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Assessing and Governing Ecosystem Services Trade-Offs in Agrarian Landscapes: The Case of Biogas

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Academic Editors: Benjamin Burkhard, Stefan Hotes, Hubert Wiggering and Peter Verburg
Received: 8 July 2015; Accepted: 12 January 2016; Published: 22 January 2016

Abstract: This paper develops a method to explore how alternative scenarios of the expansion of maize production for biogas generation affect biodiversity and ecosystem services (ES). Our approach consists of four steps: (i) defining scenario targets and implementation of assumptions; (ii) simulating crop distributions across the landscape; (iii) assessing the ES impacts; and (iv) quantifying the impacts for a comparative trade-off analysis. The case study is the region of Hannover, Germany. One scenario assumes an increase of maize production in a little regulated governance system; two others reflect an increase of biogas production with either strict or flexible environmental regulation. We consider biodiversity and three ES: biogas generation, food production and the visual landscape. Our results show that the expansion of maize production results in predominantly negative impacts for other ES. However, positive effects can also be identified, *i.e.*, when the introduction of maize leads to higher local crop diversity and, thus, a more attractive visual landscape. The scenario of little regulation portrays more negative impacts than the other scenarios. Targeted spatial planning, implementation and appropriate governance for steering maize production into less sensitive areas is crucial for minimizing trade-offs and exploiting synergies between bioenergy and other ES.

Keywords: landscape planning; ecosystem services; landscape services; landscape functions; trade-offs; biogas

1. Introduction

Policy, business and civil society actors in many EU member states have pushed for an expansion of biogas production as a renewable energy source. In Germany, for example, the Renewable Energy Sources Act (2004) has provided substantial financial incentives for the establishment of biogas plants and for the contribution of biogas to the energy system.

In response to these calls, many states, counties and communities have set themselves ambitious targets for renewable energy generation, and for biogas in particular, to be achieved approximately between 2025 and 2050. Numerous biogas plants have been installed, causing a substantial change in the crop cycles within their proximity in order to expand the production of biomass for biogas generation. In some German municipalities, for instance, increased maize cultivation for biogas and fodder production encompasses more than 85% of all arable land [1,2].

Unfortunately, in many regions, the increase in the production of maize for energy production has dramatic negative effects on biodiversity and several ecosystem services (ES) [3,4]: Trade-offs, which come from an increase in the area appropriated for the generation of biogas, include provisioning services, such as fodder and food, due to agricultural land competition [5,6], regulating services, such as decreased water quality, due to higher inputs of fertilizers and a longer period of open soil than in other crops [7], and cultural services through increased monocultures and, thus, decreases in the diversity of the visual landscape in the proximity of biogas plants [8,9].

The spatial implications of increased maize production and the resulting negative effects on biodiversity and ES are, however, only marginally considered in policy and the decision-making of counties and communities. The dearth of information is a key challenge for decision-makers, and consequently, the potential adverse effects on ES and economic losses for society are not considered [10,11].

Decision-making about the amount of biogas to be generated in a particular spatial area, as well as the siting of biogas plants, are topical issues in which the impact and trade-offs of decisions on biodiversity and ES are only partially considered. Landscape planning, as a forward-looking action to preserve, enhance and restore landscapes (*cf.* [12]), is arguably well positioned to provide the necessary environmental information, impact assessments and solution options for overcoming this shortcoming and supporting a better informed decision-making process (e.g., [13]). However, despite some initial explorations [3,10,14,15], landscape planning still lacks necessary concepts and methods. Some sophisticated approaches are available for investigating the impacts of biogas production on the farm to landscape level [16–19]. Some spatially-explicit integrated modelling frameworks also exist for exploring opportunity costs [20–22]. However, these approaches and tools are relatively complex, too resource intensive for practical application and, thus, not best suited to assist in landscape planning and decision-making.

The focus of this paper is on the development and testing of assessment methods to assist in landscape planning and decision-making. These tools are tested using simulated data on the current and potential future distribution of crops across the study area of the region of Hannover, Germany. However, these simulations are not the central concern of the paper, but are rather used to illustrate the application of the tools

2. Case Study Area

The case study for the analysis is the region of Hannover (Region Hannover), located in the south of the German federal state of Lower Saxony (Figure 1). The urban center is the city of Hannover, which is surrounded by rural areas. More than half of the region′s area is agricultural land (55% of total area). The dominant agricultural land use form is cropland (40% of total area), and about 19% of the total area is covered with forests. Region Hannover represents an interesting case study due to its varying biophysical conditions and the resulting diversity of cultivated crops. The southern part is characterized by very fertile loess soils that are almost exclusively cultivated with sugar beet and wheat. In the northern and north-eastern part, however, sandy and less fertile soils dominate, and more maize, barley and rye is cultivated. The percentage of grassland is also much higher in the north. In choosing Region Hannover as a case study, we benefited from good data availability, including statistical data on cultivated crops, spatial data on land use and biogas plants and information about objectives concerning the expansion of renewable energies. Furthermore, we could build upon prior contact to local policy makers, administrators, farmers and other civil society stakeholders, who took part in workshops in connection to the research.

In 2012, biogas plants were predominantly found in in the northern part of the study area. The installed capacity was 19,729 kW [23]. Maize cultivation took place on 11% of the arable land [24], whereas energy maize claimed only 6% (own calculation, based on [23–25]). In Lower Saxony, the share of maize cultivation was 23.8% of agricultural land, while maize cultivation for biogas took place on 9%. However, there are huge regional differences. In regions with a high demand for maize as fodder, maize cultivation for biogas has increased the already high level of cultivation to, at times, more than 50%. In these regions, the share of maize cultivation for biogas was between 19% and 38%. In other regions, maize cultivation took place on generally only 6%–13% of the arable area and is predominantly used for biogas production [26]. The potential for an increase of biogas production in the region of Hannover can thus be considered as high compared to other counties in Lower Saxony.

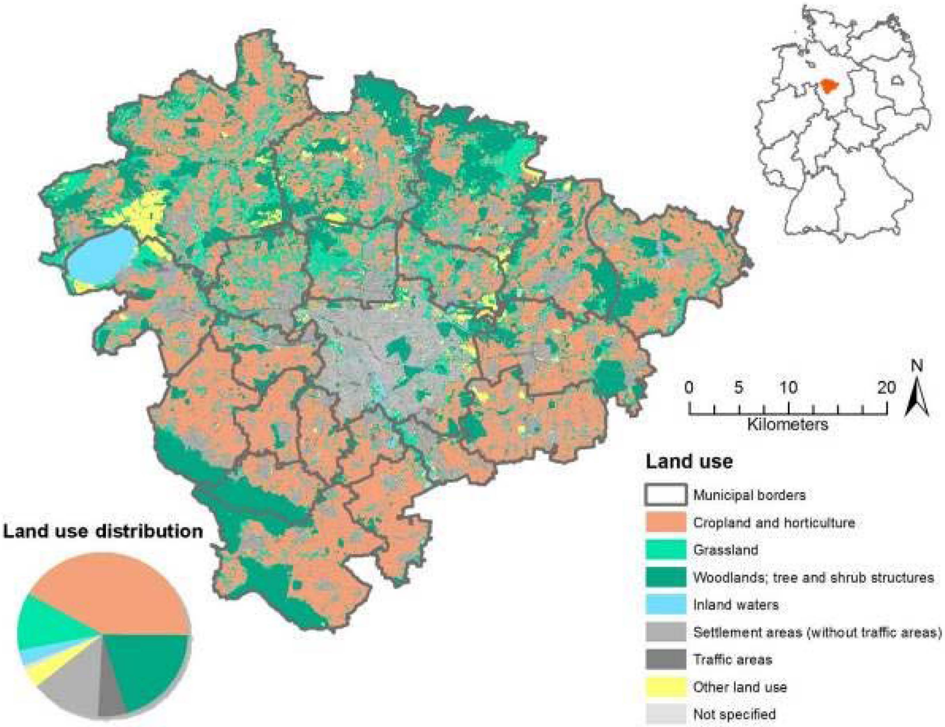

Figure 1. Land use in the case study area of the region of Hannover.

3. Methods

3.1. Research Design

Scenario-based landscape planning [27–32] is potentially a useful approach to assess possible impacts from biogas production on nature and the landscape and to develop spatially-explicit solution strategies and implementation options. Scenario-based landscape planning makes reasonable assumptions about future developments with and without planning interventions, simulates likely land use changes and analyses potential effects on nature and landscape. Scenario-based landscape planning thereby enables social learning and better informed decision-making (*cf.* [33]). More specifically in our case, it enables better decision-making about the amount of biogas that could be generated in a given region and how this production would need to be spatially allocated in order to avoid or minimize unwanted effects on biodiversity and ES.

We employed a planning and decision-support approach that aimed at connecting policy and decision-making with science and planning through exchange and discussions among scientists, decision-makers and stakeholders. Current biogas governance regulations and objectives for biogas expansion, as stated by policy- and decision-makers, were integrated in the formulation of scenario assumptions. Furthermore, the scenarios assumed different options for biogas governance. We then simulated the scenarios′ effects on agricultural land use and cropping patterns and assessed the potential impacts concerning selected biodiversity and ES indicators. The results of the scenario study were fed back to policy- and decision-makers to support their efforts in refining biogas expansion objectives and creating sustainable pathways for its governance. Finally, conclusions concerning implementation options were drawn.

3.2. Scenario Assumptions

Three scenarios were developed with a time horizon to 2050. The first scenario assumes a market-based development without environmental constraints (Table 1). The target value for the area of maize production is an increase of 280% of the share of the current area devoted to this production type. Numerically, this means an increase from 7102 ha (19,729 kW)–27,036 ha (75,100 kW). This target results from a participatory scenario-workshop on the topic of expansion of renewable energies. This was conducted with administrators from the region of Hannover in September 2012. The increase was separately calculated and simulated for each municipality, thereby respecting the local context and conditions, e.g., location characteristics, agrarian structure and cultivation preferences of farmers.

Table 1. Scenario assumptions.

	2012	2050: Market	2050: Restrictive Protection	2050: Conditional Protection
Assumptions		280% increase of biogas area (by municipality)	Max. 15% maize Exclusion of protected sites Exclusion of sensitive areas	Max. 15% maize Exclusion of protected sites
Capacity (kW)	19,729	75,100	36,689	44,669
Demanded area (ha)	7102	27,036	13,222	16,084

The second scenario is based on nature conservation requirements and contains different restrictions for biogas production; meaning that there is no (further) cultivation allowed in nature reserves, drinking water protection areas, flood plains, erosion-prone sites and areas of faunistic importance. Data layers for these restricted areas were derived from the landscape plan framework for the region of Hannover [34]. Furthermore, the maize production area was capped at 15% of the arable land outside of the excluded areas. Municipalities were regarded separately. However, in municipalities that already had more than 15% of their arable land cultivated with maize for biogas, the amount was neither reduced, nor could it be further increased. Exploiting the 15%, this scenario results in a maize cultivation for biogas area of 13,222 ha and 36,689-kW installed plant capacity.

The third scenario is a less restrictive variant of the second one. It still allows cultivation of maize for biogas on erosion-prone sites and in areas of faunistic importance. However, it is allowed only on the condition that the standards of good agricultural practice (minimum requirements for agricultural management; see regulation (EC) No. 1750/1999 Article 28) are strictly complied with and that further measures to prevent environmental deterioration are taken if necessary. Under these assumptions, the area of maize cultivation for biogas can be increased up to 16,084 ha and the installed capacity of the plants to 44,669 kW.

As an increase of maize cultivation is implemented at the cost of the area available for other crops, decisions need to be made about which crops would be most likely to "lose out" in competition with maize. We assumed that crops with the lowest contribution margins would be given up first, making way for maize cultivation for biogas. Relative contribution margins were derived from expert knowledge and, in particular, from the long-term experience of one of the co-authors (M.R.). We further assumed that the planting area of each crop would only be reduced until a minimum of 10% of the original area per municipality was reached.

3.3. Simulating the Spatial Distribution of Crops

A key challenge for the study was the lack of access to spatial data on crop distributions. Data on this issue were available in the reporting system of the EU agricultural policies' direct payments, but data are not usually available for public or research use. In the meantime, we decided to adopt an alternative approach that makes best use of the available public data. Along this line, we drew upon aggregated accounting information on crop cultivation per municipality, which is available from the statistical office of the federal state of Lower Saxony. In order to progress under these conditions of uncertainty, we decided to simulate the spatial crop distributions for the status quo and the different scenarios. While one could argue that such a simulation rarely reflects the exact distribution, we consider it useful as a first attempt to understand the effects of crop distribution. Several simulation model runs and evaluations would be needed to investigate the uncertainty inherent in the simulations we performed. However, this was not possible within the scope of this project.

The simulation of spatial crop distributions was conducted in three steps (see Figure 2). First, the area of arable land was identified using a land use map. Then, the existing biogas plants were identified and their associated areas in which enhanced pressure of maize cultivation for biogas took place. We assumed higher pressures existed for the cultivation of maize cultivation for biogas within the proximity of plants, because longer transportation distances are usually less profitable [35]. We therefore defined "areas of enhanced pressure" as those areas with increased likelihood for maize cultivation around the plants. Locating plants and areas of enhanced pressure was done with the help of the web service (energymap.info), which provides information on plant locations and production capacities. We assumed that plants would need 0.36 ha of arable land per 1 kW capacity (*i.e.*, 180 ha for a 500-kW plant) to meet their demand for maize [25]. In 2012, approximately 80% of the area used for biogas crops was cultivated with maize [24]. The size of the areas with enhanced pressures also depends on the capacities of a plant. We assumed a radii of 1.5 km for plants with less than 255 kW, 3 km for plants with 256–400 kw and 5 km for plants with more than 400 kW capacity (own elaborations based on [35,36]). The resulting basic spatial information is provided in Figure 3.

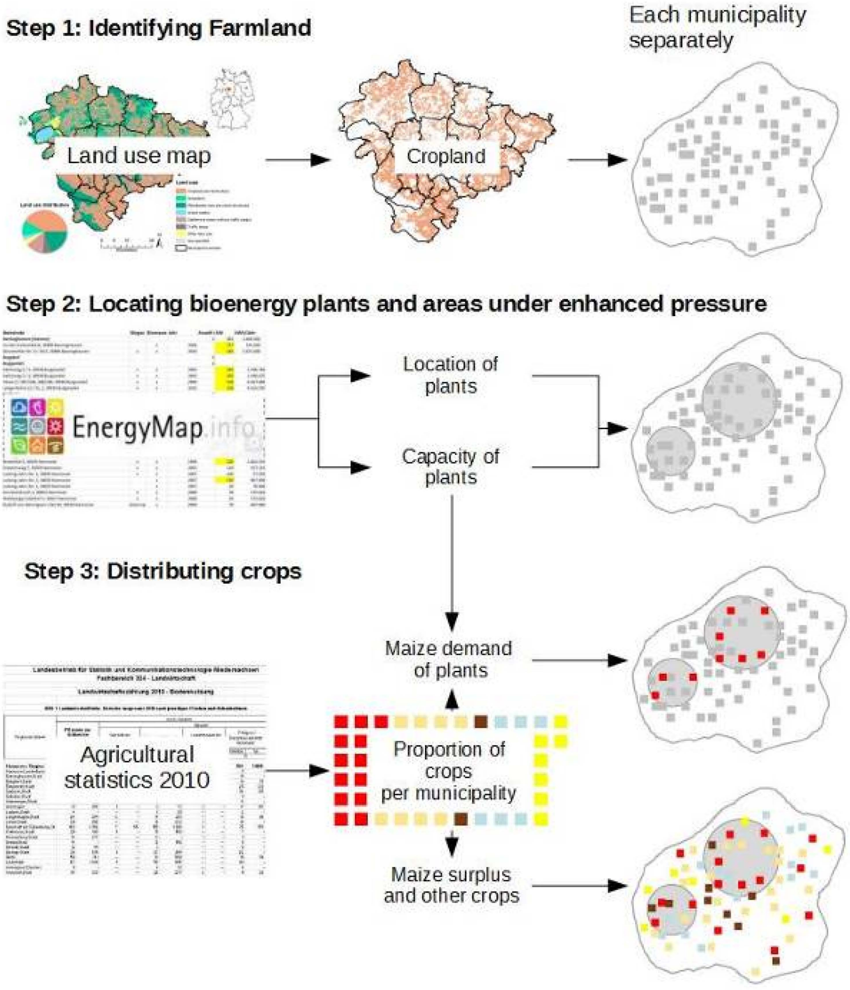

Figure 2. Approach for spatial simulation of crop distribution.

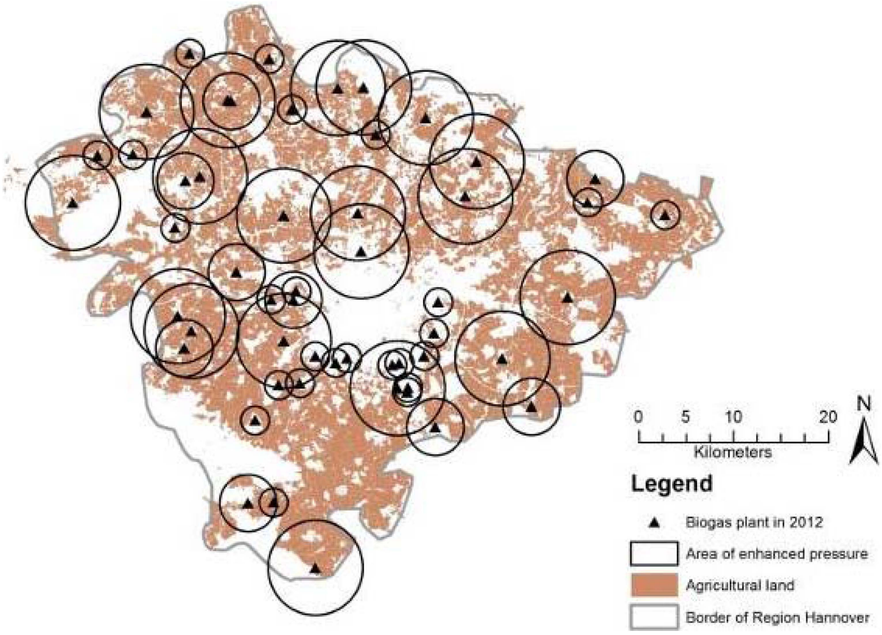

Figure 3. Locations of biogas plants [23] and areas of enhanced pressure from maize cultivation for biogas.

Data on the cultivation area for different crops are provided by the agricultural statistics [1]. As data were available for the municipal level, crop distribution could be performed separately for every municipality in the study area. Similarly, the differences in the characteristics of agricultural production between the north and the south of the study area, as described above, could be better incorporated. The simulation method consisted of several steps, performed manually with LibreOffice Calc in attribute tables from ESRI ArcGIS:

(1) Uniformly-distributed random numbers where assigned to each agricultural parcel
(2) Within each biogas plant area of enhanced pressure:
    (a) Parcels were selected with reference to the random numbers, while summing up their area until the total summed up area matched the demand of area for maize cultivation for the plant.
    (b) Maize cultivation was assigned to the selected parcels.
(3) Within each municipality:
    (a) The remaining maize cultivation area was calculated according to the agricultural statistics available.
    (b) If the distributed maize cultivation area exceeded the statistical value of that municipality and if areas of enhanced biogas pressure crossed municipal boundaries, then parcels were removed from maize cultivation, in reverse order within the one municipality, and the respective area of demand was repartitioned to the neighboring municipality(s).
    (c) The remaining maize cultivation area was distributed by selecting parcels in order of their random numbers and summing up their area until it matched the statistical value. Then, maize cultivation was assigned to the selected parcels.
    (d) The other crops were distributed on the remaining parcels using the same method as for maize, but only within the municipal borders.

The generated crop distribution map was used as the status quo for simulating changes in the scenarios. We used the same procedure as described above to simulate an increase of maize area and a decrease of other crops. However, we did not consider new plant locations in the simulation of the scenarios. The demands for maize cultivation areas, as described in the scenario assumptions, were projected within municipal borders. Furthermore, the restricted areas were introduced into the simulation of the two protection scenarios.

The approach we have taken here represents one strategy for considering possible land use change arising through scenario projections. There are also more complex models available that could be employed. For example, sophisticated approaches to modelling of potential future crop distribution patterns, such as the land use and land cover change model CLUE-S [37,38], could result in other simulated scenario outcomes that take into account more site specific characteristics and have a higher likelihood of representing future crop patterns. The application of CLUE-S is limited by the availability of relevant spatial data, which were not available for the study area. Furthermore, the decision of which approach to take will ultimately be based on the expertise, data and resources of the organization engaged in the exercise. As the focus of the current paper is on exploring methodological issues, we have employed a set of simplistic, but realistic assumptions to project possible land use futures. The paper illustrates that even without detailed data available, it is possible to use a simplified framework to examine land use change.

3.4. Assessing Potential Impacts of Scenarios on Various Ecosystem Services

Biodiversity and two ecosystem services, namely food production and landscape aesthetics, were selected to assess the potential impacts of each scenario. Biodiversity and the two ecosystem services were selected, as changes in their supply were expected to occur in response to changes in the amount of biogas produced. For each aspect considered, we first reviewed indicators proposed in the literature (e.g., [39–41]) and then selected the ones for which suitable data and methods were available. The impact evaluation of biodiversity referred to differentiated habitat value scores based on Bierhals and von Drachenfels [42] and von Drachenfels [43]. They were amended and refined for the application of different crop types [44]. This adapted method is based on the evaluation of several biodiversity indices of different crop types and farm management intensities, for instance the species richness of the field flora. A simplified approach was used that relies on expert-based classification of crop types according to their environmental risk for species and habitats [45]. Crop types with a higher risk (maize, sugar beet, winter wheat, rape, potato) were ranked lower on a scale between 1 and 2 (habitat value for arable land) [42], whilst crop types with a lower risk (oat, barley, spring wheat) were ranked higher. To evaluate the biodiversity functions of arable land with different crop types, we chose a range of 5 classes, from very low to very high, and classified the different crop types (Table 2). To this end, we split up each of the categories, “high risk” and “low risk” defined by Urban *et al.* [45], into two classes respectively, so as to get a more differentiated result that still follows the approach proposed by Bredemeier *et al.* [44].

Table 2. Ecosystem service values for biodiversity and landscape aesthetics.

	Biodiversity Refined Habitat Value Scores Following Bredemeier *et al.* [44] and Urban *et al.* [45]	**Landscape Aesthetics * Shannon Index (Crop Type Diversity) [57]**	
		Raster Cells	**Municipalities**
Very low value	Habitat value score of ⩽1.4 (for example: wheat)	H = 0–0.45	H = 1.2–1.4
Low value	Habitat value score of >1.4–1.5 (maize, sugar beet)	H > 0.45–0.90	H > 1.4–1.6
Medium value	Habitat value score of >1.5–1.6 (barley)	H > 0.90–1.35	H > 1.6–1.8
High value	Habitat value score of >1.6–1.7	H > 1.35–1.80	H > 1.8–2.0
Very high value	Habitat value score of >1.7 (rye)	H > 1.80–2.26	H > 2.0–2.2

* Habitat values (H) between reference levels (*i.e.*, raster cells and municipalities) are not comparable with each other due to the scale dependencies of the Shannon index.

The impact evaluation of food production concerned both the amount of area used for production, as well as the level of theoretical regional self-sufficiency for food consumption. The indicator value was calculated as the percentage to which the annual food demand of the region's population [46] was met by the annual food production from agriculture within the same region. The comparison was based on the amount of energy demanded/generated per year in gigajoules. The food demand modelling assumed homogenous nutrition patterns of 2400 kJ per day for males and 1900 kJ per day for females [47]. Food supply modeling was based on mean yields per soil fertility class of different crop types in the Hannover region [24] and an average energy value for each crop [48–51]. Meat production has been indirectly taken into account by using a modifier (10% of energy in plant biomass) [52] that resembles the energy conversion of fodder crops that have been cultivated in each municipality [24]. The energy values for corn silage, silage grass and pressed sugar beet pulp were calculated using the net energy lactation and the metabolic energy [51]. We calculated the level of theoretical regional self-sufficiency for food consumption for each municipality, as well as for the entire region.

Impacts on landscape aesthetics were evaluated as changes in the crop type diversity [53–55]. The value of this diversity indicator was calculated using the Shannon index [56], for each cell of a 2.5-km^2 raster grid and for each municipality in the region (Table 2). The results of the calculation have been categorized into 5 classes, ranging from very low to very high for both approaches, using equal intervals. As the actual area of arable land within each raster cell differed, we decided not to simply count the raster cells to identify shares of each class. Instead, we calculated the area of arable land for each cell that had a positive evaluation (high and very high). The results were then summarized and compared to the same results for every other class. For illustration purposes, the scenario impacts were compared against the situation in 2012 and 2009, respectively. Data for the area attributed for the cultivation of different crops for these two years could be taken from the actual production statistics [1], and the spatial allocation of crops to specific fields was done randomly as described above.

4. Results

4.1. Spatial Crop Distribution in Different Scenarios

The 2012, the simulated spatial distribution of crops reflects the differences in the natural soil fertility through the associated differences in preferences for particular crop types (see Figure 4). In the northern part of the region of Hannover, which boasts less productive soils than the southern part, there is traditionally a much stronger emphasis on the cultivation of maize and other fodder crops for livestock than in the south. Furthermore, the area utilized for fodder maize equals the area of maize demanded by the high number of biogas plants situated in this part of the region in 2012. This leads to substantial shares of maize cultivation in the north. Next to maize, rye cultivation, grasslands, barley, rape seed and potatoes are predominantly produced in the northern part. The southern part of the region of Hannover has more fertile soils and offers several profitable alternatives to maize production. In this part of the region, the cultivation of sugar beet and wheat was predominant and only a few biogas plants demanded the cultivation of maize.

In the market scenario, the simulation includes a 280% increase of each municipality's share of the area devoted to maize cultivation. This results in an accentuation of the uneven distribution of biogas production across the region of Hannover (see Figure 4). In some northern counties of the region, the share of arable land for biogas crop cultivation grew to 73%, while some municipalities in the south still exhibit maize shares of less than 10%.

The result of the crop distribution simulation using the restrictive protection scenario shows a considerably more even distribution of land shares for maize cultivation across the communities than the market scenario. In the northern part of the region, little additional increase in area shares for maize cultivation for biogas took place. This was because the maximum cap of 15% of arable land for maize cultivation for biogas per municipality was already reached or overshot. Furthermore, the scenario's exclusion of protected areas and regions sensitive to erosion or other impacts on fauna from maize cultivation for biogas only resulted in marginal changes in the north of the study area. The southern part, however, shows a considerable increase of area shares for maize for biogas production.

This results in a generally more even distribution across the region. An overall share of 14% of the region′s arable land is cultivated with maize.

The scenario of conditional protection differs only slightly from the restrictive protection scenario. The stronger increase of maize for biogas production in the south and southeast is due to less area being excluded from increases in maize for biogas production on the basis of protection status or ecological sensitivity. Altogether, 16% of the regions arable land is cultivated with maize. In this scenario, the total amount is a bit higher than the allowed 15%, because maize cultivation was not reduced in municipalities that already had more than 15%.

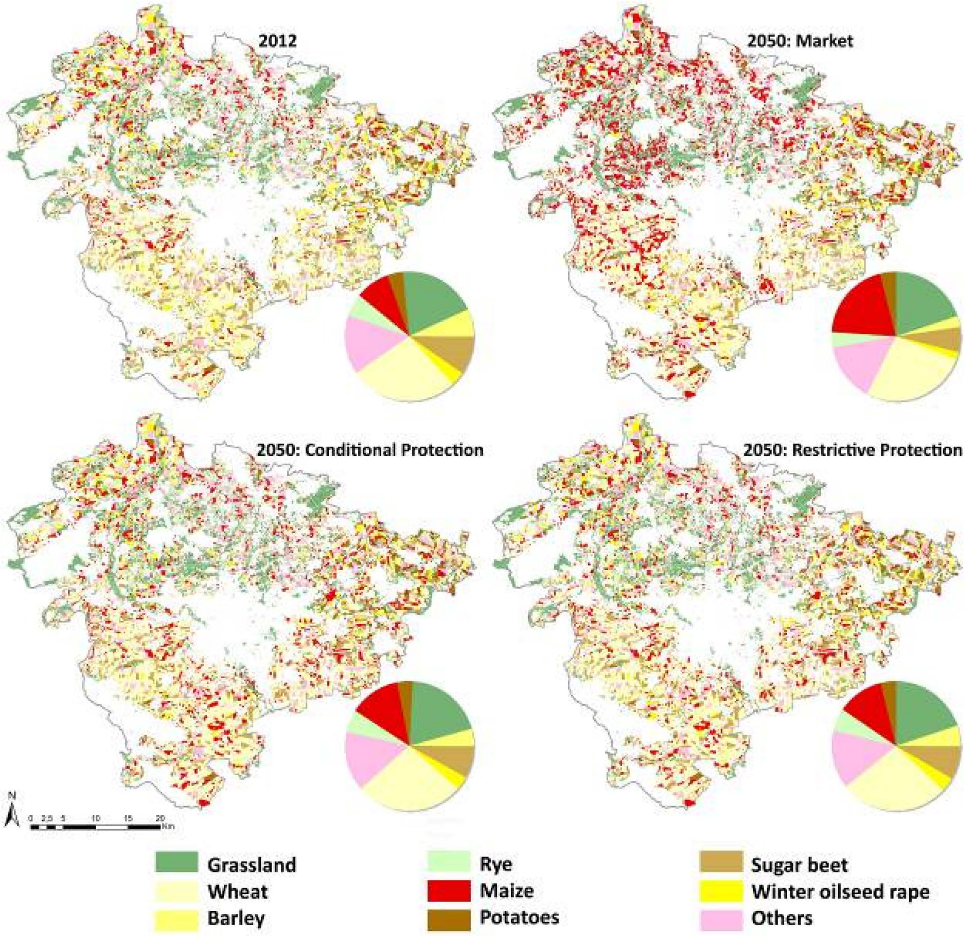

Figure 4. Results of the spatial simulation of crop distribution in the status quo and the scenarios.

4.2. Scenario Impacts on Biodiversity and Ecosystem Services

The impact evaluation for biodiversity in 2012 shows that 19.2% of the arable land is of medium to very high value in terms of cropland habitats (see Figure 5). Conducting an impact evaluation for biodiversity in the market scenario leads to a considerable decrease of this share of area to only 10.1%. In the restrictive protection and conditional protection scenarios, the area of arable land with a very high value is almost the same. However, the share of areas of medium to high value decrease respectively by 3% and 4%. This can be explained by a change in cultivation of a large percentage of areas, from barley and rye to maize, which has a slightly worse cropland habitat value.

The results of the impact evaluation for food production shows that in 2012, the region of Hannover supplied about 101% of its theoretical demand for food. In the market scenario, the level of self-sufficiency decreased to 89%. The restrictive protection and the conditional protection scenarios led to a decrease of the self-sufficiency level to 96% and 94%, respectively. The region would therefore lose its current potential of being theoretically self-sufficient in the provision of agricultural produce.

The evaluation of landscape aesthetics of arable land in terms of crop type diversity shows that in 2012, about 72% of the arable land was evaluated as of high or very high value. The simulated changes in crop distributions in the market scenario have divergent effects on crop type diversity. In total, the share of arable land within raster cells evaluated as of high or very high value decreases considerably to 64.2%. The landscape aesthetic values, in the municipalities in the western part of the region of Hannover, generally decrease by one valuation level. In the northeast region of Hannover, no changes in crop type diversity occur, as the already high share of maize production was kept more or less constant.

The restrictive protection and conditional protection scenarios lead to only marginal increases of the share of arable land within raster fields, which were evaluated as a high or very high value. A slight increase of the crop type diversity can be determined in two municipalities in both protection scenarios.

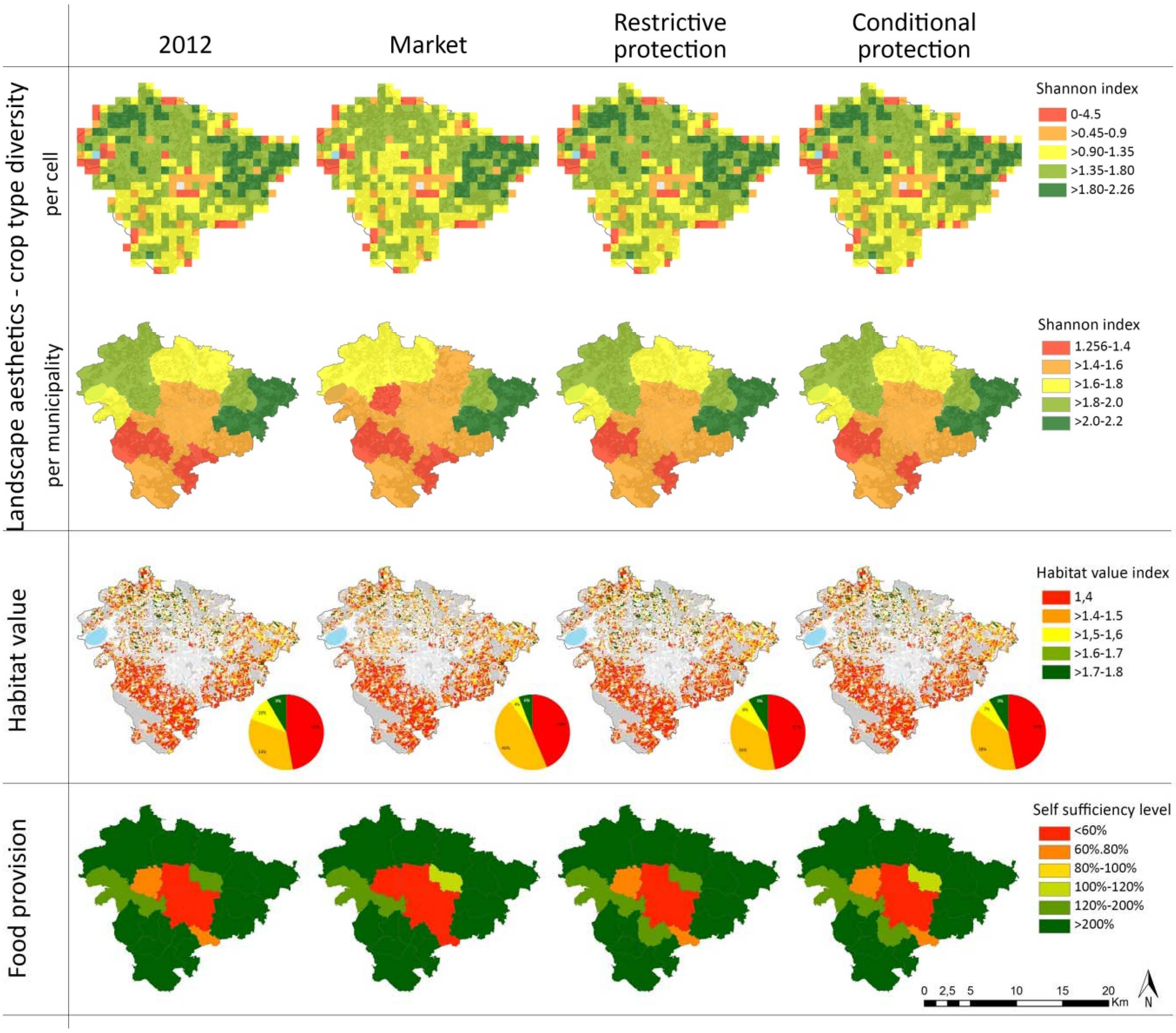

Figure 5. Results of impact modelling.

Comparing the various impacts of the three scenarios on biodiversity and the two ecosystem services, it is possible to illustrate trade-offs and synergies (Figure 6). The increase of maize production has predominantly negative effects on biodiversity, food production and landscape aesthetics. This especially applies when the share of maize is significantly increased, as shown in the market scenario. Despite these generally negative effects, an increase of maize cultivation for biogas can also have a positive effect. This can be seen in both protection scenarios. In some municipalities and raster cells, increases of the value for landscape aesthetics in terms of higher crop type diversity are found.

The effects of the two protection scenarios on other ecosystem services are considerably less negative in comparison to the market scenario. This shows that an appropriate governance of biomass cultivation in ecologically-sensitive areas can not only minimize trade-offs, but can also harness synergies among ecosystem services and eventually also biodiversity.

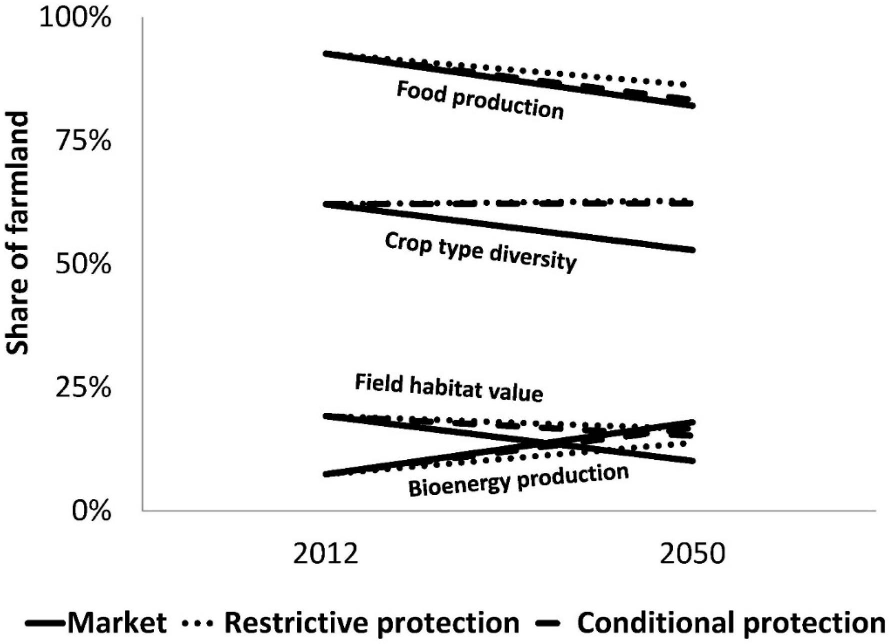

Figure 6. Trade-offs between maize cultivation for biogas (% of farmland used for substrate generation), biodiversity (% of farmland with high or very high field habitat value), food production (% self-sufficiency) and landscape aesthetics (% area with high or very high crop type diversity) in different scenarios.

5. Discussion and Conclusions

This paper has explored a landscape planning approach to provide decision-support for a sustainable development and expansion of biogas production in the face of a general lack of publicly available data on spatial crop production patterns. The application of the suggested approach in the case study area of the Hannover region shows that biogas expansion results in predominantly negative impacts for the selected ES. However, positive effects can also be identified, *i.e.*, when the introduction of biogas crops leads to higher local crop diversity and, thus, a more attractive visual landscape. The scenario results also show that the politically demanded targets for biogas expansion can only be achieved by increasing the share of maize cultivation for biogas. The scenario of little regulation illustrates more negative impacts than the other scenarios. Targeted spatial planning, implementation and appropriate governance for steering biogas maize cultivation into less sensitive areas is of crucial importance for minimizing impacts and trade-offs and for exploiting synergies between maize cultivation for biogas and other ES. Such strategic planning of biogas generation can enable higher amounts of maize cultivation to take place, with only relatively small additional impacts on biodiversity and ecosystem services.

The scenario assumptions seem generally plausible, given both the current trends of changing cropping patterns and the situation in other counties in Lower Saxony. The assumption that reductions in each crop would only continue down to a final minimum amount of 10% of the original area per municipality was made due to the fact that farm management usually does not allow for a complete abandonment of one crop. While this paper focused on maize cultivation for biogas, it needs to be acknowledged that other bioenergy aspects could also have been taken into account, e.g., the production of short rotation plantations (coppice) or Miscanthus for electricity and heat. These crops could potentially have more synergies with the ecosystem services and biodiversity proxies than we have considered.

Our analysis illustrates that moderate increases in the share of arable land, attributed to biogas crop production, are possible without considerable negative impacts on other ecosystem services in the region. In 2012, only a small share of the arable land was attributed to maize cultivation for biogas production in comparison to other administrative districts in Lower Saxony [1,2]. For Hannover, we found that even a doubling of this area would be acceptable from a nature conservation protection standpoint due to the comparatively low share of area attributed to maize cultivation in 2012. Although an increase of maize cultivation would decrease the provision of biodiversity and other ecosystem services, these changes are below thresholds considered as unacceptable in the literature. Even the within the market scenario, the amount of agricultural land cultivated with maize reached only about 30 percent. This share of maize cultivation still allows a crop rotation of three different crops, and thus, the resulting impacts from an increase in maize on ecosystem services are small [10,36,57]. This finding holds true, however, only if the increase in the area for biogas crop production is directed by effective governance interventions, so that the biogas crop production is more or less evenly distributed across the entire region. If biogas crop production increases locally, significant impacts on local biodiversity and ecosystem services may occur even if the overall amount of biogas crop production for the region is relatively small. As the two biodiversity conservation scenarios show, the degree of influence of biogas expansion on biodiversity and selected ecosystem services varies strongly with respect to the assumed governance approach. We acknowledge that the simulation result represents only one option of crop distribution, while in practice, an infinite number of crop type allocations would be possible. However, actual crop type distributions change year by year in practice, as well. Furthermore, as we cannot predict the locations of future biogas plants and, therefore, the enhanced spatial pressures in their proximity, local pressures could be higher than those illustrated in our outcomes. Another issue that requires further consideration is the selection of ecosystem services and indicators considered in the impact analysis. It is true that the selection influences the outcomes and that it is not clear how our results would have looked with different sets of ecosystem services or indicators considered. For example, we could have selected various other ecosystem services that are potentially impacted by maize cultivation, such as the provision of clean drinking water (where maize cultivation enhances the relative risks of fertilizer inflow) and preservation of fertile soil (as maize cultivation enhances the relative likelihood of soil erosion). Furthermore, various other ecosystem services, as well as indicators for each ecosystem service could have been used, and our decisions on both issues have influenced the results. We decided to focus on three indicators that are known to be of importance for land use transitions associated with enhanced maize cultivation [3,10,14,36,55,57–62]. However, the choice of indicators of ES impacts for future assessments in other regions may very well be dictated by local priorities. For example, in areas with water quality issues, ecosystem services, such as preventing soil erosion or nutrient runoff, may be the focus of the assessment. This again emphasizes the importance of stakeholder dialogue.

By focusing on the objective to develop and test an approach for generating scenarios of biogas crop expansion and exploring their impacts, it was beyond the scope of this paper to incorporate the whole range of drivers and factors that influence the spatial allocation of biogas plants, farmers′ decision-making and the impacts on various scenarios. There are complex economic, ecological and social factors that all interact to determine what crops are grown where and when. Such differences can have profound influence on land use and the provision of ecosystem services. For example, the decisions by farmers about which crops to plant where are strongly influenced by site and climate conditions, the existing infrastructure and investment capacities of farms, the expected market prices for different crop types, as well as existing incentives for certain crops (see, e.g., [35,63]).

Appropriate governance of biogas crop production would require that new biogas plants are installed in areas of the region that have not yet experienced much increase of biogas production. A case in point is the southern part of the region, which up to now has been dominated by sugar beet and wheat production. An increase in the area used for biogas production could lead to a diversification of the local crop production patterns and an enhancement of the landscape′s aesthetic quality due to higher diversity. Instead, in the northern part of the Hannover region, where biogas crop production is already one of the dominant crop types, a further increase of biogas production would lead to strongly negative impacts on biodiversity and ecosystem services [59,60].

An interesting finding was that governance of maize cultivation for biogas need not necessarily be restrictive. If existing standards of good farming practice are fulfilled (as assumed in the conditional protection scenario), most negative effects can be avoided. We also realized that impact evaluations must be scale sensitive. When assessing scenario impacts on a regional level, the cumulative impacts were relatively little. If assessed at the community level, however, sometimes, dramatic changes in impacts occurred. As an in-depth analysis of scale issues in biogas governance was beyond the scope of the research presented in this paper, we explore this topic in another paper [64].

The presentation and discussion of our research results with local decision-makers and stakeholders from the biodiversity and biogas communities yielded interesting insights relevant for planning communication and the governance of renewable energy transitions. First, we realized that the usage of terms is very important. We first talked about the planned 2.8-fold area increase of arable fields attributed to biogas crops, as this was the context in which it was discussed and negotiated in the strategy for carbon neutrality. In our discussion with stakeholders, however, using the term 2.8-fold raised strong opposition with respect to the maize cultivation for biogas, as farmers feared that such framing of the issue would raise strong resistance among nature conservationists. Instead, they proposed that the research team talk about the current and potential future shares or percentages of arable land attributed to biogas production, as this is a more objective way of conveying the same issue.

Second, we found that our findings reemphasized the suggestions made by scenario-planning experts, such as Alcamo [65], van der Heijden [29] and Schwartz [66], that scenario-based assessments can only raise interest and attention if they spur innovative thinking by reflecting dramatic changes, at least in the exploratory stage of planning and policy-making support. In the beginning of our project, we only assumed small changes in scenario assumptions that did not result in dramatic changes at the regional scale, which was of little interest to stakeholders. This could only partially be compensated by emphasizing the strong local impacts that an increase of biogas could have.

Third, the discussion of our research results with local actors helped make the biogas dispute more rational: the results helped to identify areas where conflicts with biodiversity and ecosystem services will be likely to occur, but also illustrated areas in which an increase in biogas could even enhance some ecosystem services, in our case landscape aesthetics.

Fourth, we realized that scenarios are easily dismissed in public discussions if they entail implausible assumptions (again, in line with earlier suggestions by Alcamo [65], van der Heijden [29] and Schwartz [66]). For example, one of the scenarios we suggested in the course of the project assumed a strong increase of biogas in areas of particular fertility, thus mainly in the southern part of the region. Local farms found this scenario irrelevant, as the highly fertile soils would still allow sufficient alternatives and more economically-beneficial alternatives to biogas crop production; therefore, a change in cropping patterns would be unlikely. This finding reemphasized the need for strong stakeholder engagement and involvement in scenario creation in order to enhance plausibility [33,67].

Altogether, our results suggest that the proposed scenario-based simulation and assessment approach provides new and relevant insights into the spatial implications of quantitative biogas expansion targets. The approach is applicable for landscape planners with experiences in GIS analyses and simulation and who have access to required spatial datasets, statistical data on shares of arable land attributed to different crops and on the amount of biogas produced. The approach can be applied well by consultancies or county planning departments to support and guide renewable energy and nature-conservation policy and decision-making. The approach could be integrated into the development of landscape plans that focus on nature conservation issues, as well as on regional development concepts.

The information generated with the suggested approach can be useful in several ways. It can help stakeholders and decision-makers to better understand the capacities, limitations and implications of alternative biogas targets for their county. It can help nature conservation policy-makers to better design and implement governance, planning and management measures for protecting sensitive areas against increased maize production. It can further contribute to the distribution of additional area for biogas production in order to minimize local impacts. The use of the concept of ecosystem services proved useful for the consideration of the various "benefits" people acquire from nature. In following the ecosystem services approach of quantitatively assessing impacts and analyzing trade-offs, the implications of an expansion of maize production for biogas on different ecosystem services could be illustrated in a way that is easy to communicate and understand. Finally, the approach can help the public to engage in a more informed debate about how society can transition towards climate neutrality.

Issues for further research include the development of methods for assessing a broader range of ecosystem services trade-offs and evaluations of how the information yielded from applying the suggested approach actually influences preferences and decision-making of relevant audiences. While this contribution has arguably provided useful first steps towards a method for assessing the impacts of potential maize cultivation for biogas expansions on biodiversity and ecosystem services, further research is needed to provide more accurate simulations of potential future land use changes, to take into account a broader set of ecosystem services and to quantify and minimize the inherent uncertainties in the assessment results.

Acknowledgments: We acknowledge the interest of the stakeholders and decision-makers who participated in a related workshop. Funding for this study was provided by the Lower Saxony Ministry for Education and Culture in support of the project "Biomasse im Spannungsfeld". We would like to thank four anonymous referees for their comments which strongly improved the manuscript and Louise von Falkenhayn for polishing the language. Bea Achtermann documented the workshop results, and Peter Haus helped with the GIS analyses; their help is also gratefully acknowledged.

Author Contributions: C.A. led the research and manuscript writing. J.H. and F.H. conducted the analyses and helped in the manuscript writing. C.V.H. and M.R. provided guidance on the research design and implementation and contributed to the manuscript writing.

Conflicts of Interest: The authors declare no conflict of interest.

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