

Article

A Model Approach for Yield-Zone-Specific Cost Estimation of Greenhouse Gas Mitigation by Nitrogen Fertilizer Reduction

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Abstract: Nitrogen use in agriculture has been intensified to feed the growing world population, which led to concerns on environmental harms, including greenhouse gas emissions. A reduction in nitrogen fertilization can abate greenhouse gas emissions, however, it may result in crop yield penalties and, accordingly, income loss. Assessment tools are necessary to understand the dynamics of nitrogen management issues both in environmental and economic aspects and both at low and high aggregation levels. Our study presents a model approach, estimating yield-zone-specific costs of greenhouse gas mitigation by moderate reduction of mineral nitrogen fertilizer application. Comparative advantages of mitigating greenhouse gas emissions by nitrogen fertilizer reduction were simulated for five yield-zones with different soil fertility in the state of Brandenburg, Germany. The results suggest that differences in yield response to nitrogen fertilizer lead to considerable differences in greenhouse gas mitigation costs. Overall cost-efficiency of a regional greenhouse gas mitigation by nitrogen fertilizer reduction can be substantially improved, if crop and yield-zone-specific yield responses are taken into account. The output of this study shall help to design cost-efficient agro-environmental policies targeting with specific crop yield response functions at different sites.

Keywords: reactive nitrogen; yield response function; normalization; comparative advantage; GHG abatement

1. Introduction

Nitrogen (N) use in agriculture is of concern due to the dilemma of agricultural intensification to cope with the global food demand and the efforts to reduce emission of reactive N, which is one of the vital environmental challenges [1]. To feed the growing world population, mineral N fertilizer production and application have grown ten-fold in the second half of the last century [2]. Every kg of mineral N fertilizer application increases the global stock of reactive N which keeps partly circulating (i.e., manure recycling) in agricultural systems. Increasing use of N fertilizers causes impacts on soil, air, water, biodiversity and climate change [3]. The application of mineral N fertilizers is the biggest source of global anthropogenic N₂O emissions [4] which are the fastest growing source of agricultural greenhouse gas (GHG) emissions [5]. N₂O emissions are expected to rise further and this may offset GHG mitigation efforts from other sectors [6]. At farm level, more than half of GHG emissions generated in crop production originate from N fertilizer application [7,8]. Besides, production of fertilizers is an energy intensive process that is responsible for a considerable amount (0.6–1.2%) of total GHG emissions worldwide [9] with the highest contribution from N fertilizer production [10]. Thus, if emissions due to mineral N fertilizer production were accounted for, in addition to N₂O

emissions due to application, the importance of N fertilizer in total agriculture induced GHG emissions would be even higher [11].

Measures to tackle the N use dilemma mainly focus on how to achieve more efficient N use [7,12]. However, it is particularly challenging to increase N use efficiency, since reactive N is bound and cycled in various chemical pathways in agricultural soils [3] and easily distributed by hydrologic and atmospheric transportation [13]. Roughly half of the N added into agricultural systems in Europe is lost to the surrounding environment [3]. Facing the high impact of N fertilizer use on the environment and especially global warming, reduction of N fertilizer seems to be an effective GHG mitigation measure. Reduction in N fertilizer related GHG emissions can be achieved by changing input management or change in cropping systems (selection of crops with lower N input). A direct reduction of N input supply into agricultural systems is an obvious mitigation measure which was suggested 20 years ago (e.g., Kroeze [14]). Denmark implemented an N input quota system in the early 1990s setting norms for the N fertilization equal to the economic optimum N rate which was subject to further reduction up to 15% below the economic optimum [15]. Furthermore, GHG mitigation options based on N input management were often suggested as technological approaches such as variable rate technology in precision farming [16,17]. While the acceptance level of such technologies still remains in a tardy progress at the global scale [18], the returns of investments in precision farming technologies are often low [19,20]. One reason for the limited economic returns of precision farming practices is the flatness of profit functions around the assumed economic optimum [21]. However, flat profit functions also provide an opportunity to reduce N input and thus associated GHG emissions, without affecting farm profitability heavily. In the same vein, McSwiney & Robertson [22] stated that mitigation of N₂O emissions by N fertilizer reduction could be achieved without causing a strong yield penalty. Furthermore, Meyer-Aurich et al. [23] reported that a moderate reduction of N fertilizer can be an effective measure to lower GHG emissions; and such straightforward N fertilizer reduction—without any technology investment—requires more attention as an alternative to mitigate GHG emissions in agriculture.

N fertilizer reduction has been considered from GHG mitigation point of view at different scales. For instance, Domínguez et al. [24] evaluated the EU-wide implications of a reduction in N fertilizer input—while maintaining output constant—via eliminating assumed over-fertilization and/or achieving more balanced N fertilizer management between mineral and organic N fertilization. Mérel et al. [25] assessed the effects of an N fertilizer tax on N mitigation at the intensive (input intensity adjustments) and extensive margins (acreage reallocation) at the regional scale. While there is information at aggregated levels in terms of to what extent and at what costs N fertilizer reduction offers GHG mitigation potentials, there is little information on cost-efficient GHG mitigation at different sites considering different yield responses to stepwise reduction of N fertilization. Such indication of GHG mitigation costs could enable comparability of GHG mitigation potentials by N fertilizer reduction among sites, since site-dependent climate and soil characteristics result in differences in crop yield potentials which in turn may lead to different GHG mitigation costs. This was already shown for GHG mitigation potentials and costs of biogas production in Brandenburg, if different feedstock are grown at sites with different yield potentials [26].

In terms of N fertilizer, yield and GHG interactions, the first step towards understanding site-dependent GHG mitigation potentials and opportunity costs of reducing N supply would be to understand crop yield response to N fertilizer reduction. On the one hand, reduction in N fertilization abates GHG emissions—first, due to reduced energy demand for less N fertilizer production and secondly because of fewer N inputs into agricultural soils, resulting in fewer N₂O emissions. On the other hand, it can be expected that yield penalties occur, which may be a major constraint for farmers to reduce N fertilizer [27]. The magnitude of yield penalty depends on yield response to reduced N application. Thus, cost estimation of GHG mitigation by N fertilizer reduction requires the estimation of GHG mitigation potential and thereby the economic returns of reduced N fertilization. While the former can be estimated by means of emission factors per kg N input, the latter

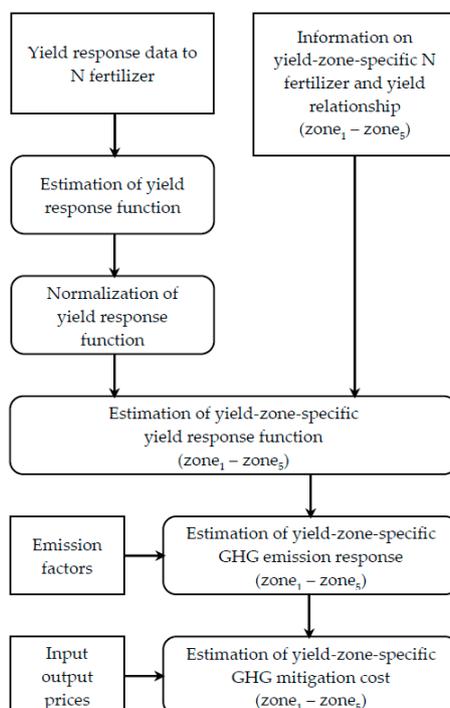
requires the identification of production functions relating crop yield to N fertilizer application. Yield response functions can be estimated on the basis of long-term field experiments; however, such empirical data do not exist for all crops at all sites. In this context, this study aims to identify the comparative advantage of different sites (yield-zones) in Brandenburg with specific crop yield responses to N fertilizer to mitigate GHG by N fertilizer reduction. Hanff & Lau [28] suggested yield-zone-specific N fertilizer rates but information on yield-zone-specific response to reduced N supply is not available. Therefore, we estimated yield-zone-specific response functions based on a normalization approach [29], which enables transferring yield response to N fertilizer from sites with empirical data to the yield-zones lacking that information. The normalization approach was applied in earlier studies addressing environmental issues regarding N use in agriculture [30–32]. For instance, Baudoux [31] evaluated environmental and economic implications of a complete renunciation of mineral N fertilization. However, to our knowledge the comparative advantages of specific sites to mitigate GHG emissions by moderate N fertilizer reduction have not been shown yet.

In this context, our paper presents a model approach to estimate yield-zone-specific costs of GHG mitigation by mineral N fertilizer reduction. In addition, it provides a basis to analyse implications of different GHG mitigation policies on N fertilizer reduction, e.g., N fertilizer tax, incentives, or N fertilizer cap. The output of this study has potential to contribute as an aiding tool to identify cost-efficient agro-environmental policies.

2. Materials and Methods

2.1. Methodological Concept

We constructed a model which reflects yield and economic response to N fertilizer reduction in yield-zones with different yield potentials in order to identify comparative advantages for GHG mitigation. A normalization approach following Krayl [29] was employed to transfer yield response to N fertilizer from sites with known input-output relations to yield-zones lacking that information. The workflow of the methodological approach is shown in Scheme 1.



Scheme 1. The workflow of the methodological approach. Normal rectangles are the data and assumptions taken, and the curve edged rectangles are the calculations performed.

We applied our model to estimate winter wheat (further referred to as wheat) and winter rye (further referred to as rye) yield response to N fertilizer reduction in five yield-zones in the state of Brandenburg, Germany. Wheat and rye are dominant cereals in Brandenburg, while wheat is grown predominantly in high yield-zones, rye is grown rather in low yield-zones. Therefore, modelling both cereals with respect to GHG mitigation potentials provides representation of all possible yield-zones in the region, and, thus respective comparative advantages.

Yield response functions with respect to N fertilizer were estimated based on long-term experiments for wheat and rye (see Section 2.2) and transferred by the normalization approach to the five yield-zones in Brandenburg (see Section 2.3). Yield-zone-specific yield response functions were estimated to provide the base for the subsequent estimations of GHG emission response to N fertilizer reduction (see Section 2.3). Costs of yield-zone-specific GHG mitigation were estimated combining N fertilizer reduction induced GHG mitigation (see Section 2.4) with the economic returns (see Section 2.5). In addition, an uncertainty analysis was executed to identify the most influential parameters on and the ranges of GHG mitigation costs by N fertilizer reduction (see Section 2.6). Considering a constant regional demand for wheat and rye, we applied a system expansion to include possibly emerging GHG emissions by offsetting yield penalties due to N fertilizer reduction (see Section 2.7). Furthermore, we conducted a case study on regional optimization of GHG mitigation by N fertilizer reduction in wheat and rye production in Brandenburg (see Section 2.8).

2.2. Data

Empirical data on crop yield response to N fertilizer were taken from two long-term experiments located in north-eastern Germany (Table 1). Data for wheat (*Triticum aestivum* L.) yield response were taken from 1986 until 1999 in Dahlem [33]; and for rye (*Secale cereal* L.) yield response from 1996 until 2010 in Thyrow [34]. The annual average precipitations were 545 mm and 495 mm and the annual average temperatures were 9.3 °C and 8.9 °C for Dahlem and Thyrow, respectively. The experiments were designed with various fertilizer treatments. For wheat, four different mineral N fertilizer application rates were used. Wheat was in rotation with barley (*Hordeum vulgare* L.) and potato (*Solanum tuberosum* L.) and 30 t of farmyard manure was applied on potato cultivation in the rotation triennially. For rye, three different mineral N fertilizer application rates were used; and rye was in rotation with winter barley (*Hordeum vulgare* L.), oil seed rape (*Brassica napus* L.), cocksfoot (*Dactylis glomerata* L.) and potato. The rotation received organic fertilizer as straw after harvesting winter barley and rye.

Information on yield and N fertilizer relationships in the yield-zones were derived from Hanff & Lau [28]. They provided input-output patterns including yield potentials and N fertilization rates for five differentiated yield-zones in Brandenburg. Yield-zones are categorized based on a soil fertility index where yield-zone-1 has the highest and yield-zone-5 has the lowest yield potential. We assumed that the data on N fertilizer can be interpreted as the recommended N fertilizer intensity to reach an expected economic optimum yield level in respective yield-zone. Table 2 presents yield-zone-specific N fertilization rates and corresponding yield levels.

Table 1. Yield response data with respect to N fertilizer for wheat from Dahlem (1986–1999) based on [33] and for rye from Thyrow (1996–1999) based on [34].

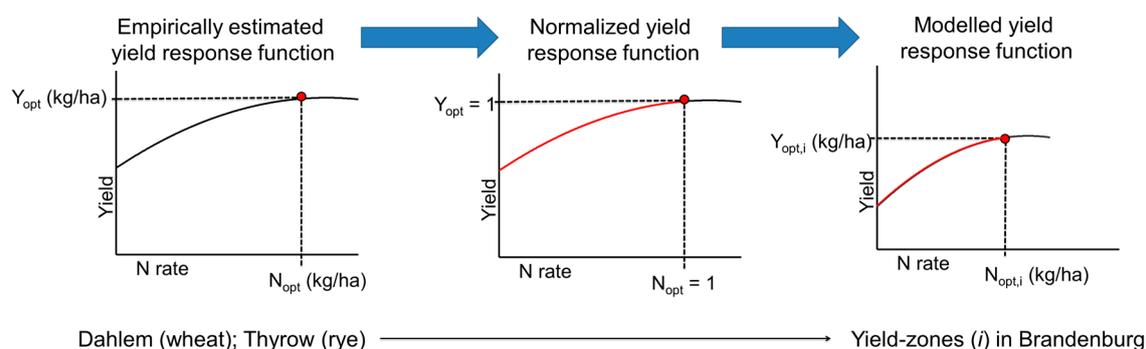
Wheat		Rye	
Fertilizer (kg N ha ⁻¹)	Average Yield (Mg ha ⁻¹)	Fertilizer (kg N ha ⁻¹)	Average Yield (Mg ha ⁻¹)
0	3.25	0	2.11
60	5.28	60	4.57
110	5.68	120	5.20
160	5.98		

Table 2. Yield-zone-specific N fertilizer rates and corresponding crop yield levels in five yield-zones in Brandenburg according to Hanff & Lau [28].

	Yield-Zones in Brandenburg									
	1	2	3	4	5	1	2	3	4	5
	Wheat					Rye				
Yield (Mg ha ⁻¹)	7.70	6.50	5.00	3.80	2.30	7.40	6.60	5.30	4.00	2.50
Fertilizer (kg N ha ⁻¹)	170	144	111	84	51	145	130	104	78	49

2.3. Estimation of Yield-Zone-Specific Yield Response Functions

Yield-zone-specific yield response functions were modelled in three steps: (i) estimation of yield response functions based on the empirical data; (ii) transforming them by the normalization approach and (iii) transferring the normalized yield response functions to the yield-zones in Brandenburg (Figure 1).

**Figure 1.** Workflow for modelling yield-zone-specific yield response functions.

Quadratic polynomial functions were estimated by ordinary least square method (Equation (1)) using the data on crop yield response to N fertilizer for wheat and rye from the considered long term field experiments (Dahlem and Thyrow). Meyer-Aurich et al. [35] reported that quadratic functions showed the best statistical fit for wheat yield response to N fertilizer. Nonetheless, functional specification of yield response to N fertilizer does not have a strong impact on economic assessments [36].

$$Y = aN^2 + bN + c \quad (1)$$

where Y is yield (Mg ha⁻¹), N is N fertilization rate (kg N ha⁻¹), a is the quadratic coefficient, b is the linear coefficient and c is a constant.

We deployed the normalization approach transforming the above-mentioned crop specific polynomial function to build crop specific yield response functions for each of the five yield-zones in Brandenburg (Equation (2)).

$$Y = a_i N^2 + b_i N + c_i \quad (2)$$

where i denotes yield-zone.

For the transfer of yield response functions, reference points of both sites were required and all quantities of yield and N rate were subject to be relative to these reference points. We used economic optimum N rate and corresponding yield level as reference points in the normalization approach. Economic optimum fertilizer rate maximizes profit and was found by solving the first order derivation of the yield response function. At the economic optimum N rate (N_{opt}), marginal product is equal to the input-output price ratio (P_N/P_Y) (Equations (3)–(5)). The economic optimum N rates and the corresponding yields (Y_{opt}) were calculated using coefficients of respective yield response functions

for wheat and rye at fixed price ratio (5.96 € kg⁻¹ N/€ kg⁻¹ wheat; 7.80 € kg⁻¹ N/€ kg⁻¹ rye) of N fertilizer (input) and crops (output).

$$\frac{dY_{opt}}{dN_{opt}} = \frac{P_N}{P_Y} \quad (3)$$

$$\frac{dY_{opt}}{dN_{opt}} = 2aN_{opt} + b \quad (4)$$

$$N_{opt} = \frac{\frac{P_N}{P_Y} - b}{2a} \quad (5)$$

The coefficients of the normalized production function were derived from the coefficients of the empirically estimated yield functions a , b , c (in Equation (1)) for wheat from Dahlem and rye from Thyrow; and transformed into (Equation (6)) where Y_{norm} is the normalized production function with normalized N application rate (N_{norm}) and normalized coefficients a_{norm} , b_{norm} and c_{norm} .

$$Y_{norm} = a_{norm}N_{norm}^2 + b_{norm}N_{norm} + c_{norm} \quad (6)$$

Y_{norm} was defined as Y divided by Y_{opt} and N_{norm} was found as N divided by N_{opt} . By using these relations, Equation (1) was reformulated as:

$$Y_{opt}Y_{norm} = aN_{opt}^2N_{norm}^2 + bN_{opt}N_{norm} + c \quad (7)$$

By dividing Equation (7) by Y_{opt} , we re-arranged the equation and generated Y_{norm} function as:

$$Y_{norm} = \left(\frac{aN_{opt}^2}{Y_{opt}} \right) N_{norm}^2 + \left(\frac{bN_{opt}}{Y_{opt}} \right) N_{norm} + \frac{c}{Y_{opt}} \quad (8)$$

From Equation (8), we identified normalized coefficients (Equations (9)–(11)) by comparing Equation (8) with Equation (6):

$$a_{norm} = \frac{aN_{opt}^2}{Y_{opt}} \quad (9)$$

$$b_{norm} = \frac{bN_{opt}}{Y_{opt}} \quad (10)$$

$$c_{norm} = \frac{c}{Y_{opt}} \quad (11)$$

Once the empirically estimated yield response functions were transformed into normalized yield response functions, they were transferred to the yield-zones of Brandenburg, where only N_{opt} and Y_{opt} were known. We transferred the normalized yield response functions for wheat and rye to the five yield-zones in Brandenburg. Following the assumption of the normalization approach, the second-degree derivations of the normalized yield response functions at respective N_{opt} points were equal (Equation (12)).

$$Y''_{norm} = Y''_{norm_i} \quad (12)$$

Given this assumption, we calculated the quadratic coefficient of respective yield-zone in Brandenburg as follows:

$$a_i = \frac{a_{norm}Y_{opt_i}}{N_{opt_i}^2} \quad (13)$$

After the quadratic coefficient of the yield response function of the yield-zones was determined based on the normalization approach, we calculated the linear coefficient derived from N_{opt} calculation in Equation (5):

$$b_i = \frac{P_N}{P_Y} - 2a_i N_{opt_i} \quad (14)$$

Once quadratic (a) and linear (b) coefficients of the production function of each yield in Brandenburg were determined, we calculated the constant (c) given the economic optimum N rate (N_{opt_i}), the yield (Y_{opt_i}) at N_{opt_i} and the prices of input and output based on Equation (2):

$$c_i = -a_i N_{opt_i}^2 - b_i N_{opt_i} + Y_{opt_i} \quad (15)$$

Following normalization of the yield response functions based on the empirical data and transformation of the normalized functions into five different yield-zones in Brandenburg, yield response functions for wheat and rye in each yield-zone were constructed. Consequently, yield response on adjusted N fertilization intensities could be drawn in differentiated yield-zones, so that yield-zone-specific marginal GHG mitigation costs could be identified accordingly.

2.4. Partial Budgeting of GHG Emissions of N Fertilizer

For the partial budgeting of GHG emissions, we included direct and indirect N₂O emissions due to mineral N fertilizer application and CO₂ emissions generated due to mineral N fertilizer production. Calcium ammonium nitrate (CAN) with 27% N content was chosen as the mineral N fertilizer type which is commonly used in Brandenburg. It was assumed that no manure was applied to fields of wheat and rye and above-ground crop residues were removed from fields. Change in below-ground biomass was ignored, since root biomass was expected to be only marginally affected by moderate adjustments of N fertilization. Table 3 shows the emission factors considered in the calculation. N₂O emissions were estimated according to the Intergovernmental Panel on Climate Change (IPCC) guideline [37].

Table 3. GHG emission factors regarding mineral N fertilizer production and application.

	GHG Emission Factors (kg CO ₂ e kg ⁻¹ N)	Source
Direct emissions (EF_D)	4.68	
Indirect emissions:		[37]
Volatilization (EF_V)	0.47	
Leaching/Runoff (EF_L)	1.05	
Fertilizer production (EF_P)	3.70	[8]
Sum (EF_{Total})	9.91	

Direct N₂O emissions considered in this study included N₂O emissions occurring due to N mineralization directly from soil where N fertilizer was applied to. Indirect emissions considered consist of N₂O emissions via volatilization, leaching and runoff of N added. N₂O emissions were converted into CO₂e according to the global warming potential (GWP) as reported in [38]. The 100-year GWP (298) was applied for the conversion. For the GHG emissions regarding the production of N fertilizer (CAN), the average of European production technology was taken according to Bentrup & Palliere [8]. The total emission factor (EF_{Total}) including production and application of mineral N fertilizer added up to 9.91 kg CO₂e kg⁻¹ N. GHG emissions ($GHG_{i,c}$) of mineral N fertilization in each yield-zone (i) were calculated according to Equation (16).

$$GHG_{i,c} = (EF_D + EF_V + EF_L + EF_P) N_{i,c} \quad (16)$$

Total GHG emissions ($GHG_{i,c}$; kg CO₂e ha⁻¹) of mineral N fertilization ($N_{i,c}$) were calculated for each yield-zone (i) and crop (c) using emission factors EF_D (emission factor for direct N₂O emissions; kg CO₂e kg⁻¹ N), EF_V (emission factor for volatilization of N₂O; kg CO₂e kg⁻¹ N), EF_L (emission

factor of leaching and runoff; $\text{kg CO}_2\text{e kg}^{-1} \text{ N}$) and EF_P (emission factor for CAN production; $\text{kg CO}_2\text{e kg}^{-1} \text{ N}$).

2.5. Net Return over N Fertilizer and Yield-Zone-Specific GHG Mitigation Cost Functions

In our calculation for net return, we performed a partial budgeting. N fertilizer was the only production factor that was adjusted affecting yield. Net return over N fertilizer applied (€ ha^{-1}) was calculated as the difference between revenue of crop sales and cost of N fertilizer applied (Equation (17)). Table 4 presents the prices of N fertilizers and crops considered in this study.

$$NR_{i,c} = P_Y Y_{i,c} - P_N N_{i,c} \quad (17)$$

where $NR_{i,c}$ —Net return, P_Y —Price of crop (€ Mg^{-1}), $Y_{i,c}$ —Yield (Mg ha^{-1}), P_N —Price of N fertilizer ($\text{€ kg}^{-1} \text{ N}$), $N_{i,c}$ —N fertilizer rate (kg N ha^{-1}), i —Yield-zone and c —Crop.

Table 4. Mineral N fertilizer price (P_N) and crop prices for wheat (P_W) and rye (P_R) according to Hanff & Lau [28].

P_N ($\text{€ kg}^{-1} \text{ N}$)	0.96
P_W (€ Mg^{-1})	161
P_R (€ Mg^{-1})	123

Crop and yield-zone-specific GHG mitigation cost functions were estimated by coupling change in net return and change in GHG emissions when N fertilizer application was reduced (Equation (18)).

$$GHG_cost_{i,c} = \frac{NR_{i,c_R} - NR_{i,c_A}}{GHG_{i,c_R} - GHG_{i,c_A}} \quad (18)$$

where $GHG_cost_{i,c}$ —Crop (c) and yield-zone-specific (i) cost of GHG mitigation, NR_{i,c_R} —Crop and yield-zone-specific net return in reference scenario (status quo), NR_{i,c_A} —Crop and yield-zone-specific net return in alternative scenario (N fertilizer reduction), GHG_{i,c_R} —Crop and yield-zone-specific greenhouse gas emissions in reference scenario (status quo) and GHG_{i,c_A} —Crop and yield-zone-specific GHG emissions in alternative scenario (N reduction).

2.6. Uncertainty Analysis

In order to identify the most influential parameters on and the range of GHG mitigation costs, we carried out an uncertainty analysis on cost estimation of GHG mitigation by N fertilizer reduction. We considered uncertainties of the prices of N fertilizer and crops, the emission factors related to the N transformation processes and the standard deviation of crop yields at the economic optimum. The standard deviations of crop and yield-zone-specific yields were estimated based on the assumption that the coefficient of variance for a given crop would be the same in yield-zones as well as in Dahlem and Thyrow for wheat and rye respectively. The coefficients of variance were calculated in Dahlem (wheat) and Thyrow (rye) based on the empirical data and used to estimate the standard deviation of yields in the five yield-zones in Brandenburg. A normal distribution with the respective standard deviation was modelled for each crop and yield-zone. Apart from the standard deviation of yields, all parameters were modelled in a Monte Carlo simulation with a log-triangular distribution (Table 5), 5000 iterations were run using @Risk (Palisade Corporation Software, Ithaca, NY, USA). A multivariate regression analysis was conducted to identify the influence of uncertainty of input parameters on GHG mitigation costs. The expected value (mean) and the standard deviation of GHG mitigation costs in each yield-zone were estimated based on the simulation results.

Table 5. Parameters for the uncertainty analysis; EF_1 : Direct N_2O -N emission factor as a function of EF_D ; EF_4 : Indirect N_2O -N emission factor and $FRAC_G$: Volatilization for mineral fertilizer from N volatilization as a function of EF_V ; EF_5 : Indirect N_2O -N emission factor from leaching and runoff and $FRAC_L$: Nitrogen losses by leaching and runoff as a function of EF_L ; EF_P : Emission factor of mineral N fertilizer production; Crop prices (€ Mg^{-1}) for wheat (P_W) and rye (P_R), P_N : Mineral N fertilizer price (€ kg^{-1} N), Y : Yield ($Mg\ ha^{-1}$).

Variable	Parameters			Source
	Default	Min	Max	
EF_1	0.01	0.003	0.03	[37]
EF_4	0.01	0.002	0.05	[37]
EF_5	0.0075	0.0005	0.025	[37]
$FracL$	0.3	0.1	0.8	[37]
$FracG$	0.1	0.03	0.3	[37]
EF_P	3.70	3.02	9.56	[37]
P_W	161	100	238	[28]
P_R	123	76	210	[28]
P_N	0.96	0.81	1.07	[28]
Y	See the text above (2.6)			

2.7. System Expansion

A system expansion was applied for N fertilizer reduction to include GHG emissions ($EF_{Y,c}$) that were assumed to be generated at a different site to offset yield penalties due to N fertilizer reduction in the considered yield-zones in Brandenburg (Equation (19)). The European Union average of GHG emissions per kg product for retail sale of wheat (409 kg $CO_2e\ Mg^{-1}$ product) and rye (299 kg $CO_2e\ Mg^{-1}$ product) were taken from ProBas database [39].

$$GHG_{se_{i,c}} = (EF_D + EF_V + EF_L + EF_P)N_{i,c} + EF_{Y,c}Y_{-p_{i,c}} \quad (19)$$

In system expansion, total crop (c) and yield-zone-specific (i) GHG emissions ($GHG_{se_{i,c}}$; kg $CO_2e\ ha^{-1}$) included emissions to compensate yield penalties ($Y_{-p_{i,c}}$; kg product ha^{-1}) coupled with the emission factor per kg product ($EF_{Y,c}$), in addition to GHG emissions ($GHG_{i,c}$) highlighted in Section 2.4.

2.8. Case Study

In order to simulate a comparative investigation, we conducted a case study on optimization of regional costs due to N fertilizer reduction to mitigate GHG emissions. As regional GHG mitigation goal 33.5 Gg CO_2e was set, which is equivalent to 10 kg ha^{-1} on average for the given total wheat and rye production area in five yield-zones in Brandenburg. No land use change was allowed. The extension of land use of the respective crops is given in Table 6.

Table 6. Land use of two major cereals in Brandenburg [28].

	Yield-Zones in Brandenburg (ha)				
	1	2	3	4	5
Wheat	56,100	50,900	20,600	9470	3650
Rye	7960	36,700	49,900	57,300	45,500

We applied two strategies to reach the GHG mitigation target: Uniform reduction (the same reduction rate for both crops in all yield-zones) and smart reduction considering comparative advantages of crop- and yield-zone-specific GHG mitigation costs.

Uniform reduction implies equal amount of mineral N reduction per hectare to reach an overall reduction target. In other words, the overall reduction target was distributed to every hectare evenly independent of site qualities, crop selection and input and output prices (Equation (20)).

$$N_{red_uni} = \frac{GHG_{red_target}}{\sum_i^n \sum_c^m \frac{EF_{Total}}{L}} \quad (20)$$

N_{red_uni} —Uniform N fertilizer reduction (kg ha⁻¹), GHG_{red_target} —GHG mitigation target of the region (kg CO₂e), EF_{Total} —Total emission factor (kg CO₂e kg⁻¹ N), L —Land use (ha) for every yield-zone (i) and crop (c).

Smart reduction was defined as cost-minimizing yield-zone-specific N fertilizer reduction that considered the individual yield response to N for each crop, yield-zone, cultivated areas and input and output prices. The total reduction was achieved by considering the yield response to reduced N fertilization for wheat and rye in every yield-zone. The loss in total net return of the region was minimized as the objective function of a nonlinear optimization; while GHG mitigation induced reduction for N supply was held as constraint reflecting the mitigation goal (Equation (21)). Additionally, land use of wheat and rye in respective yield-zones were held constant.

$$\text{Objective : MINIMIZE } \sum_i^n \sum_c^m L_{i,c} \Delta(P_Y Y_{i,c} - P_N N_{i,c}) \quad (21)$$

$$\text{subject to : } L_{i,c_A} = L_{i,c_R} \text{ and } \sum_i^n \sum_c^m \Delta N_{i,c} = \frac{GHG_{red_target}}{EF_{Total}}$$

$L_{i,c}$ —Land use of crop (c) in respective yield-zone (i), P_Y —Price of crop (€ Mg⁻¹), Y —Yield (Mg ha⁻¹), N —N fertilizer rate (kg N ha⁻¹), P_N —Price of N fertilizer (€ kg⁻¹ N), L_{i,c_A} —Land use of crop in respective yield-zone in the alternative scenario (N fertilizer reduction), L_{i,c_R} —Land use of crop in respective yield-zone in the reference scenario.

3. Results and Discussion

3.1. Model Results

According to the regression analysis, Table 7 presents the coefficients of yield response functions based on the long-term field experiments in Dahlem for wheat and Thyrow for rye.

Table 7. Coefficients of estimated quadratic polynomial functions of yield (Mg ha⁻¹) response to N fertilizer (kg ha⁻¹) for wheat (Dahlem) based on [33] and rye (Thyrow) based on [34]; a : Quadratic coefficient, b : Linear coefficient, c : Constant.

	Dahlem (Wheat) (R ² = 0.66)	Thyrow (Rye) (R ² = 0.79)
a	−0.000139	−0.000254
b	0.0386	0.0562
c	3.30	2.11

The coefficients of the modelled yield functions for five yield-zones in Brandenburg are presented in Table 8. The normalization approach enabled to depict differentiated yield response functions of the yield-zones in Brandenburg reflecting differentiated yield potentials.

According to our model calculations, wheat and rye yield responses to N supply followed a similar pattern. Rye yields were consistently lower than wheat yields within the same yield-zone. Yield response to N in low yield-zones was stronger compared to high yield-zones for both wheat and rye (Figure 2). Accordingly, yield penalties due to N fertilizer reduction were higher in low yield-zones, for instance, 20 kg ha⁻¹ N fertilizer reduction from the respective economic optimum caused the yield

penalty for wheat 154 and 234 kg ha⁻¹ in the highest (W1) and the lowest yield-zone (W5) respectively. Higher yield penalties occurred due to stronger yield responses to N fertilizer reduction towards the low yield-zones. Furthermore, rye yield responded stronger to N fertilizer reduction compared to wheat. Yield penalties for rye were higher than for wheat at every N reduction level within the same yield-zone. For instance, 20 kg ha⁻¹ N fertilizer reduction resulted in yield penalties ranging from 219 to 342 kg ha⁻¹ in the highest (R1) and lowest (R5) yield-zone respectively.

Table 8. Coefficients of modelled yield-zone-specific quadratic polynomial functions of yield (Mg ha⁻¹) response to N fertilizer (kg ha⁻¹) for wheat and rye; *a*: Quadratic coefficient, *b*: Linear coefficient, *c*: Constant.

Yield-Zones in Brandenburg (Wheat)					
	1	2	3	4	5
<i>a</i>	−0.000087	−0.000102	−0.000132	−0.000175	−0.000287
<i>b</i>	0.0354	0.0353	0.0352	0.0353	0.0352
<i>c</i>	4.19	3.53	2.71	2.07	1.25
Yield-Zones in Brandenburg (Rye)					
	1	2	3	4	5
<i>a</i>	−0.000157	−0.000174	−0.000219	−0.000294	−0.000465
<i>b</i>	0.0534	0.0532	0.0533	0.0536	0.0534
<i>c</i>	2.96	2.64	2.12	1.60	1.00

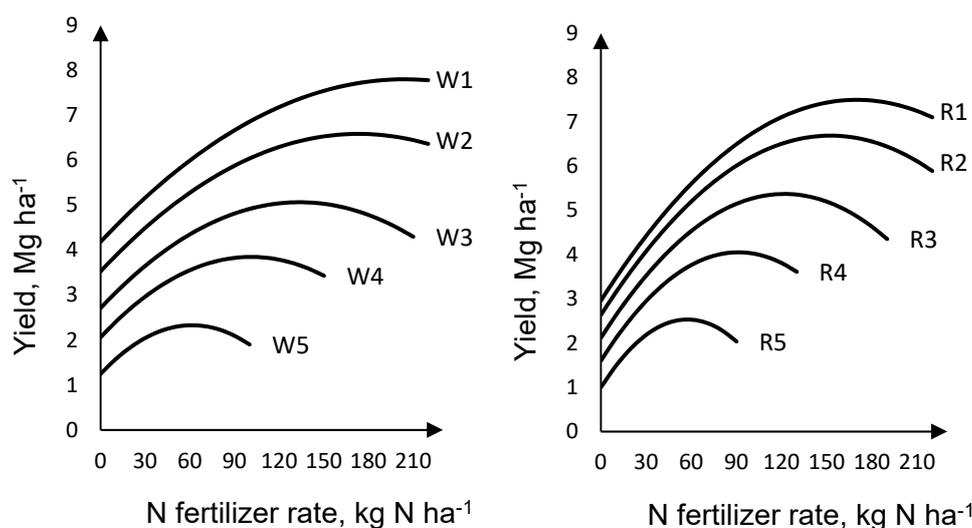


Figure 2. Yield response functions with respect to nitrogen (N) fertilizer; W: wheat; R: rye; 1–5 yield-zones.

N fertilizer reduction led to net return loss, since cost savings due to less N fertilizer use did not compensate for the costs of yield penalties. Change in net return was bound to respective yield penalty and crop price. Even though rye yield was strongly affected by N fertilizer reduction, the total loss in net return for the same level of N fertilizer reduction was slightly lower for wheat than for rye due to the higher crop price for wheat (Figure 3). The reduction of 20 kg ha⁻¹ N fertilizer from the respective economic optimum affected the net return between 6 and 18 € ha⁻¹ for wheat and between 8 and 23 € ha⁻¹ for rye.

Differences in yield response to N strongly affected GHG mitigation costs. Parallel to loss in net return, costs of GHG mitigation were slightly lower for wheat compared to rye (Figure 4) within the same yield-zone.

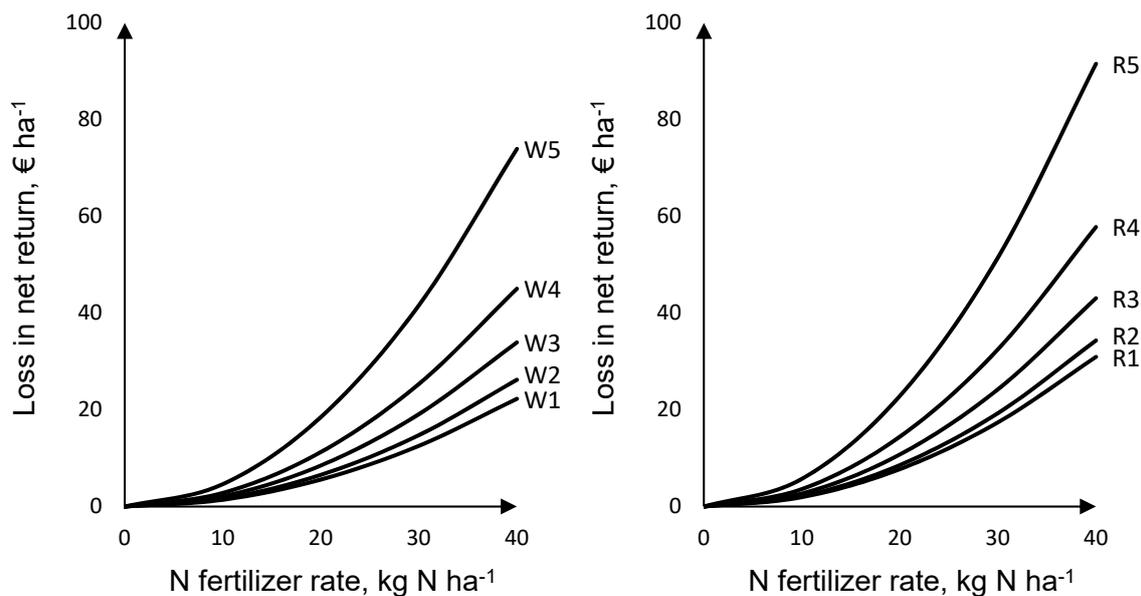


Figure 3. Economic response to reduced N fertilizer application; W: wheat; R: rye; 1–5 yield-zones.

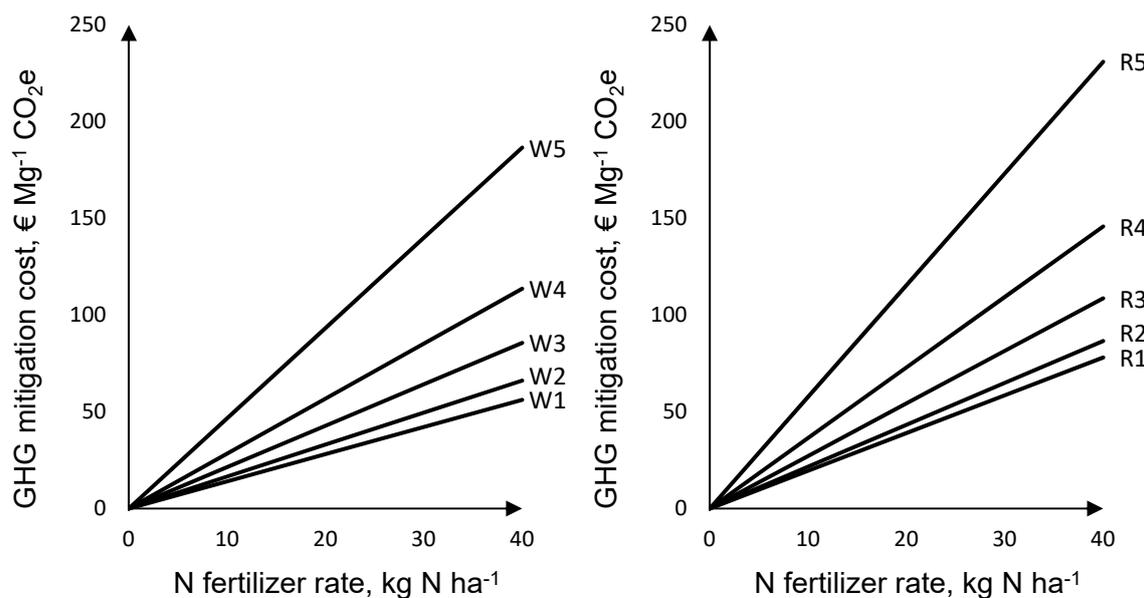


Figure 4. Costs of greenhouse gas (GHG) mitigation by nitrogen fertilizer reduction; W: wheat; R: rye; 1–5 yield-zones.

The marginal costs of GHG mitigation at N fertilizer reduction rate of 20 kg N ha⁻¹ increased from 28 € Mg⁻¹ CO₂e in the highest yield-zone to 93 € Mg⁻¹ CO₂e in the lowest yield-zone for wheat and from 39 € Mg⁻¹ CO₂e to 115 € Mg⁻¹ CO₂e for rye (Table 9). The expected value (mean) of GHG mitigation costs based on the Monte-Carlo simulation increased gradually from high yield-zones to low yield-zones, while the mean was found considerably higher for rye than for wheat compared to respective default values. This can be explained by rather less favorable site conditions for rye production which was incorporated by means of yield functions in our model where rye yield responds stronger to reduced N input. Besides, rye yield has higher standard deviation than wheat. The standard deviation of GHG mitigation costs increase from high yield-zones to low yield-zones and it is relatively lower for wheat than rye. The results suggest lower uncertainty for GHG mitigation costs by N fertilizer reduction for wheat in high yield-zones.

Table 9. Costs of GHG mitigation ($\text{€ Mg}^{-1} \text{CO}_2\text{e}$) at 20 kg ha^{-1} N fertilizer reduction; Default: Costs estimated through the defaults values given under Section 2; Expected value (mean) and standard deviation (SD) of simulations: Values acquired from the Monte-Carlo simulations with 5000 iterations.

	Yield-Zones in Brandenburg									
	Wheat					Rye				
	1	2	3	4	5	1	2	3	4	5
$\text{€ Mg}^{-1} \text{CO}_2\text{e}$										
Default	28	33	43	57	93	39	43	54	73	115
Mean (simulations)	31	36	45	58	93	51	55	66	85	128
SD (simulations)	22	24	26	29	39	32	33	36	42	55

The crop-specific N fertilizer reduction showed differences in GHG mitigation costs, since crop yields reacted differently to N fertilizer reduction even within the same yield-zone. Besides, crop prices had a high influence on GHG mitigation costs. With higher N fertilizer reduction, GHG mitigation costs increased linearly (Figure 4).

Our findings indicate that the cost level of GHG mitigation by moderate N reduction could be considered in the lower bound compared to other GHG mitigation measures. Smith et al. [40] published a wide cost range of GHG mitigation measures ($1\text{--}2500 \text{ \$ Mg}^{-1} \text{CO}_2\text{e}$), while the range for nutrient management measures, such as improved timing and placement of N fertilizers and avoiding over-fertilization, was reported between 8 and $15 \text{ \$ Mg}^{-1} \text{CO}_2\text{e}$ depending on the climate zone. Scholz et al. [41] identified mitigation costs of GHG emissions by biogas production in the state of Brandenburg (Germany) between $288 \text{ € Mg}^{-1} \text{CO}_2\text{e}$ and $1135 \text{ € Mg}^{-1} \text{CO}_2\text{e}$. Teichmann [42] made an ex-ante simulation on the effects of biochar to mitigate GHG emissions. The author reported a wide range of GHG mitigation costs, from $68 \text{ € Mg}^{-1} \text{CO}_2\text{e}$ to over $4000 \text{ € Mg}^{-1} \text{CO}_2\text{e}$, depending on the feedstock used for biochar production. Similarly, GHG mitigation measures in meat and dairy production systems reflect a wide range (1:3 quartile) from $58 \text{ \$ Mg}^{-1} \text{CO}_2\text{e}$ to $856 \text{ \$ Mg}^{-1} \text{CO}_2\text{e}$ [43]. There are also studies showing much lower GHG mitigation costs or even negative costs (cost savings) due to, for instance, improved nutrient management [44,45]. Nevertheless, if such measures do not result in any cost, a wide adoption would be expectable which has not been largely observed [45]. A possible reason for this paradox is that GHG mitigation measures estimated in studies can be more costly in practice due to omitted transaction or learning costs [45]. Furthermore, uncertainties on costs and benefits of precision farming technologies could play a role [20].

One possible reason for the relatively low opportunity costs for GHG mitigation by moderate N fertilizer reduction can be explained by the flat profit functions, as reported in Pannell [21]. Marginal adjustments in N intensity around the economic optimum do not result in high costs, since marginal benefit diminishes towards the economic optimum rate and does not drop steeply immediately, so that the returns do not severely vary in both directions (intensifying or reducing) around that rate. It is noteworthy to mention that we assumed that grain quality of wheat was not affected by moderate N fertilizer reduction. Wheat price of feed quality is around 10 € Mg^{-1} lower than baking quality [28]. Loss in grain quality would increase the GHG mitigation costs due to reduced N fertilizer application.

The results of the multivariate regression analysis indicated that the variance of crop prices was the most influential factor followed by the N fertilizer price variance in determining the overall variance of the cost estimation of GHG mitigation (Table 10). The uncertainties of the variables for direct N_2O emissions (EF_1) and for mineral N production (EF_P) had a higher impact on the overall uncertainty than other variables related to N transformation processes. The impact of standard deviation of crop yield on the overall variance within the assumed ranges was close to zero, even though they showed an impact on the change in output mean. This can be explained by the fact that GHG mitigation costs were calculated for each Monte Carlo simulation comparing the mitigation scenario (reduced N fertilizer) with the reference scenario respectively for the same yield-zone and crop, a marginal N fertilizer reduction at slightly higher or lower yield level resulted in—on average—very low impact. The uncertainty analysis in this study was conducted to provide a figure of the range of the GHG

mitigation costs, as well as an overall notion of the importance of the considered input parameters and, therefore, has limitations for a more detailed analysis of the distribution of the outcome.

Table 10. Regression coefficients of uncertainty variables from stepwise multivariate regression analysis for GHG mitigation costs by 10 kg ha⁻¹ reduction of N fertilizer for wheat and rye in five yield-zones; Prices of crops (€ Mg⁻¹), P_N: Mineral N fertilizer price (€ kg⁻¹), EF₁: Direct N₂O-N emission factor, EF_p: Emission factor of mineral nitrogen fertilizer production, EF₅: Indirect N₂O-N emission factor from leaching and runoff, FRAC_L: Nitrogen losses by leaching and runoff, EF₄: Indirect N₂O-N emission factor from N volatilization, Y: Yield (Mg ha⁻¹), FRAC_G: Volatilization for mineral N fertilizer.

Variable	Yield-Zones in Brandenburg									
	Wheat					Rye				
	1	2	3	4	5	1	2	3	4	5
Prices of crops	-0.91	-0.91	-0.90	-0.89	-0.85	-0.91	-0.91	-0.90	-0.88	-0.85
N fertilizer price	0.25	0.25	0.23	0.22	0.18	0.19	0.18	0.17	0.16	0.13
EF ₁	0.17	0.19	0.23	0.27	0.35	0.23	0.24	0.26	0.30	0.36
EF _p	0.10	0.11	0.13	0.15	0.20	0.13	0.14	0.15	0.17	0.21
EF ₅	0.05	0.06	0.07	0.08	0.10	0.07	0.07	0.08	0.09	0.10
EF ₄	0.04	0.04	0.05	0.06	0.07	0.05	0.05	0.05	0.06	0.07
FRAC _L	0.03	0.04	0.04	0.05	0.06	0.04	0.04	0.05	0.05	0.06
FRAC _G	0.03	0.03	0.04	0.04	0.05	0.04	0.04	0.04	0.05	0.05
Y	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00

In the analysis of system expansion, the inclusion of additional GHG emissions due to compensation of yield penalties affected the cost-efficiency of GHG mitigation for both crops in all yield-zones negatively. Nevertheless, the comparative advantage of N fertilizer reduction in high yield-zones was relatively improved when compared with low yield-zones (Figure 5). Note that the system expansion did not include GHG emissions due to a possible land use change. It can be expected that additional GHG emissions due to a possible land use change would affect the cost-efficiency of GHG mitigation in the same direction as described above.

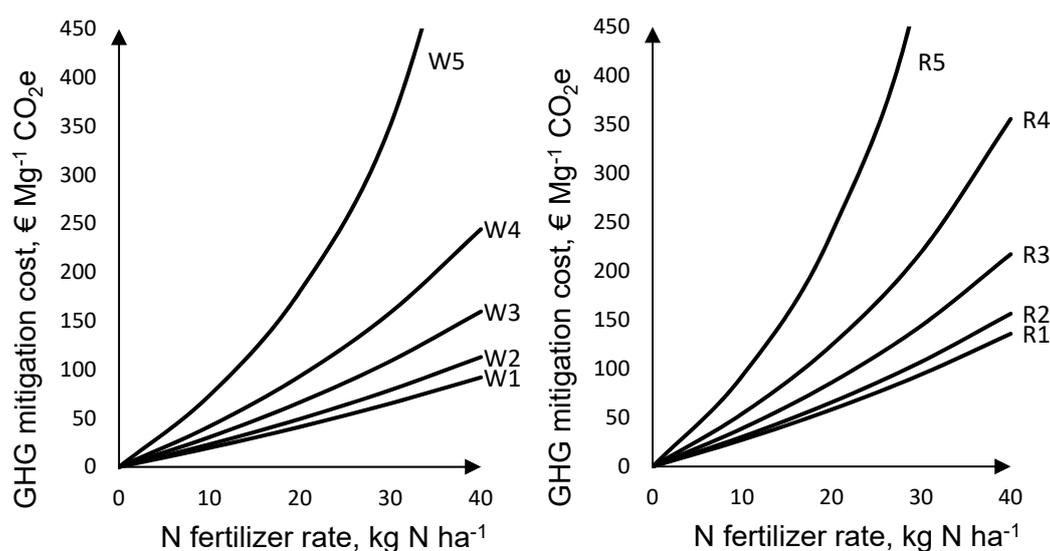


Figure 5. Costs of GHG mitigation in the system expansion; W: wheat; R: rye; 1–5 yield-zones.

3.2. Case Study

In the case study, it was observed that if crop and yield-zone-specific marginal costs of GHG mitigation by N fertilizer reduction were taken into account, regional economic loss could be minimized.

The results of the scenario analysis indicated that smart N fertilizer reduction offered a potential to improve the cost-efficiency of GHG mitigation even further. This alternative N fertilizer reduction strategy resulted in 19% cost savings for GHG mitigation and induced overall economic loss of the region compared to the uniform reduction (Table 11). With the smart N fertilizer reduction strategy, the marginal cost of GHG mitigation was reduced by approximately 5 € Mg⁻¹ CO₂e, (from 27 € Mg⁻¹ CO₂e to 22 € Mg⁻¹ CO₂e) for the given land use patterns and the mitigation target.

Table 11. Scenario analysis for optimized regional N fertilizer reduction (W: wheat; R: rye; 1–5 yield-zones; NR: Net return; Uni: Uniform).

	Land Use (ha)	N Reduction (kg ha ⁻¹)		Total N Reduction (kg)		Loss in NR (€ ha ⁻¹)		Total Regional Loss in NR (€)	
		Uni	Smart	Uni	Smart	Uni	Smart	Uni	Smart
W1	56,100	10	16	561,000	915,370	1.39	3.71	78,129	208,008
W2	50,900	10	14	509,000	705,921	1.64	3.15	83,399	160,413
W3	20,600	10	11	206,000	220,684	2.12	2.43	43,697	50,148
W4	9470	10	8	94,700	76,445	2.82	1.83	26,658	17,371
W5	3650	10	5	36,500	17,945	4.62	1.12	16,871	4078
R1	7960	10	12	79,600	93,529	1.93	2.67	15,394	21,253
R2	36,700	10	11	367,000	388,632	2.15	2.41	78,755	88,312
R3	49,900	10	8	499,000	421,135	2.69	1.92	134,358	95,698
R4	57,300	10	6	573,000	360,424	3.61	1.43	207,004	81,902
R5	45,500	10	4	455,000	180,715	5.72	0.90	260,323	41,065
Sum	338,080			3,380,800	3,380,800			944,587	768,249

4. Conclusions

The results indicate the feasibility of our model's approach, which can be applied to various aspects of N fertilizer and GHG mitigation. The approach provides a modelling tool to simulate the yield and economic responses of stepwise reduction of mineral N fertilizer and assess their implications for yield-zone-specific GHG mitigation potential and costs. Our application of the model to Brandenburg implies that moderate reduction of mineral N fertilizer can mitigate GHG emissions at reasonable opportunity costs as they are in the lower-bound of wide-ranged mitigation costs across the agriculture related measures. High yield-zones show advantages over low yield-zones in terms of cost-efficient GHG mitigation. Therefore, N fertilizer reduction should be applied rather to high yield-zones as long as marginal mitigation costs do not exceed the one in the subsequent lower yield-zone. N reduction in wheat production offers GHG mitigation at lower costs with lower uncertainty compared to N fertilizer reduction in rye production. Our study assumes no change in grain quality due to moderate N fertilizer reduction. If N fertilizer reduction results in grain quality loss, GHG mitigation costs would increase due to higher income loss.

N fertilizer reduction in a given region can be optimized considering crop and yield-zone-specific yield responses (smart reduction) and, thus, the total cost-efficiency to mitigate regional GHG emissions can be improved. A total GHG mitigation target of 35.5 Gg CO₂e was achievable with the smart N fertilizer reduction strategy with 19% cost savings—compared to uniform reduction—in wheat and rye production in Brandenburg. Our model can be used in further studies for policy analysis comparing different GHG mitigation strategies aiming N fertilizer reduction, e.g. incentives, N fertilizer tax, or N application cap, targeting policies to different sites with different yield potentials.

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