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Model-Based Valuation of Ecosystem Services Using Bio-Economic Farm Models: Insights for Designing Green Tax Policies and Payment for Ecosystem Services

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Abstract: The integration of ecosystem services (ESs) valuation into agricultural policy frameworks is critical for fostering sustainable land management practices. This study leverages the redesigned version of the bio-economic farm model MODAM (Multi-Objective Decision Support Tool for Agro-Ecosystem Management) to estimate the shadow prices of ESs, enabling the derivation of demand and supply curves for nitrate leaching and soil erosion control, respectively. Two hypothetical farms in Brandenburg, Germany—a smaller, arable farm in Märkisch-Oderland and a larger, diversified farm with livestock in Oder-Spree—are analyzed to explore the heterogeneity in shadow prices and corresponding cropping patterns. The results reveal that larger farms exhibit greater elasticity in response to green taxes on nitrate use and lower costs for supplying erosion control compared to smaller farms. This study highlights the utility of shadow prices as proxies for setting green taxes and payments for ecosystem services (PESs), while emphasizing the need for differentiated policy designs to address disparities between farm types. This research underscores the potential of model-based ESs valuation to provide robust economic measures for policy design, fostering sustainable agricultural practices and ecosystem conservation.

Keywords: ecosystem services valuation; bio-economic farm models; MODAM; shadow prices; green tax policy; payment for ecosystem services; nitrate leaching; soil erosion control

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1. Introduction

Ecosystem services (ESs) are vital for agricultural sustainability but are frequently undervalued in traditional policy frameworks [1–3]. Policies such as payments for ecosystem services (PESs) and green taxes require precise valuation methods to encourage sustainable agricultural practices [4,5].

Conventional survey-based methods, such as contingent valuation and choice experiments, are widely used but often fail to capture the complex economic interdependencies present at the farm level [6,7]. Consequently, they can lead to inaccurate valuations and ineffective policy outcomes. These methods rely on respondents' answers to hypothetical scenarios, which may not reflect actual behavior or true valuations, leading to potential overestimation or underestimation of the intrinsic value individuals place on ESs [8]. Furthermore, assigning monetary value to non-market goods, such as biodiversity and ESs, is inherently complex due to subjective individual preferences and the difficulty in quantifying non-use values [9]. Additionally, the economic value of ESs can vary significantly based on local ecological and socio-economic contexts, which standard survey-based methods may not capture effectively [10]. These methods also tend to overlook non-monetary contributions, such as traditional knowledge and sustainable land management practices, resulting in an incomplete assessment of benefits and costs for farmers [11]. Schläpfer [12] addresses the significant challenges posed by customary valuation methods for public goods and ESs. The authors argue that existing standards fail to adequately capture the complex, multifaceted benefits provided by these goods and services, often undervaluing their true societal importance. This misrepresentation leads to suboptimal policymaking and resource allocation. Similarly, studies like those by Flood et al. [13] and Cai and Aguilar [14] underline the challenges of applying economic valuation methods to complex ecological systems and agroforestry practices, respectively, emphasizing the risk of overlooking critical aspects and undervaluing economic returns.

Recognizing these shortcomings, this study aims to demonstrate the utility of model-based valuation of ESs using bio-economic farm models to inform the design of green tax policies and PES schemes. By focusing on two representative farm types in Brandenburg, Germany, the research analyzes the economic trade-offs associated with nitrate leaching and soil erosion control at the farm level, while also demonstrating the feasibility of integrating shadow price estimates into incentive-based policies for sustainable agriculture. This study is conducted within the framework of the Digital Agricultural Knowledge and Information System (DAKIS) project, which aims to develop a decision support system (DSS) that integrates ESs as economically valuable, non-commodity outputs of agriculture [15]. A central objective of the project is the incorporation of shadow prices for ESs into policy instruments like PESs and green taxes, fostering alignment between economic and environmental objectives. Shadow prices, which reflect the marginal economic value of ESs, provide a robust measure for policy design by quantifying the additional income generated or costs incurred from changes in the availability of these services [1,16,17]. This dual consideration of ecological and economic dimensions supports more sustainable agricultural practices.

To address the limitations of traditional survey-based valuation methods, this study employs a redesigned version of the bio-economic farm-level model MODAM (Multi-Objective Decision Support Tool for Agro-Ecosystem Management) [18–20]. The updated MODAM model integrates ecological and economic interactions, including production options, input-output price dynamics, and constraints related to on-farm demand and supply of ESs, to estimate shadow prices for ESs. The model facilitates the derivation of demand and supply curves, offering a quantitative estimation of farmers' willingness-to-pay (WTP) and willingness-to-accept (WTA) for specific ESs. Unlike conventional methods, this model-based approach accounts for the inherent trade-offs and synergies in ESs provision and use.

The model-based methodology of this study quantifies shadow prices for ESs and highlights their variability across different farm types and management practices. By elucidating the economic trade-offs involved in ESs provision and consumption, this study demonstrates the feasibility of establishing markets for ESs and improving policy tools to promote efficiency and equity.

Beyond practical applications, this research contributes to the academic discourse by advancing a model-based alternative to traditional survey-based valuation techniques. Recent progress in dynamic and joint optimization models for ESs valuation [21–23] has underscored their effectiveness in supporting PESs and green tax policy development. This study extends those insights, offering actionable recommendations for policymakers to advance sustainable agricultural systems and environmental stewardship.

The remainder of this paper is organized as follows: Section 2 details the materials and methods, including the structure of the MODAM model and its application for deriving on-farm demand and supply curves of ESs. Section 3 presents the results. Section 4 provides a discussion of the findings emphasizing their relevance to policy design. Section 5 concludes with key insights and directions for future research.

2. Materials and Methods

This study integrates bio-economic modeling to evaluate the shadow prices of ESs as a basis for improved policy design. The analysis is grounded in the redesigned version of bio-economic farm model MODAM and the broader framework of the DAKIS project. This section outlines the modeling approach and the methodologies employed to derive demand and supply curves for ESs.

Two hypothetical farms located in Brandenburg, Germany, were selected as case studies to investigate the interplay between farm characteristics and the shadow prices of ESs. These farms were derived from a dataset presented in Bethwell et al. [24], which utilized statistical data, interviews with regional farmers, and expert knowledge to establish a detailed picture of crop and production process-specific inputs for three case study regions in Germany. The dataset includes key agricultural inputs and outputs, such as seed amounts, fertilization rates, pest and disease management practices, machinery use, fuel demand, labor, and economic parameters such as gross margins and subsidies under the CAP regulations. From this dataset, we selected two typical farm structures representative of Brandenburg's agricultural systems. Although these farms were not selected to be statistically representative of all Brandenburg farms, they were designed to be structurally typical of the region. These selections were based on structural characteristics and subjective judgment to capture typical farming practices in the region.

The first farm, situated in Märkisch-Oderland, is a smaller operation encompassing approximately 240 hectares, including intercropping areas. This farm focuses exclusively on crop production and does not engage in livestock breeding. The second farm, located in Oder-Spree, represents a larger, mixed crop-livestock operation covering approximately 900 hectares. This farm combines crop production with livestock breeding activities. To integrate these farms into the DAKIS project landscape windows, their structures were placed within a typical Brandenburg landscape, rather than their original locations. The landscape size and structure correspond to the parameters defined within the DAKIS project. Additional data and parameters, including inputs related to production processes, were updated and validated using KTBL databank [25] to ensure accuracy and relevance to the study context. This approach allows us to analyze variations in scale and activity within typical Brandenburg farm structures and their influence on the shadow prices of ESs while situating the analysis in a modelled but realistic landscape framework.

This study specifically examines two key ESs: nitrate leaching and erosion control. Nitrate leaching at the farm level is treated as a demanded service, essential to agricultural production, with shadow prices reflecting the income generated by utilizing an additional unit of this service. The threshold for nitrate leaching represents a capacity provided by society that farmers can utilize for their farming activities, effectively making it societal supply of nitrate leaching to agriculture. Conversely, erosion control at the farm level is regarded as a supplied service, with shadow prices representing the cost incurred by farmers to produce one additional unit of this service. The sustainability goal for erosion control reflects societal demand for this service, emphasizing the importance of preserving soil health and reducing erosion.

Shadow prices were derived using the updated version of MODAM bio-economic farm-level model, which effectively captures the physical interactions between ecosystem components and the economic trade-offs inherent in farm management. The new version of MODAM framework integrates biophysical parameters, such as crop yields, soil characteristics, and the supply and demand for on-farm ESs, alongside economic ratios, including input costs and output prices. For each hypothetical farm, demand and supply curves were extracted to quantify the economic value of nitrate leaching and the economic cost of erosion control.

The demand curve for nitrate leaching illustrates its economic value as a critical service in agricultural production, while the supply curve for erosion control reflects the economic costs borne by farmers to provide this service. Together, these analyses provide insights into the trade-offs and economic dynamics underpinning ESs management in agricultural systems.

The general simplified form of the mathematical model of the bio-economic farm model MODAM is as follows:

Objective function

$$\underset{X}{\text{Max}} \quad GM = \sum_{t=1}^{T} \sum_{f=1}^{F} \sum_{j=1}^{J} (1+r)^{-t} gm_{t,j} X_{t,f,j} \tag{1}$$

Physical, financial and legal constraints

$$\sum_{f=1}^{F} \sum_{j=1}^{J} a_{t,i,f,j} X_{t,f,j} \leq b_{t,i} \qquad for\ t = 1,2,\ldots,T\ and\ i = 1,2,\ldots,I \tag{2}$$

On-farm ecosystem service demand constraint

$$\sum_{f=1}^{F} \sum_{j=1}^{J} c_{t,s,f,j} X_{t,f,j} \leq ess_{t,s} \qquad for\ t = 1,2,\ldots,T\ and\ s = 1,2,\ldots,S \tag{3}$$

On-farm ecosystem service supply constraint

$$\sum_{f=1}^{F} \sum_{j=1}^{J} p_{t,d,f,j} X_{t,f,j} \geq esd_{t,d} \qquad for\ t = 1,2,\ldots,T\ and\ d = 1,2,\ldots,D \tag{4}$$

Non-negativity

$$X_{t,f,j} \geq 0 \tag{5}$$

where GM is the maximized net present value of the farmer's total gross margin during the planning years, r is the discount rate, $gm_{t,j}$ is the gross margin of one unit of crop j in year t, $X_{t,f,j}$ is the optimal cultivation area of crop j at field f in year t, $a_{t,i,f,j}$ is the technical coefficient of constraint i for producing one unit of crop j at field f in year t, $b_{t,i}$ is the total available amount of constraint i in year t, $c_{t,s,f,j}$ is the consumption of ESs s for producing one unit of crop j at field f in year t, $ess_{t,s}$ is the total societal supply of ESs s in year t, $p_{t,d,f,j}$ is the provision of ESs d by producing one unit of crop j at field f in year t and $esd_{t,d}$ is the total societal demand of ESs d in year t.

Taking into account the slack variable of constraint i in year t ($Slack_{t,i}^{b}$), the slack variable of societal supply of ESs s in year t ($Slack_{t,s}^{ess}$) and the surplus variable of societal demand of ESs d in year t ($Surplus_{t,d}^{esd}$) to convert the constraints with unequal signs to equalities, the above model can be transformed into the following Lagrange function. The Lagrange function is utilized here to incorporate the economic interpretation of shadow prices into the model, facilitating the simultaneous consideration of physical constraints and their associated economic trade-offs.

$$\underset{X}{\text{Max}} \quad \mathcal{L} = \sum_{t=1}^{T} \sum_{f=1}^{F} \sum_{j=1}^{J} (1+r)^{-t} gm_{t,j} X_{t,f,j}$$
$$+ \sum_{t=1}^{T} \sum_{i=1}^{I} \Lambda_{t,i} \left[b_{t,i}, -, \sum_{f=1}^{F}, \sum_{j=1}^{J}, a_{t,i,f,j} X_{t,f,j}, -, Slack_{t,i}^{b} \right]$$
$$+ \sum_{t=1}^{T} \sum_{s=1}^{S} SR_{t,s} [ess_{t,s}$$
$$- \sum_{f=1}^{F} \sum_{j=1}^{J} c_{t,s,f,j} X_{t,f,j} - Slack_{t,s}^{ess}]$$
$$+ \sum_{t=1}^{T} \sum_{d=1}^{D} SC_{t,d} [esd_{t,d}$$
$$- \sum_{f=1}^{F} \sum_{j=1}^{J} p_{t,d,f,j} X_{t,f,j} + Surplus_{t,d}^{esd}] \quad (6)$$

where $\Lambda_{t,i}$, $SR_{t,s}$ and $SC_{t,d}$ are Lagrange multipliers, representing the dual or shadow prices of $b_{t,i}$, $ess_{t,s}$ and $esd_{t,d}$ respectively, and they can be defined as follows:

$$\Lambda_{t,i} = \frac{\partial \mathcal{L}}{\partial b_{t,i}}, \quad SR_{t,s} = \frac{\partial \mathcal{L}}{\partial ess_{t,s}}, \quad SC_{t,d} = \frac{\partial \mathcal{L}}{\partial esd_{t,d}} \quad (7)$$

$SR_{t,s}$ represents the change in the farmer's gross margin due to consuming an additional unit of ESs s in year t, while $SC_{t,d}$ measures the change in gross margin resulting from providing one more unit of ESs d in year t, assuming other factors remain constant. These shadow prices are calculated based on the income generated by the consumption of each unit of ESs or the cost incurred by producing each unit of ESs, irrespective of the farmer's willingness to pay or accept. Furthermore, these values are calculated simultaneously, taking into account the interactions and trade-offs between ESs.

$SR_{t,s}$ can guide the implementation of a green tax on ESs consumption, while $SC_{t,d}$ can help determine payments for ESs provision [1].

Of course, the level of these shadow prices depends entirely on the societal supply and demand of each ESs. This dependence can be quantified through a sensitivity analysis of the societal supply and demand of each ESs [26]. By performing this sensitivity analysis, it is possible to determine the shadow price of ESs within different ranges of societal supply and demand. For example, if the shadow return of ESs s in year t is $SR_{t,s}^{*}$, this value will be valid within the societal supply levels $ess_{t,s}^{min}$ and $ess_{t,s}^{max}$. Increasing the societal supply beyond $ess_{t,s}^{max}$ will reduce the shadow price to $SR_{t,s}^{**}$, while decreasing the societal supply below $ess_{t,s}^{min}$ will increase the shadow price to $SR_{t,s}^{***}$. Deviations outside this range affect the shadow price, as shown in Table 1.

Table 1. Sensitivity analysis of societal supply of ESs s in year t. Adapted from Kaiser and Messer (2012) [17].

Range of Feasibility of Societal Supply of ESs s in Year t	Shadow Return of ESs s in Year t
$0 \leq ess_{t,s} < ess_{t,s}^{nmin}$	$SR_{t,s}^{****}$
$ess_{t,s}^{nmin} \leq ess_{t,s} < ess_{t,s}^{min}$	$SR_{t,s}^{***}$
$ess_{t,s}^{min} \leq ess_{t,s} \leq ess_{t,s}^{max}$	$SR_{t,s}^{*}$
$ess_{t,s}^{max} < ess_{t,s} \leq ess_{t,s}^{nmax}$	$SR_{t,s}^{**}$
$ess_{t,s}^{nmax} < ess_{t,s} \leq \infty$	0

Using this data, the farmer's demand curve for ESs s in year t can be derived, as shown in Figure 1.

Building upon the description provided above, the extraction of demand curves for nitrate leaching can be achieved using the previously introduced MODAM framework. The initial model run excludes constraints on nitrate leaching, resulting in maximum nitrate leaching levels and cropping patterns with zero shadow prices. Subsequently, allowable nitrate leaching thresholds can be iteratively reduced based on sensitivity analyses of the right-hand side of the constraint. Each iteration reveals changes in cropping patterns and corresponding shadow prices. These results form the foundation for constructing demand curves, illustrating economic trade-offs under varying green tax levels.

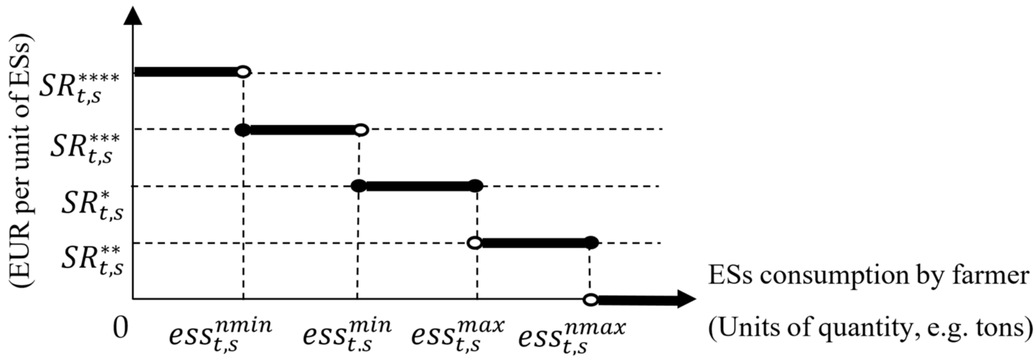

Figure 1. Farmer's demand curve for ESs *s* in year *t*. Adapted from Kaiser and Messer (2012) [17].

Similarly, the societal demand for each ESs can be analyzed sensitively, and the corresponding shadow prices for each range of societal demand can be determined. For instance, if the shadow cost of ESs *d* in year *t* within the range of societal demand $esd^{min}_{t,d}$ to $esd^{max}_{t,d}$ is equal to $SC^{*}_{t,d}$, then an increase in societal demand beyond $esd^{max}_{t,d}$ leads to a rise in the shadow price to the level $SC^{***}_{t,d}$. Conversely, a decrease in societal demand below $esd^{min}_{t,d}$, causes the shadow price to fall to the level $SC^{**}_{t,d}$. By continuing this sensitivity analysis, the shadow price of ESs *d* in year *t* for each range of societal demand is detailed in Table 2.

Table 2. Sensitivity analysis of societal demand of ESs *d* in year *t*. Adapted from Kaiser and Messer (2012) [17].

Range of Feasibility of Societal Demand of ESs *d* in Year *t*	Shadow Cost of ESs *d* in Year *t*
$0 \leq esd_{t,d} < esd^{nmin}_{t,d}$	0
$esd^{nmin}_{t,d} \leq esd_{t,d} < esd^{min}_{t,d}$	$SC^{**}_{t,d}$
$esd^{min}_{t,d} \leq esd_{t,d} \leq esd^{max}_{t,d}$	$SC^{*}_{t,d}$
$esd^{max}_{t,d} < esd_{t,d} \leq esd^{nmax}_{t,d}$	$SC^{***}_{t,d}$
$esd^{nmax}_{t,d} < esd_{t,d} \leq \infty$	$SC^{****}_{t,d}$

Using this information, the supply curve of ESs *d* in year *t* by the farmer can be derived as shown in Figure 2.

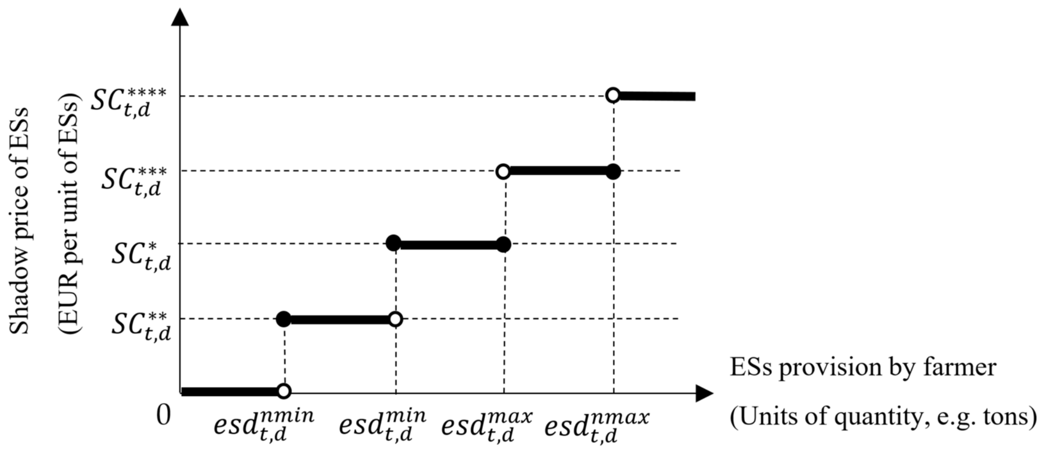

Figure 2. Farmer's supply curve for ESs *d* in year *t*. Adapted from Kaiser and Messer (2012) [17].

In alignment with the methodology outlined above, the derivation of supply curves for erosion control can be conducted through simulations using the previously introduced MODAM framework. Starting with unrestricted soil erosion, equivalent to zero erosion control, the initial model run produces cropping patterns with minimal erosion control and zero shadow prices. By progressively tightening erosion control constraints in line with sensitivity analyses, adjustments in cropping patterns can be observed, and shadow prices can be calculated for different levels of erosion control. These curves represent the minimum payments farmers are willing to accept for providing erosion control services under PES schemes.

3. Results

Figure 3 illustrates the nitrate leaching demand curve for the hypothetical farm type in Märkisch-Oderland along with its optimal cropping patterns simulated under varying levels of a green tax.

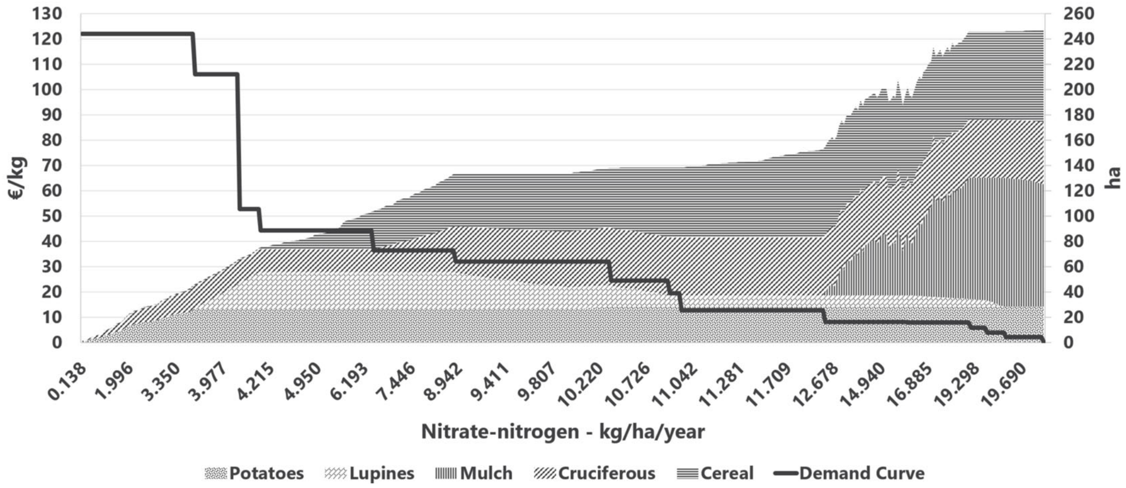

Figure 3. Nitrate leaching demand curve of the hypothetical farm type in Märkisch-Oderland (Brandenburg, Germany) and its optimal cropping patterns simulated under different levels of a green tax. Source: Own processing, results obtained using MODAM model implemented in GAMS software (Release 48.4.0).

The nitrate leaching demand curve of this farm reveals distinct trends in cropping patterns under varying green tax levels. At the zero green tax level, nitrate leaching reaches its maximum, with a cumulative value of approximately 19.69 kg/ha/year. Under these conditions, the dominant crop in the optimal cropping pattern is cereal, covering the majority of the farm's area. Cruciferous crops and potatoes make smaller contributions, primarily due to their relatively lower economic returns under unrestricted nitrogen use.

As the level of green tax gradually increases, farmers begin to adjust their cropping patterns to reduce nitrate leaching. Initially, cereal cultivation declines, replaced incrementally by crops such as cruciferous and lupines, which require less nitrogen input. At intermediate levels of green tax, there is a noticeable shift toward mulching practices and further diversification of cropping patterns, as these measures offer cost-effective ways to lower nitrate leaching without severely impacting economic returns.

At higher levels of green tax, nitrate leaching drops below 10 kg/ha/year, corresponding to a tax level higher than 30 EUR/kg/ha. During this stage, the cultivation of nitrogen-intensive crops like cereals is significantly minimized, with cruciferous crops, potatoes and lupines dominating the cropping pattern, reflecting the necessity of adopting low-nitrogen practices to comply with stricter regulations.

Finally, at the highest levels of green tax, nitrate leaching falls to its minimum level, approximately 0.138 kg/ha/year, which corresponds to a tax level of 120 EUR/kg/ha. In this scenario, the farm adopts an almost exclusive focus on low-nitrogen crops and practices, with only cruciferous crops and potatoes becoming the primary land uses. This extreme shift demonstrates the farm's capacity to adapt to strong economic incentives, although such high taxes may have implications for overall farm profitability and feasibility.

As the nitrate leaching threshold is reduced to lower levels, farmer faces constraints that make certain agricultural activities unviable, ultimately forcing them to abandon cultivation on some fields. Conversely, imposing higher green taxes on nitrate leaching would have a similar effect, discouraging farming on less profitable fields.

Also as shown in Figure 4, the nitrate leaching demand curve for the hypothetical farm in Oder-Spree highlights the economic trade-offs associated with varying levels of nitrate use under different green tax scenarios. At the zero green tax level, corresponding to the maximum nitrate leaching level of approximately 19.705 kg/ha/year, cereal cultivation dominates the cropping pattern, utilizing the majority of the available land area. This reflects the economic viability of cereal production under unrestricted nitrogen input conditions. Potatoes and cruciferous crops contribute less to the overall area, while lupines do not occupy any proportion of the farm's land.

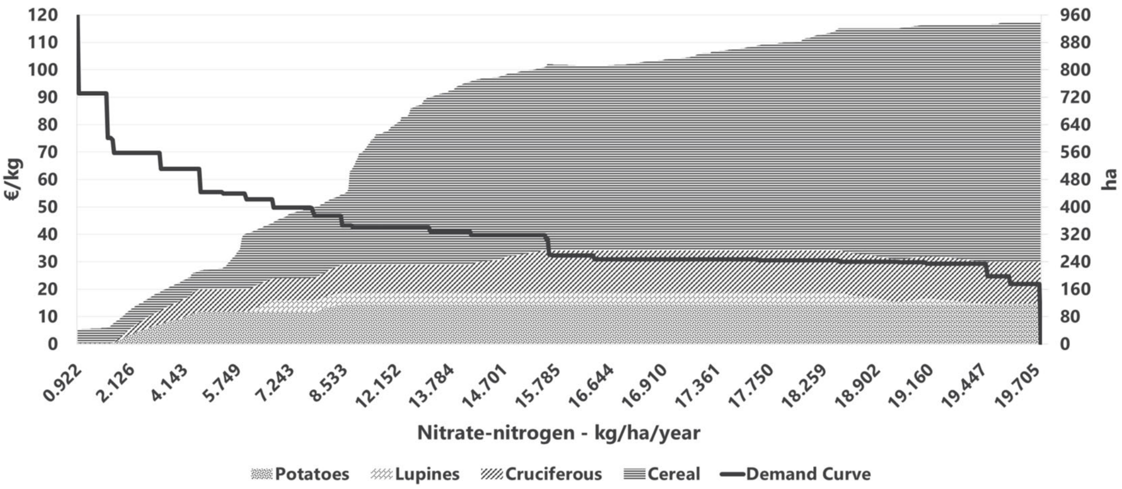

Figure 4. Nitrate leaching demand curve of the hypothetical farm type in Oder-Spree (Brandenburg, Germany) and its optimal cropping patterns simulated under different levels of a green tax. Source: Own processing, results obtained using MODAM model implemented in GAMS software (Release 48.4.0).

As green tax levels increase and nitrate leaching is reduced, the cropping pattern undergoes significant shifts. At a tax level of 40 EUR/kg/ha, nitrate leaching declines to approximately 15 kg/ha/year, and the area allocated to cereal begins to decrease, with cruciferous crops and lupines gradually gaining prominence. Potatoes also expand their share, indicating their comparative adaptability to higher green tax levels.

At intermediate levels of nitrate leaching, between 10 and 12 kg/ha/year, which correspond to a tax level of approximately 45 EUR/kg/ha, the farm's cropping pattern becomes increasingly diversified. Cruciferous crops and lupines exhibit notable growth in their cultivated areas, while cereals are further minimized. Potatoes continue to hold a stable proportion of the land, reflecting their economic resilience under moderate nitrogen restrictions.

As nitrate leaching drops below 5 kg/ha/year under green tax levels higher than 55 EUR/kg/ha, the farm prioritizes low-nitrogen crops. Lupines and cruciferous crops become dominant, supported by the adoption of mulching practices. Cereal cultivation is almost entirely phased out, highlighting the economic pressures placed on nitrogen-intensive crops under stringent environmental policies.

At a tax level of approximately 70 EUR/kg/ha, nitrate leaching drops to approximately 3 kg/ha/year, and the farm operates under a highly restrictive green tax regime. Cruciferous crops form the backbone of the cropping pattern, with minimal contributions from potatoes. This extreme adjustment demonstrates the farm's capacity to comply with stringent green tax requirements, albeit at the cost of reduced flexibility and potential profitability.

Imposing stricter nitrate leaching thresholds significantly limits farming options, compelling farmers to discontinue operations on fields where maintaining compliance becomes economically unsustainable. Similarly, higher green taxes on nitrate leaching would lead to reduced farming activities on marginal lands

In order to better illustrate the differences and interactions between nitrate leaching demand curves across the two farm types, Figure 5 combines the respective demand curves for Märkisch-Oderland and Oder-Spree.

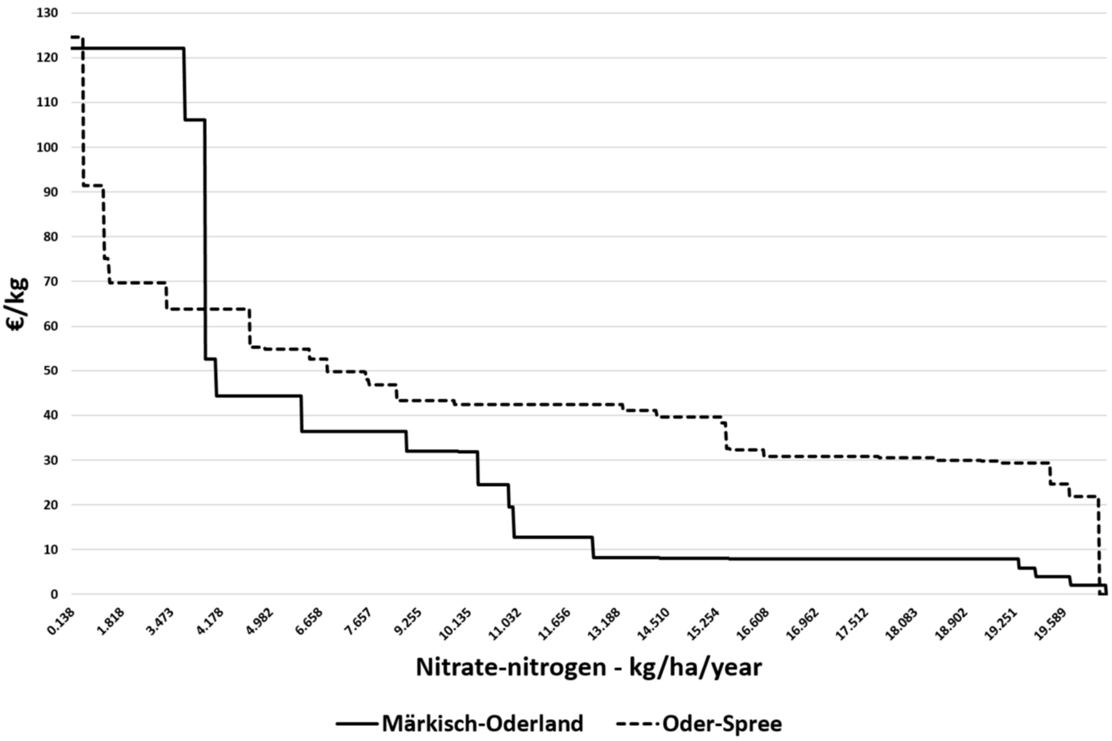

Figure 5. Nitrate leaching demand curves of two hypothetical farm types in Märkisch-Oderland and Oder-Spree. Source: Own processing, results obtained using MODAM model implemented in GAMS software (Release 48.4.0).

The demand curve for nitrate-nitrogen usage per hectare per year illustrates the maximum willingness of farmers in Märkisch-Oderland and Oder-Spree to pay for nitrogen use under various green tax levels. The curve highlights significant differences between the two farm types in terms of their economic responses to nitrogen taxation.

For the Märkisch-Oderland farm, which is smaller in size and focused solely on crop production, the demand curve indicates a steep decline in willingness to pay as nitrogen usage increases. At the lower consumption levels of approximately 1–5 kg of nitrogen per hectare, the farm is willing to pay approximately 120 to 45 EUR/kg. However, this willingness decreases sharply, reaching below 10 EUR/kg for nitrogen usage exceeding 12 kg/ha. The reason behind this sharp decrease in willingness to pay is that stricter nitrate leaching limits restrict land use and exclude nitrogen-intensive crops like cereals. As the threshold increases, more land can be cultivated, and cropping options expand, reducing the marginal value of additional nitrogen and thus lowering willingness to pay.

In contrast, the Oder-Spree farm, which is larger and diversified with livestock and crop production, demonstrates a higher and more elastic demand curve for nitrogen use. At nitrogen consumption levels of 1–5 kg/ha, the farm is willing to pay approximately 120 to 55 EUR/kg. Even at higher consumption levels (e.g., 15–20 kg/ha), the willingness to pay remains relatively higher compared to the Märkisch-Oderland farm, ranging between 40 to 30 EUR/kg.

The disparity in willingness to pay between the two farm types is particularly notable at higher nitrogen usage levels. For example, at a usage level of 19.5 kg/ha, the Oder-Spree farm is willing to pay more than 20 EUR/kg, whereas the Märkisch-Oderland farm's willingness to pay approaches zero. This suggests that larger and more diversified farms are better equipped to absorb green taxes, possibly due to their greater economic flexibility and higher revenues from diversified activities.

The relationship between soil erosion control levels and optimal cropping patterns under varying PES scenarios for the hypothetical farm in Märkisch-Oderland is depicted in Figure 6.

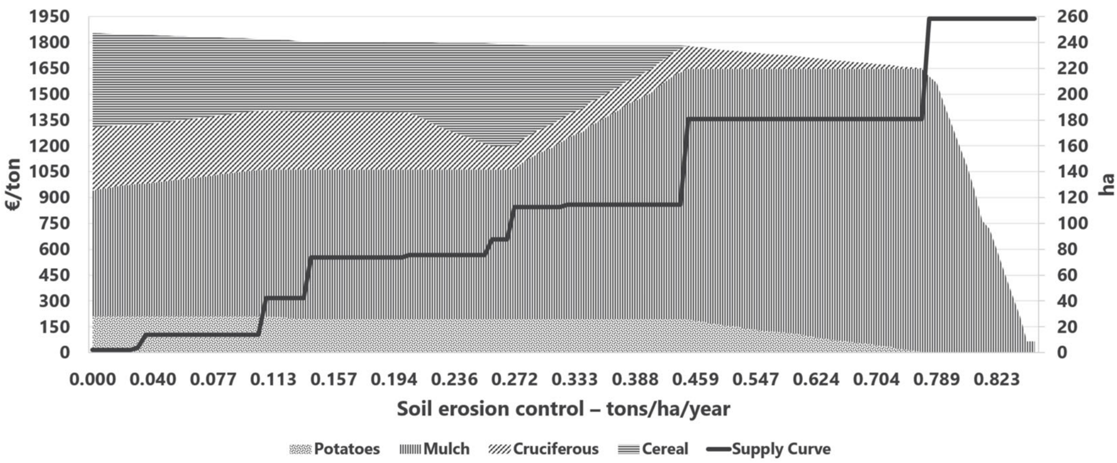

Figure 6. Erosion control supply curve of the hypothetical farm type in Märkisch-Oderland and its optimal cropping patterns simulated under different levels of a PES. Source: Own processing, results obtained using MODAM model implemented in GAMS software (Release 48.4.0).

The erosion control supply curve for the this farm illustrates the minimum price the farm is willing to accept for providing additional levels of erosion control under varying PES scenarios. The supply curve begins at approximately 150 EUR/ton of erosion control and steadily rises to nearly 1950 EUR/ton as the production of erosion control increases. This escalation reflects the increasing opportunity costs associated with higher levels of erosion control.

The cropping pattern associated with this supply curve demonstrates the farm's strategic adaptation to PES incentives. At lower levels of erosion control, the majority of land is allocated to high-return crops such as cereals, which have a higher risk of soil erosion. As the level of erosion control increases and PES payments rise, the cropping pattern shifts significantly. Activities like mulch and cruciferous crops, which contribute to improved soil stability and erosion prevention, gain prominence in the land use distribution.

At moderate levels of erosion control, the farm exhibits a balanced cropping pattern, with a noticeable increase in mulching and a reduction in cereals. As erosion control requirements escalate further, the dominance of mulch crops becomes evident, while the area dedicated to cereals diminishes sharply. This trend reflects the farm's adjustment to maximize economic returns while adhering to the constraints imposed by the PES framework.

When higher levels of erosion control are mandated, farmer must forego farming on particular fields, as the required measures to prevent soil erosion outweigh the economic returns of agricultural production. Likewise, offering higher PESs for erosion control could incentivize farmer to prioritize soil conservation over farming in such areas.

In order to provide a broader perspective on the evolution of cropping patterns in response to environmental policies, it is useful to compare the adjustments observed on the Märkisch-Oderland farm under PES incentives with those under the green tax scenarios described earlier. Under PES incentives, the focus shifts from high-return cereals to soil-stabilizing practices like mulch and cruciferous crops as erosion control requirements increase, demonstrating a prioritization of soil conservation. Conversely, under the green tax regime, the adjustments emphasize reducing nitrate leaching, with cereals being replaced by low-nitrogen crops such as cruciferous and lupines, as shown in Figure 3. At the most stringent levels, both scenarios converge toward minimal cultivation on less profitable fields to comply with environmental goals, reflecting the economic trade-offs inherent in adapting the farm's cropping pattern to targeted policy mechanisms.

Figure 7 presents the dynamic interplay between PESs for soil erosion control levels and optimal cropping patterns in the hypothetical farm type located in Oder-Spree.

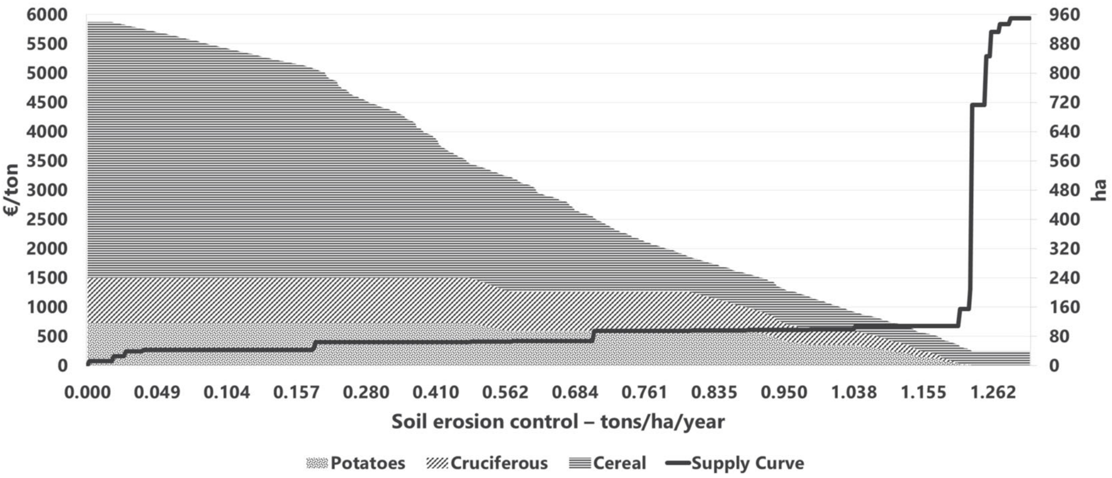

Figure 7. Erosion control supply curve of the hypothetical farm type in Oder-Spree and its optimal cropping patterns simulated under different levels of a PES. Source: Own processing, results obtained using MODAM model implemented in GAMS software (Release 48.4.0).

The erosion control supply curve in this farm demonstrates the farm's minimum willingness to accept payments for increasing erosion control under varying PES levels. The supply curve begins at approximately 200 EUR/ton of erosion control and steeply rises to approximately 5500 EUR/ton as erosion control provision increases. This sharp escalation highlights the growing opportunity costs and economic adjustments required for higher levels of ESs provision.

The cropping patterns associated with this supply curve illustrate the farm's response to PES incentives. At lower levels of erosion control, the dominant crop is cereal, which maximizes economic returns while contributing relatively less to erosion control. As PES payments increase, incentivizing greater erosion control, the cropping pattern shifts towards cruciferous crops, which provide better erosion control benefits. At intermediate levels of erosion control, the farm balances its cropping strategy by allocating significant portions of land to cruciferous crops while maintaining cereal production at a reduced level.

At higher levels of PES payments and erosion control provision, there is a visible dominance of cruciferous crops, reflecting their superior ability to mitigate soil erosion and adapt to the economic incentives provided. Meanwhile, the allocation to cereal declines sharply, and the inclusion of potatoes becomes more pronounced. This shift underscores the economic trade-offs involved, as the farm reallocates land to crops that are less economically lucrative but more ecologically beneficial.

With stringent erosion control requirements, farmer is forced to halt agricultural activities on fields where compliance costs surpass the profitability of farming, leading to land abandonment. Similarly, higher PESs for erosion control would encourage the transition of such lands toward conservation efforts rather than agricultural production.

To provide a more comprehensive comparison of erosion control supply curves of the two hypothetical farm types, Figure 8 juxtaposes the respective curves for Märkisch-Oderland and Oder-Spree under varying PES scenarios.

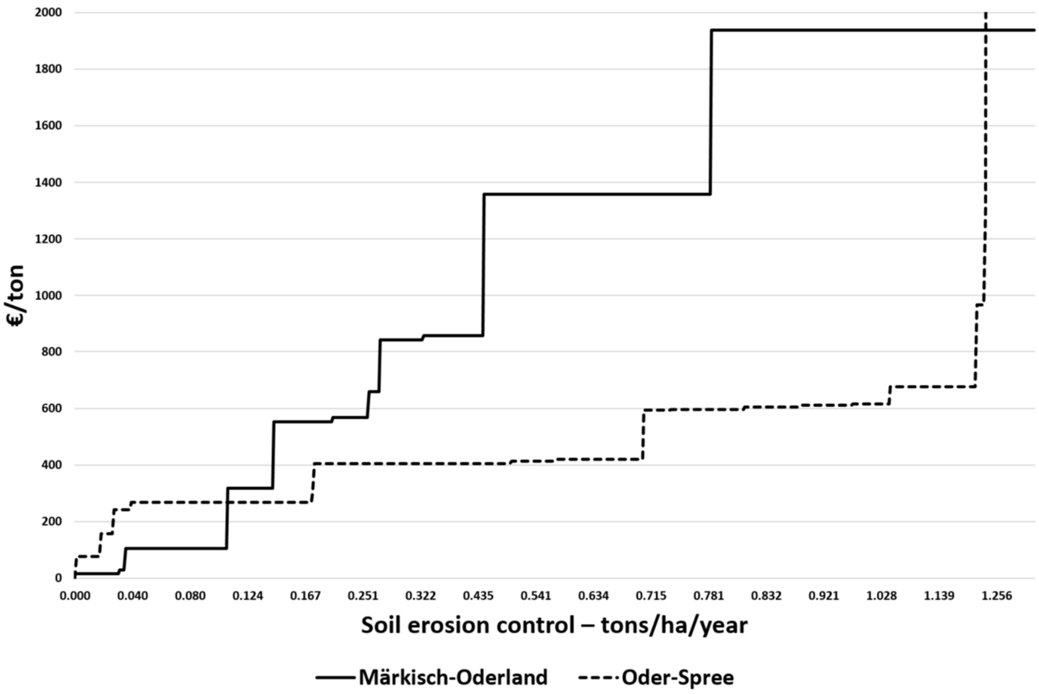

Figure 8. Soil erosion control supply curves of two hypothetical farm types in Märkisch-Oderland and Oder-Spree. Source: Own processing, results obtained using MODAM model implemented in GAMS software (Release 48.4.0).

The supply curve for erosion control per hectare per year depicts the minimum payment that farmers in Märkisch-Oderland and Oder-Spree are willing to accept for providing erosion control services under various PES schemes. This curve reveals notable differences in the economic thresholds for implementing erosion control practices between the two farm types.

For the Märkisch-Oderland farm, the supply curve starts at lower erosion control levels, with the willingness to accept payments beginning at approximately 150 EUR/ton of erosion control provided. As the level of erosion control increases, the required payment rises incrementally. At higher levels of erosion control, such as approximately 0.5 tons/ha/year, the willingness to accept payments sharply increases, reaching close to 1400 EUR/ton. This pattern indicates that the incremental cost of providing additional erosion control becomes significantly higher as the capacity for such practices nears its upper limit.

In contrast, the Oder-Spree farm demonstrates a more elastic supply curve, reflecting its greater adaptability and capacity for providing erosion control services. At lower levels of erosion control, the willingness to accept payments starts at approximately 200 EUR/ton, higher than the Märkisch-Oderland farm. However, the increase in required payments is more gradual, and the farm can sustain higher levels of erosion control at relatively lower marginal costs. For instance, at approximately 0.5 tons/ha/year, the willingness to accept payments remains approximately 400 EUR/ton, highlighting the farm's greater efficiency in implementing erosion control practices.

4. Discussion

This study highlights the vital importance of bio-economic modeling frameworks, such as MODAM, in assessing ESs like nitrate leaching and erosion control. These tools are instrumental in analyzing the economic behavior of farms under incentive-based policies, offering strategies to harmonize agricultural practices with environmental sustainability. By modeling how farms respond to economic incentives, bio-economic farm models shed light on the intricate relationship between ecological objectives and financial constraints, demonstrating the potential of market-based mechanisms to encourage sustainable land management.

A key finding is the variation in economic responses across different farm types. The analysis uncovered notable differences between the smaller, crop-focused Märkisch-Oderland farm and the larger, mixed crop-livestock Oder-Spree farm. The Oder-Spree farm, benefiting from its diversified operations, showed greater flexibility in both willingness to pay for nitrate leaching and willingness to accept payments for erosion control. This adaptability stems from its multiple revenue streams, enabling it to respond more effectively to economic incentives. In contrast, the Märkisch-Oderland farm, with its specialized focus, faced higher marginal costs due to its limited capacity to redistribute resources and modify practices. These findings underscore the economic pressures on smaller farms and the risks of one-size-fits-all incentive schemes, which may disproportionately affect them. To address these challenges, policies need to account for the unique characteristics and constraints of individual farms, ensuring equity and effectiveness in ESs market mechanisms. These findings align with prior research highlighting the differing capacities of small and large farms to adapt to economic incentives. For instance, Tacconi et al. [27] demonstrated that smallholder farmers often adopt diversification strategies to manage risks but may gravitate toward specialization when market opportunities and technologies favor it, posing challenges to adaptation. Similarly, Awiti et al. [28] noted that while diversification enhances resilience, it increases production costs, limiting smallholders' ability to respond to such incentives. Research by Thottadi and Singh [29] underscores the socio-economic and institutional complexities affecting small farms' adoption of climate-smart practices, highlighting limited resources as a key constraint. In contrast, studies such as Wimmer and Sauer [30] and Tarruella et al. [31] demonstrate that larger, diversified farms are better equipped to leverage economies of scale and manage heterogeneous abatement costs, enhancing their ability to adapt. These insights collectively emphasize that farm size and diversification play critical roles in shaping adaptive responses to economic policies.

This study also underscores the impact of economic incentives, such as green taxes and PESs, on farming decisions. Both farms exhibited shifts in cropping patterns, moving away from nitrogen-intensive crops like cereals toward alternatives such as lupines and cruciferous vegetables. Additionally, higher PES levels spurred the adoption of soil-conserving measures, including mulching and cover crops. This adaptability demonstrates the effectiveness of economic tools in fostering sustainable agricultural practices. However, it also highlights the trade-offs farmers face in balancing environmental goals with economic viability. Policymakers must carefully set incentive levels to adequately compensate farmers for the opportunity costs of these changes, especially for smaller or less diversified operations. The results highlight that green taxes on nitrate leaching and PESs for erosion control significantly impact farming decisions, driving shifts toward sustainable practices or, at higher levels, land abandonment. Policies must balance environmental goals with economic viability, tailoring thresholds to regional and farm-specific contexts to ensure sustainability without compromising agricultural productivity. The adoption of soil-conserving measures in response to higher PES levels, as highlighted in this study, aligns with the extensively documented role of financial incentives in promoting sustainable agricultural practices. Aznar-Sánchez et al. [32] emphasized that subsidies and financial facilities significantly facilitate the adoption of sustainable soil management practices, including erosion control measures. Similarly, Calixto et al. [33] highlighted financial constraints as key barriers to implementing erosion control techniques, advocating for enhanced resource provision and knowledge dissemination to address these challenges. Touhami et al. [34] underscored the importance of financial incentives and subsidies in making soil conservation practices economically viable for small-scale farmers. Leyva et al. [35] provided a specific case study in southern Spain, showing how subsidies motivated farmers to adopt soil conservation practices like contour tillage and stonewall maintenance. Collectively, these studies affirm that financial support plays a pivotal role in overcoming economic barriers to adopting sustainable erosion control practices.

Shadow pricing, as applied through the MODAM framework, offers a valuable method for determining green taxes and PES rates. These prices capture the true economic value of ESs, enabling policymakers to design market-based instruments that internalize the costs of ecosystem degradation. By tying economic incentives to the societal value of ESs, shadow pricing can drive sustainable practices while maintaining farm profitability. The application of shadow prices to evaluate nitrate leaching and erosion control provides a robust framework for policy design, as highlighted in various studies. Dang and Mourougane [17] emphasized the utility of shadow prices in reflecting economic trade-offs, supporting their use in green taxes and PES rate setting. Similarly, Zhang et al. [36] found that incorporating livestock into carbon shadow pricing in China's agricultural sector was crucial for accurate estimations, reinforcing shadow pricing's role in balancing economic and environmental objectives. De Bruyn et al. [37] also provided standardized methodologies for assigning monetary values to emissions, aiding policymakers in internalizing environmental externalities. Collectively, these works demonstrate the feasibility and effectiveness of using shadow prices as benchmarks for designing green taxes, PES rates, and other market-based environmental policies. However, the sensitivity of shadow prices to fluctuations in ESs supply and demand underscores the need for adaptive policy frameworks. Regular evaluations of policy outcomes and farm-level responses are essential to refining incentives, ensuring they achieve both environmental and economic objectives. An adaptive and iterative policy framework is essential for addressing the dynamic nature of ecosystem services supply and demand, ensuring that policies remain effective and equitable under changing conditions.

The findings also emphasize differences in adaptability between farms of varying sizes and levels of diversification. Larger, more diversified farms, like Oder-Spree, showed greater resilience in adjusting cropping patterns to meet environmental goals, absorbing the economic impacts of stricter erosion control and nitrogen use limitations. These farms achieved this flexibility through diverse crop selection and efficient resource allocation. In contrast, smaller farms, such as Märkisch-Oderland, exhibited heightened sensitivity to economic incentives, facing significant reductions in their capacity to pay for nitrogen use under high tax scenarios. Their steeper supply curves for erosion control illustrate the considerable trade-offs they encounter when reallocating resources to enhance ESs provision. These disparities highlight the necessity of tailoring PES schemes to farm-specific characteristics, ensuring equitable and effective promotion of ESs. The observed disparities in ESs valuation between the Märkisch-Oderland and Oder-Spree farms align with findings in the literature that highlight the significance of regional differences in ESs provision and policy design. Barton et al. [38] emphasized that the effectiveness of economic instruments, such as PESs, varies across regions due to ecological, social, and economic factors, necessitating context-specific approaches. Similarly, Frank et al. [39] demonstrated how reducing water erosion in Saxony, Germany, influences trade-offs among multiple ESs, reinforcing the need for tailored regional policies. Furthermore, Thorsen et al. [40] underscored how variability in forest ESs provision costs is shaped by regional economic and ecological factors, highlighting the importance of designing economic mechanisms that reflect these disparities. Together, these studies affirm the necessity of adapting policy instruments to regional and farm-specific contexts to achieve balanced and effective outcomes.

This study's findings on cropping pattern adjustments under varying green tax levels align with insights from previous research on agricultural policies. Buchholz and Musshoff [41] demonstrated that a pesticide tax and green nudge both reduced pesticide applications in their experimental analysis, though the tax led to significant profit loss and changes in cropping and tillage strategies. Similarly, Dumortier and Elobeid [42] observed that a U.S. carbon tax increased production costs for crops like corn, cotton, and sorghum, driving shifts in land use and cropping patterns. Dragicevic and Pereau [43] further reinforce the role of fiscal measures by demonstrating that eco-taxation significantly outperforms climate pledges in reducing global agricultural emissions. Their study highlights a 57.87% reduction in emissions and a 45.68% greater reduction in emission intensity compared to pledges, positioning eco-taxation as a critical tool for achieving climate targets like the EU's objectives. These studies collectively highlight how fiscal and regulatory policies can influence sustainable agricultural transitions.

While these findings offer valuable insights into the economic dynamics of ESs provision, this study has certain limitations. The focus on two hypothetical farms in Brandenburg limits the generalizability of the results to other regions with differing environmental and socio-economic conditions. Expanding the analysis to include diverse geographic and agricultural settings could enhance its relevance. Furthermore, this study primarily examined nitrate leaching and erosion control, leaving out other critical ESs, such as carbon sequestration and biodiversity preservation. Broader ESs assessments could support the development of more comprehensive policy solutions.

Lastly, while the MODAM successfully integrates ecological and economic dynamics, its reliance on fixed prices for outputs and inputs—even after the imposition of green taxes or the implementation of PESs—may oversimplify real world farming systems. Incorporating mechanisms to account for price fluctuations and market dynamics, could address these limitations, enhancing the model's predictive power and policy relevance. Such improvements would enable the generation of more nuanced and effective policy recommendations, fostering agricultural practices that better align with environmental objectives in a sustainable manner.

5. Conclusions

This study demonstrates the utility of bio-economic modeling, exemplified by the MODAM framework, in connecting ESs valuation to policy design for sustainable agriculture. By integrating ecological and economic dynamics, the model provides a structured approach to evaluate how market-based instruments, such as green taxes and PESs, influence farm behavior. These insights support the formulation of targeted policies that align agricultural practices with environmental sustainability while accommodating economic realities.

The findings underscore the necessity of tailoring incentives to diverse farm structures, recognizing the variability in economic adaptability among farms. Larger, diversified operations exhibit greater resilience to policy changes, while smaller, specialized farms face heightened economic challenges, highlighting the need for equitable solutions. However, this study is limited by its focus on two hypothetical farms in Brandenburg, which may restrict the applicability of the results to other regions with differing contexts. Additionally, it primarily addresses nitrate leaching and erosion control, leaving out other critical ESs. Future research should explore diverse agricultural systems, include a broader range of services, and address price fluctuations in economic models to enhance the robustness and relevance of policy recommendations.

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