Eutrophication, freshwater	0.42	kg P eq.
Eutrophication, marine	16.24	kg N eq.
Eutrophication, terrestrial	94.00	mol N eq.
Human toxicity, cancer	1.51×10^{-6}	CTUh
Human toxicity, non-cancer	3.49×10^{-5}	CTUh
Ionizing radiation	42.79	kBq U-235 eq.
Land use	5.10×10^5	Pt
Ozone depletion	8.82×10^{-5}	kg CFC11 eq.
Particulate matter	0.00015	disease inc.
Photochemical ozone formation	4.98	kg NMVOC eq.
Resource use, fossils	9949.30	MJ
Resource use, minerals and metals	0.02	kg Sb eq.
Water use	394.86	m^3 water eq.

In Table 6, the monetized environmental impacts are shown applying the low, central and high monetization factors. The costs of the environmental impacts are, to a great extent, caused by the impact categories climate change (fossil fuel combustion and fertilizer production, as well as fertilizer-induced emissions), land used for agricultural production, and particulate matter formation (fertilizer-induced ammonia emissions).

Table 6. Monetized environmental impact of miscanthus cultivation applying the monetization factors by Trinomics (2020) [22].

Environmental Impact Categories	Monetized Environmental Impacts (EUR_{2018})		
	Low	Central	High
Acidification	4.04	7.90	37.16
Climate change	76.75	127.92	241.61
Ecotoxicity, freshwater	7.44×10^{-20}	1.19	5.85
Eutrophication, freshwater	0.11	0.81	0.92
Eutrophication, marine	52.13	52.13	52.13
Eutrophication, terrestrial	0	0	0
Human toxicity, cancer	0.26	1.36	4.21
Human toxicity, non-cancer	1.05	5.70	26.36
Ionizing radiation	0.03	0.05	1.97
Land use	44.39	89.29	178.07
Ozone depletion	2.01×10^{-3}	2.77×10^{-3}	0.01
Particulate matter	99.30	117.62	180.69
Photochemical ozone formation	4.34	5.93	9.47
Resource use, fossils	0	12.93	67.66
Resource use, minerals and metals	0	0.03	0.11
Water use	1.65	1.97	93.15
Total (EUR ha^{-1} yr^{-1})	**284.06**	**424.84**	**899.36**

Figure 2 shows the "Standard scenario" in which average ESs are provided by the miscanthus cultivation and central monetization factors are applied. The ES provided are divided into provisioning services, which are mainly dominated by revenues generated through the sale of the biomass, regulating and habitat services, and cultural services. In the standard scenario, the monetarized benefits of miscanthus cultivation considerably outweigh the economic and environmental costs resulting in a true benefit of 1762 EUR ha^{-1} yr^{-1}.

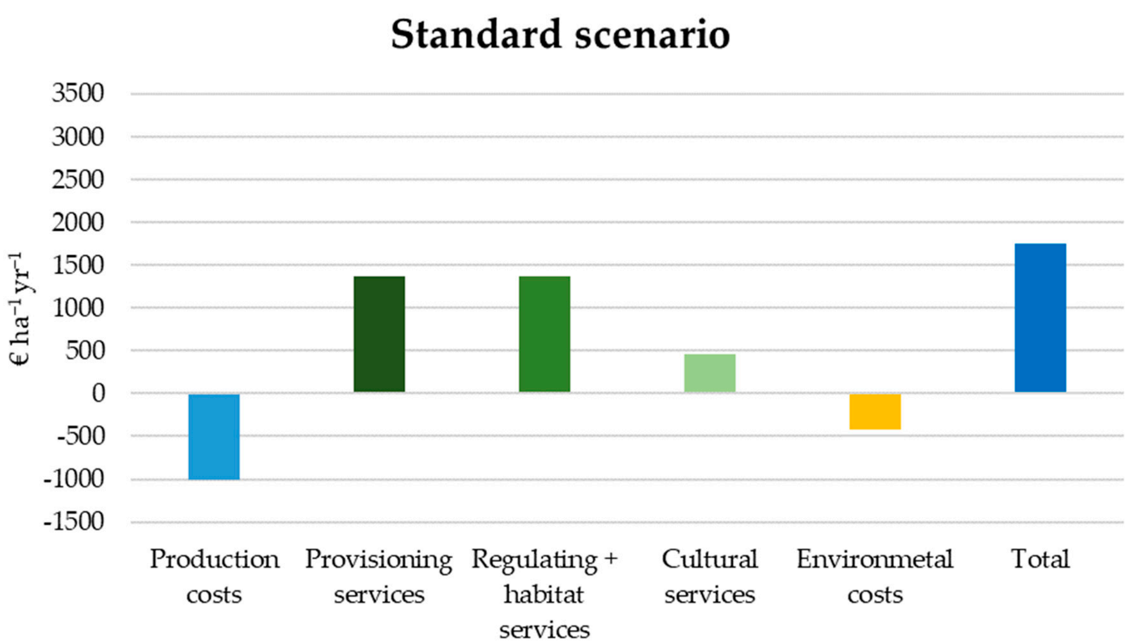

Figure 2. True costs and benefits in the standard scenario, assuming average ESs provision and central monetization factors for environmental impacts.

Figure 3 shows the "Best-case scenario", in which maximum ESs are provided by the miscanthus cultivation (including location-specific ESs) and low monetization factors are applied. The substantially higher location, specific ESs and the low environmental costs lead to a total benefit of miscanthus cultivation of 3051 EUR ha^{-1} yr^{-1} (see Figure 3).

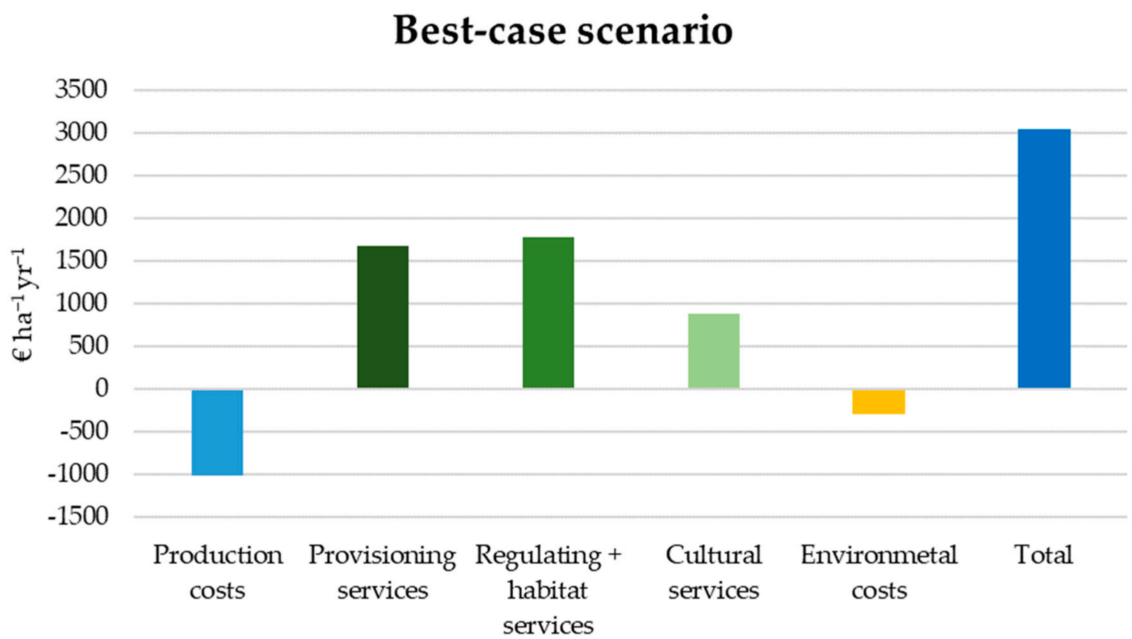

Figure 3. True costs and benefits in the best-case scenario assuming maximum ESs provision and low monetization factors for environmental impacts.

Figure 4 shows the "Worst-case scenario", in which minimum ESs are provided by the miscanthus cultivation (excluding location-specific ES) and high monetization factors are applied. This still leads, in total, to a benefit of 140 EUR ha^{-1} yr^{-1} (see Figure 4).

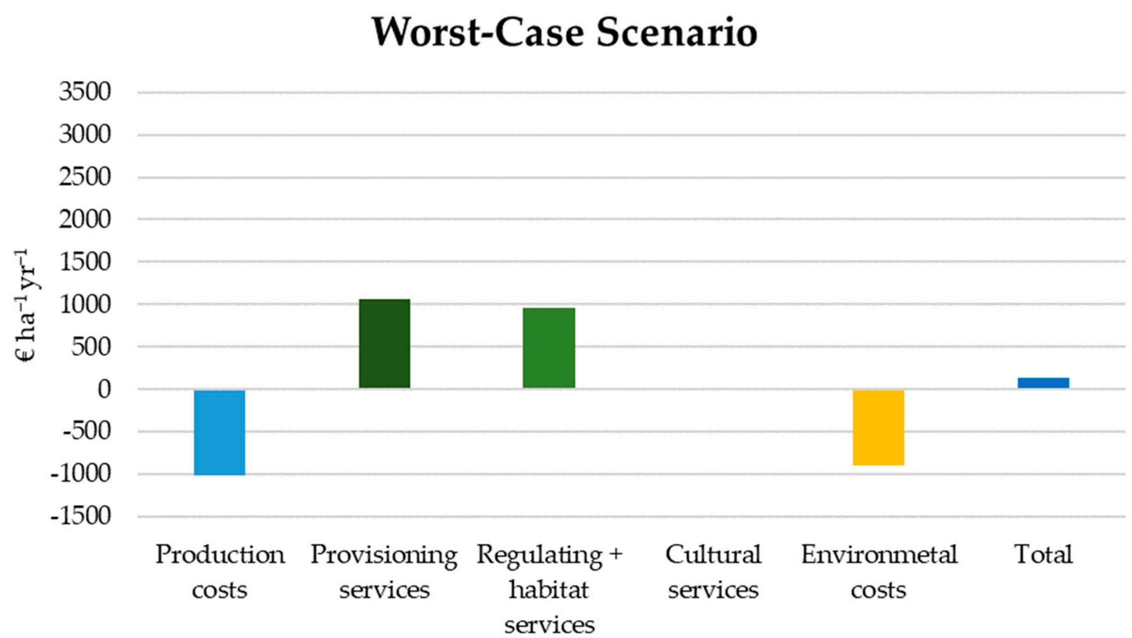

Figure 4. True costs and benefits in the worst-case scenario assuming minimum ESs provision and high monetization factors for environmental impacts.

4. Discussion

4.1. Discussion of the Data Used and the Methodologies Applied

In the following, the influence of the data used and the methodologies applied on the results are critically discussed. In particular, the biomass selling price is an important factor in the assessment of the economic costs and benefits of miscanthus cultivation. In the current study, a conservative biomass selling price of 80 EUR Mg^{-1} DM was applied. If the miscanthus is cultivated for other utilization pathways, the selling price could be substantially higher (105–600 EUR Mg^{-1} DM) [19]. As a result, the monetary value provided by the cultivation of 1 ha miscanthus would increase significantly. Besides the selected utilization pathway, also the annual fluctuations in biomass demand have a considerable influence on the biomass selling price. For a realistic evaluation of the costs and benefits of different cropping systems, it has, therefore, to be emphasized that it is crucial to use average data and to assess and discuss the uncertainty included in the results.

Besides the availability of reliable data, one significant barrier to the implementation of the approach described is the variety of methods available for assessing the economic costs, the environmental benefits and impacts, as well as their monetization, which hinders the comparability of the results. For example, no standardized life-cycle costing (LCC) framework is available for the agricultural and food sector [35]. According to Degieter et al. (2022) [35], it is crucial to include all cost categories (e.g., inputs, labor) and to report all methodological choices made during the preparation of the study to provide comparable and comprehensible results.

In addition to the method used to estimate the costs, the selected life-cycle impact assessment (LCIA) method and the chosen monetization approach significantly influence the results [17,18]. In order to evaluate this impact, the monetized environmental impacts of the miscanthus cultivation were also assessed in the current study applying the LCIA method Recipe 1.13 Midpoint (Hierarchist) and the monetization approach described in the Environmental Prices Handbook [36,37]. Using these two approaches, the monetized environmental impacts of 1 ha miscanthus cultivation amount to 1266 EUR ha^{-1} yr^{-1} (see Table S1 in the supplementary material) and are therefore slightly higher than the values applied in the worst-case scenario (899 EUR ha^{-1} yr^{-1}). Applying the costs assessed in the sensitivity analysis in the standard scenario, would still yield a significant benefit. Only the worst-case scenario would lead to net costs due to the cultivation of miscanthus.

The values from the study by von Cossel et al. (2020b) [9], which were used for the assessment of the monetary values of the ESs, are subject to a large degree of uncertainty. One reason is the large temporal and spatial variability of the assessed Ess, for instance, due to variations in the biomass yield. These might be caused by climate change-induced variations in growing conditions such as drought periods [38,39], changes in precipitation distributions [40], or frost damage due to lack of a snow cover [41]. In addition, temporal and spatial variations may also occur in the synergies and trade-offs between individual ESs. The age of the miscanthus stand has, for example, a significant influence on erosion control [42] due to better ground cover and biomass yield. After the establishment phase, both increase significantly. However, there are also trade-offs between different ESs, such as biomass yield and pollination. Gaps in the miscanthus stand could lead to an increased appearance of wild plants, which on the one hand, provide the fauna with an additional food spectrum [43,44]. However, on the other hand, the gaps could permanently worsen the biomass yield performance of miscanthus in the following years [19,44].

A more accurate and reliable assessment of the overall monetary value of the ESs provided by different agroecosystems, therefore, requires region- and year-specific calculation. Nevertheless, despite the uncertainty included in the calculation of the ESs monetary values, the overall values considered here in the best-, standard- and worst-case scenarios provide a reliable basis to serve as a benchmark for future studies, as also critically discussed by von Cossel et al. (2020b) [9].

In a combined assessment of environmental impacts and ESs, as was undertaken in the context of the present study, it is crucial to ensure that double counting of environmental impacts is avoided. One example of this is the ES *carbon sequestration* and the LCA impact category of *climate change*. Various LCA studies include the carbon sequestered in the soil in their LCIA results [45]. In case the carbon sequestered in the soil is already accounted for in the LCIA results in the impact category *climate change*, it cannot be accounted for in the monetization of the ESs. The same could be the case for the ES *improvement of the soil quality*, for which LCIA methods also already exist or are in development [46]. Alejandre et al. (2019) [47] analyzed which ESs can be evaluated via existing LCIA methods and which have to be evaluated by other ES assessment methods. Their study could be used to identify possible areas of overlap between ESs and LCA results and thus reduce the risk of double counting.

In addition, it has to be emphasized when discussing the different assessment approaches that the evaluation of the economic and environmental costs of miscanthus production includes the whole previous value chain (e.g., production of the input substrates). The evaluation of the environmental benefits, however, only focuses on the field level and excludes the upstream processes since there is not enough information available for a holistic ESs assessment across the entire whole value chain. Another methodological consideration is the inclusion of social costs and benefits in the future to complement the economic and environmental towards a holistic true cost accounting approach for the assessment of agricultural production systems.

4.2. Discussion of the Results and Applicability in Practice

The results of the current study demonstrate a clear total benefit of the miscanthus cultivation independently of the scenarios assessed. However, as also discussed in the section above, these results are associated with a high degree of uncertainty. Increased harmonization and standardization regarding the monetization of the LCA results and especially the assessment of ESs is needed to reduce this uncertainty and to ensure comparability within studies, but also with other true-cost accounting studies in the agricultural sector [48]. In order to use these results in the decision process or for the development of subsidies, comparable assessments for other cropping systems are needed. Only by comparing the local costs and benefits of different cropping systems well-founded decisions about the advantageousness of the respective systems can be made. Thereby it is crucial to apply a holistic view of the cropping systems under study, especially when evaluating the costs and benefits of annual crops, and to include crop interactions in the assessment, such as positive effects between different crops in a crop rotation [49].

In the current study, a cradle-to-farm gate approach was applied. However, depending on the goal of the study, other system boundaries may be more suitable because the selection of the system boundaries can have a significant influence on the results. Von Cossel et al. (2020b) [9], for example, showed in their publication that the substitution of the fossil alternatives by miscanthus-based isobutanol could lead to CO_2 savings of 19.1 Mg CO_2-eq. ha^{-1} a^{-1}. This would correspond to an additional benefit of 1958 EUR ha^{-1} yr^{-1}.

The results presented here demonstrate that ESs provided by miscanthus cultivation have a significant value besides the sole provision of biomass. However, these ESs are currently not included in the management process. One possibility to holistically include the ESs provided by the cultivation systems into the farmer's management process is to encourage sustainable agricultural practices via subsidies [50] or direct payments for ecosystem services (PES) [51]. Miscanthus, for example, has been included on the positive list for cultivation in ecological focus areas by the European Commission in 2018 [52]. For farmers, this means that they can receive an extra subsidy for cultivating miscanthus. The careful development of subsidies could thereby lead to crop selection and rotation planning, which is not only based on the sale price of the biomass but also on much-needed and wanted ESs. Knowing the true costs and benefits of different cropping systems could be a valuable basis for making decisions about the development of such subsidies.

5. Conclusions

The approach applied in the current study allows for a holistic assessment of the benefits and costs of agroecosystems through the inclusion of the monetary value of various ESs, the production costs as well as the monetized environmental impacts. For miscanthus, it could be shown that the monetary value of the ESs provided by its cultivation considerably outweigh the internal and external costs. This approach thereby enables management decisions, which are not only based on the biomass yield but include the various interactions with the environment. In addition, the results of such an approach provide valuable insights for the development of environmental incentives and the determination of the amount of payment farmers receive for environmental-friendly farming practices.

However, there is still considerable uncertainty associated with the results. Standardized ES assessment and monetization methods are required in order to enable sound comparison between different cultivation systems in terms of economic and environmental sustainability. Furthermore, the approach has to be applied using local data because ESs provided by agroecosystems can vary greatly locally, for example, in regard to erosion control or flood prevention.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12123071/s1, Table S1: Monetized environmental impacts of miscanthus cultivation per hectare and year applying the ReCiPe (H) 1.13 methodology.

Author Contributions: Conceptualization, all authors; methodology, B.W., J.L., M.v.C. and M.W.; software, M.W.; investigation, J.L., M.v.C. and M.W.; writing—original draft preparation, B.W., J.L., M.v.C. and M.W.; writing—review and editing, all authors; visualization, M.v.C. and M.W. All authors have read and agreed to the published version of the manuscript.

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