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Greenhouse Gas Mitigation Costs of Reduced Nitrogen Fertilizer

Andreas Meyer-Aurich [1,*] and Yusuf Nadi Karatay [2]

[1] Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany
[2] Embrapa Digital Agriculture, Campinas 13083-886, SP, Brazil
* Correspondence: ameyer@atb-potsdam.de

Abstract: The reduction of nitrogen (N) fertilizer use is a possible greenhouse gas (GHG) mitigation option, whereas cost estimation highly depends on assumptions of the yield response function. This paper analyzes the potential and range of GHG mitigation costs with reduced N fertilizer application based on empirical yield response data for winter rye (*Secale cereale* L.) and rapeseed (*Brassica napus* L.) from field experiments from 2013 to 2020 in Brandenburg, Germany. The field experiments included four to five N rates as mineral fertilizer treatments. Three different functional forms (linear-plateau, quadratic, and quadratic-plateau) were estimated to model yield response as a function of N supply. Economic calculations were based on relevant price–cost ratios. The results indicate that the opportunity costs of applying less fertilizer and the resulting GHG mitigation thereof vary in a great range across the years and crops estimated by different yield response functions. The linear-plateau function predominantly results in lower GHG mitigation costs than the quadratic and the quadratic-plateau function. On average, over eight years, a moderate reduction of N fertilizer (up to 20 kg/ha) offers a cost-efficient option for mitigating GHG emissions below EUR 50 per ton of CO_2eq, even resulting in net profit gain in some cases.

Keywords: GHG mitigation costs; opportunity costs; yield response function; nitrogen fertilizer; winter rye; rapeseed; canola

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1. Introduction

Nitrogen (N) plays a crucial role for all living organisms, since it is an essential element of all amino acids and nucleic acids. Besides water, the availability of N controls plant growth and determines the structure and function of most ecosystems [1]. In contrast to other plant nutrients, N cannot be made available for plants from solid rocks after weathering, but needs to be added to the mineral soil system with rainwater, dry deposition, organic material or chemical fertilizer, containing plant-available N. Plants take up N as nitrate or ammonium from the soil. Since nitrate and ammonium are highly volatile, various pathways for N losses to the environment are causing significant damage to humans, climate and ecosystems, and lead to the limited efficiency of N fertilizer use [2,3].

While until now more than half of the world's population depends on crops fertilized with synthetic N fertilizer, the social costs of N use, especially via environmental damage steadily increase [3–5]. The growing world population, planetary boundaries and climate change urge all actors to find solutions for the sustainable use of N fertilizer in agriculture [6]. Among other actions, increased fertilizer-use efficiency is a crucial necessity to respond to these challenges, which can provide economic and environmental benefits [6–9]. This may involve technological approaches [10] or simply a reduction of the amount of N fertilizer applied [11]. However, the positive effects of reduced fertilizer use have to be traded off against the possible negative impacts of increased fertilizer use at other locations to compensate yield loss incurred by reduced fertilizer use [12]. Adequate modeling of the world-wide effects needs to take into account trade, and the comparative advantages and disadvantages of agricultural production at different places in the world. While global land-use models can model world-wide food production according to a specific demand [13], it is not yet possible to adequately take into account the site-specific yield response to N, nor the response of N to the locally specific environmental damage [14].

A reduction in N fertilizer use often results in higher N use efficiency and lower GHG emissions [15,16]. GHG mitigation costs emerge in the case of yield penalties. The mitigation costs of reduced fertilizer use are a function of reduced emissions due to reduced fertilizer use and opportunity costs of altered fertilizer use. The GHG mitigation effect can be estimated according to internationally agreed emission coefficients of fertilizer use and manufacturing. The opportunity costs of reduced fertilizer levels can be estimated from yield response functions [11]. However, calculations based on the economic optimum as a reference might over- or underestimate the opportunity costs since, at the time of fertilizer application, farmers have limited information about the most probable yield response to the fertilizer [17]. In addition, it has been shown that even in the presence of yield response data to given fertilizer rates, it is difficult to estimate robust economically optimal fertilizer levels due to intrinsic uncertainties about the production functions. Henke et al. [17], for example, have shown that for various cereal crops in Northern Germany, different production functions (quadratic, quadratic-plateau and linear-plateau) can be applied to model the yield response of N fertilizer. Based on their data, it was not possible to identify the most suitable response functions for all situations, while the calculated economic optimum input rates and the marginal responses at the economic optima varied substantially. Similar results have been published by others [18,19].

Due to the different shape of production functions, the marginal opportunity costs differ significantly. Consequently, by selection of the shape of the response function, the marginal opportunity costs for quadratic and quadratic-plateau functions are zero at the economically optimal fertilizer rate [20]. This is because the condition for profit maximum is that the marginal return equals the marginal cost. In contrast, the opportunity costs of fertilizer use are constant and non-zero according to the slope of the linear-plateau function for any N level lower than the profit maximizing N rate, which results in a plateau. While the economic optimum (profit maximum) for the linear-plateau function is either fixed at the kink of the function or at zero, when the slope of the function is lower than the marginal economic return of the fertilizer input, the economic optimum for the quadratic function is subject to crop and fertilizer price and typically varies according to the cost–price ratio.

Often, the economically optimal N rate determined with a linear plateau function is lower than the economic optimum calculated with quadratic and quadratic-plateau functions. For example, based on the data from Henke et al. for three crops over seven years, the economic optima with a quadratic production function were on average 45 kg/ha higher N rate (range: 11–97 kg/ha) than the economic optima with the linear plateau function [17]. While the implications of the choice of the production function on optimal N rates is obvious, to our knowledge, no study has investigated the implications of the choice of a production function on GHG mitigation potential and costs.

The aim of this paper was to analyze the GHG mitigation costs of reduced mineral N fertilizer use with respect to three commonly used production functions (linear-plateau, quadratic, and quadratic-plateau), based on data from fertilizer response experiments in Brandenburg, Germany. Estimations following a range of assumptions provide cost-efficient opportunities for GHG mitigation measures based on adjusted fertilizer levels. Moreover, this study aimed to highlight the effects of changing input-output price ratio on the relative differences of different production functions. Thus, the present paper contributes to the scientific literature by showing the implications of the choice of functional forms modeling crop yield response to N fertilization on the cost-efficiency of fertilizer reduction for mitigating GHG emissions.

2. Materials and Methods

2.1. Data on Crop Yield Response to Nitrogen Fertilizer

Data for the analysis of yield response to mineral N fertilizer were taken from field experiments in the state of Brandenburg (Germany) from 2013 to 2020. In 2020, the experiment in rapeseed was disturbed by a frost event, thus data for rapeseed were not included for that year. The average annual precipitation was 536 mm [21]. Over the considered years of the experiment, four to five N rates were selected in the experimental design, reflecting recommended, increased and reduced N application ranging from 0 to 270 kg/ha (Tables 1 and 2). The recommended fertilizer rates were calculated every year by the Brandenburg State Agency taking into account the N requirements for expected crop yields and soil N before the first fertilizer application [21–27]. Winter rye and rapeseed were considered in this study, as they differ in their nutrient requirement and yield response to N fertilizer. Crop yields are shown in Tables 3 and 4.

Table 1. Fertilizer treatments with N rates (kg N/ha) in winter rye from 2013 to 2020 [21–27].

	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
	(kg N/ ha)							
Without N	0	0	0	0	0	0	0	0
Reduced rate (−50%)	-	-	-	-	-	43	35	45
Reduced rate (−30%) [1]	88	77	87	80	66	64	53	68
Recommended rate	125	110	125	115	95	85	70	90
Increased rate (+30%) [2]	163	143	163	150	124	106	88	113
Increased rate (+50%)	-	170	170	160	155	-	-	-

[1] 2018: −25%, [2] 2018: +25%.

Table 2. Fertilizer treatments with N rates (kg N/ha) in rapeseed from 2013 to 2019 [21–27].

	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
	(kg N/ha)						
Without N	0	0	0	0	0	0	0
Reduced rate (−50%)	-	-	-	-	-	83	60
Reduced rate (−30%) [1]	123	137	140	129	136	124	90
Recommended rate	175	195	200	185	195	165	120
Increased rate (+30%) [2]	225	254	260	241	254	206	150
Increased rate (+50%)	250	270	-	-	-	-	-

[1] 2018: −25%, [2] 2018: +25%.

Table 3. Crop yields (winter rye) from 2013 to 2020 [21–27].

	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
	(metric tons/ha)							
Without N	2.39	3.29	3.69	2.29	1.75	1.74	2.07	2.34
Reduced rate (−50%)	-	-	-	-	-	2.34	3.52	3.51
Reduced rate (−30%) [1]	6.64	5.72	4.46	4.5	3.04	2.34	3.58	3.58
Recommended rate	7.01	5.81	4.6	4.87	3.26	2.67	3.83	3.99
Increased rate (+30%) [2]	7.64	6.06	5.05	4.7	3.34	2.76	3.78	4.32
Increased rate (+50%)	-	5.93	5.35	4.67	3.35	-	-	-

[1] 2018: −25%, [2] 2018: +25%.

Table 4. Crop yields (rapeseed) from 2013 to 2019 [21–27].

	2013	2014	2015	2016	2017	2018	2019
	(metric tons/ha)						
Without N	3.35	3.12	2.99	2.68	2.02	1.26	2.97
Reduced rate (−50%)	-	-	-	-	-	2.08	3.43
Reduced rate (−30%) [1]	4.73	4.87	4.93	3.25	3.52	2.13	3.84
Recommended rate	4.97	4.96	5.11	3.45	3.8	2.29	3.65
Increased rate (+30%) [2]	5.37	4.97	5.4	3.39	3.5	2.39	3.83
Increased rate (+50%)	5.21	5.19	-	-	-	-	-

[1] 2018: −25%, [2] 2018: +25%.

2.2. Calculation of Crop Yield Response Functions

Coefficients for the crop yield response were calculated for three functional forms with the R-package "easynls" [28]. The quadratic form (1) presumes a smooth, continuously differentiable functional form, while the linear plateau function relies on the assumption of a linear response up to a certain point, from which no additional yield response to N fertilizer is assumed (plateau) (2). The quadratic plateau function assumes a quadratic response up to a plateau, from where on a linear response is expected.

$$y = a + b \times x + c \times x^2 \tag{1}$$

$$y = a + b \times (x - c) \times (x \leq c) \tag{2}$$

$$y = \left(a + bx + c \times Ix^2\right)\left(x \leq -0.5\frac{b}{c}\right) + \left(a + I\left(\frac{-b^2}{4c}\right)\right)\left(x\ -0.5\frac{b}{c}\right) \tag{3}$$

where y is crop yield in metric tons per ha, x is N fertilizer rate in kg per ha, a, b, c are the coefficients of the functions, the logical functions are "1" when the inequation is true, otherwise it is "0". Goodness of fit is provided with the adjusted R^2 for all models which includes a penalty for the potential overfit of the different models and therefore it can be considered a better measure of accuracy than the simple R^2. Homoscedasticity was visually examined from plotted graphs of all regressions (see Supplementary Materials). For the linear-plateau functions, initial values for the parameters were required for most of the estimations.

2.3. GHG Emissions and GHG Mitigation Costs

GHG emissions were accounted for mineral N fertilizer application as well as N fertilizer production, while other emissions were assumed to remain unchanged. N fertilizer application leads to N_2O emissions that stem from microbial conversion processes in soil, i.e., nitrification and denitrification, and occur directly where it is applied and indirectly in other environments beyond the agricultural field [29]. Widely used emission factors following the IPCC methodology at Tier 1 level were utilized for computing direct N_2O emissions from soil at 4.68 kg CO_2eq per kg N and indirect emissions at 1.52 kg CO_2eq per kg N occurring via volatilization, leaching and runoff of N applied [30]. Emissions from manufacturing N fertilizers include CO_2 emissions in ammonia synthesis and N_2O emissions in nitric acid production [31]. N fertilizer production is an energy intensive process and the emissions associated rely on assumptions on fertilizer product types and underlying technologies. As a major N fertilizer form in the study area, calcium ammonium nitrate with 27% N content was considered with production-related emissions at 3.70 kg CO_2eq kg^{-1} N for an average European fertilizer production technology [32]. Emissions accounted for in this study were converted into CO_2eq according to the 100-year global warming potential (GWP) following Forster et al. [33]. Land use change effects were not explicitly taken into account. However, GHG emissions for winter rye and rapeseed to be produced at other locations in the case of reduced crop yields were accounted for with 0.87 kg CO_2eq per kg winter rye [34] and 1.064 kg CO_2eq per kg rapeseed [35].

GHG mitigation costs were calculated based on the change in net return (opportunity costs) due to reduced N fertilizer application and compared against the respective change in accounted GHG emissions. The recommended fertilizer rate was considered as the reference fertilizer application. For comparison, economically optimal (profit maximizing) N rates were calculated analytically for the different functional forms. Mitigation costs are expressed as EUR per ton of CO_2eq. Fertilizer costs and crop prices were taken from available data from the Bavarian State Agency for Agriculture for the respective years [36]. For scenario analyses, the range of different cost–price relationships for the years 2013 to 2020 were considered in a Monte-Carlo simulation (@Risk, Palisade Corporation, Ithaca, NY, USA).

3. Results

3.1. Crop Yield Response

Crop yield response varied substantially from year to year, which was due to different weather conditions. The coefficients for the response functions suggested considerably different courses (Tables 5 and 6). The adjusted R^2 for all models ranged between 0.69 and 0.99, suggesting high accuracy of most of the models. All statistical outcomes of the regression analyses, including R^2, AIC, BIC, statistical significance of the coefficients, are provided in the Supplementary Material along with the R scripts to calculate the regressions. Mostly, the estimation of the linear-plateau models required initial values for the estimation, which in some cases resulted in more than one possible solution. In the case of more than one possible function, we selected the model which resulted in the best homoscedasticity. Mostly the adjusted R^2 values were similar across different models, giving few arguments favoring one or the other functional form. However, in 2018 (winter rye), 2018 and 2019 (rapeseed), the quadratic and quadratic-plateau function outperformed the linear-plateau function.

Table 5. Coefficients (equations see Equations (1)–(3)) for yield response functions (winter rye).

	2013	2014	2015 [1]	2016	2017	2018	2019	2020
Linear-plateau								
a	7.33	5.93	5.18	4.75	3.32	2.76	3.73	4.32
b	0.0483	0.0316	0.0089	0.0276	0.0195	0.0104	0.0414	0.0176
c	102	84	170	89	80	95	40	106
adj R^2	0.9652	0.9885	0.975	0.9885	0.9948	0.92092	0.9672	0.9402
Quadratic								
a	2.41	3.32	n.a.	2.29	1.76	1.75	2.10	2.38
b	0.063	0.041		0.041	0.025	0.013	0.048	0.025
c	-1.9×10^{-4}	-1.5×10^{-4}		-1.6×10^{-4}	-9.7×10^{-5}	-3.5×10^{-5}	-3.4×10^{-4}	-6.8×10^{-5}
adj R^2	0.9811	0.9797		0.9981	0.9948	0.96	0.96	0.9633
Quadratic-plateau								
a	2.41	3.12	n.a.	2.29	1.75	1.75	2.08	2.38
b	0.063	0.021		0.042	0.027	0.013	0.054	0.025
c	-1.9×10^{-4}	-5.9×10^{-5}		-1.8×10^{-4}	-1.1×10^{-4}	-3.5×10^{-5}	-4.4×10^{-4}	-6.8×10^{-5}
Ymax	163	177		116	119	190	62	180
adj. R^2	0.9811	0.9885		0.99	0.9885	0.9601	0.9601	0.9633

[1] Yield response did not diminish in the range of the tested N rates in 2015. Therefore, only a linear response was assumed up to the highest level of N.

Table 6. Coefficients for yield response functions (rapeseed).

	2013	2014	2015	2016	2017	2018	2019
Linear-plateau							
a	5.18	5.04	5.26	3.42	3.65	2.34	3.83
b	0.011	0.013	0.014	0.004	0.011	0.007	0.007
c	163	150	163	167	148	139	122
adj R^2	0.937	0.9765	0.965	0.986	0.931	0.8972	0.695
Quadratic							
a	3.34	3.14	3.00	2.68	2.01	1.28	2.97
b	0.01	0.02	0.02	0.01	0.02	0.011	0.012
c	-2.63×10^{-5}	-3.60×10^{-5}	-3.44×10^{-5}	-1.52×10^{-5}	-4.74×10^{-5}	-2.67×10^{-5}	-3.97×10^{-5}
adj R^2	0.978	0.964	0.980	0.962	0.982	0.970	0.812
Quadratic-plateau							
a	3.34	3.12	3.00	2.68	2.02	1.28	2.95
b	0.01	0.02	0.02	0.01	0.02	0.010	0.012
c	-2.63×10^{-5}	-5.04×10^{-5}	-3.44×10^{-5}	-1.52×10^{-5}	-4.54×10^{-5}	-2.73×10^{-5}	-4.17×10^{-5}
Ymax	250	195	250	224	189	198	141
adj R^2	0.977	0.977	0.982	0.96	0.931	0.96	0.812

3.2. Economically Optimal Rates Versus Recommended Rates

The analysis of the 8 years shows that on average the recommended N rate was mostly close to the economically optimal rate (profit maximizing rate) for the three different yield response functions (Tables 7 and 8). However, from year to year, the economically optimal fertilizer rate can be 20 kg higher or lower than the recommended rate. The data from all years suggested systematically higher profit maximizing N rates with the quadratic and the quadratic-plateau functions than with the linear-plateau functions. However, due to the limited number of years of observation, this could be biased by the weather conditions in the selected years. Overall, it can be seen that the plateau was reached at quite different levels of N supply, indicating different profit-maximizing N-levels for the different yield response models. For example, in rye, based on the data in 2014, the yield maximum was achieved at N = 84 kg/ha for the linear-plateau function, while the plateau was only reached at N = 106 kg/ha for the quadratic-plateau function (Table 7).

Table 7. Recommended versus profit maximizing N rates for winter rye (kg N/ ha).

	2013	2014	2015	2016	2017	2018	2019	2020	Average
	(kg N/ha)								
Recommended N rate	125	110	125	115	95	85	70	90	102
Profit maximizing N rate									
Linear-plateau	102	84	170	89	80	95	40	106	96
Quadratic	140	107	n.a.[1]	98	97	101	61	119	103
Quadratic-plateau	161	106	n.a.[1]	114	116	181	61	174	130

[1] No response function.

Table 8. Recommended versus profit maximizing N rates for rapeseed (kg N/ha).

	2013	2014	2015	2016	2017	2018	2019	Average
	(kg N/ha)							
Recommended N rate	175	195	200	185	195	165	120	176
Profit maximizing N rate								
Linear-plateau	163	150	163	167	148	139	122	150
Quadratic	180	180	208	117	162	146	100	156
Quadratic-plateau	180	157	197	117	159	145	104	151

3.3. Opportunity Costs of Reduced Fertilizer Use

The opportunity costs of reduced N fertilizer application stem from yield penalties due to crop yields below the economic optimum, which are partly compensated by reduced fertilizer costs. If recommended fertilizer rates were higher than profit maximizing fertilizer rates, opportunity costs of reduced N fertilizer application were negative (net positive contributions to profit).

On average, opportunity costs for fertilizer reductions were negative or negligible in the range up to 20 kg/ha for winter rye and rapeseed (Tables 9 and 10). The highest opportunity costs were calculated with the quadratic response functions. In general, the opportunity costs for rapeseed were slightly lower than for winter rye. The low opportunity costs can be partly explained by the observation of lower profit maximizing N-rates compared to the recommended N-rates for these response functions for many of the years. In individual years, opportunity costs were much higher according to the potential yield response in specific years. For example, for winter rye in 2013, 2018 and 2020, despite unfavorable growing conditions, profit maximizing N rates were higher than the recommended N rates, resulting in relatively high opportunity costs of reduced fertilization in these years (up to EUR 139/ha with a reduction of 50 kg N). On average, a reduction of 50 kg N in winter rye resulted in opportunity costs between EUR 46 and EUR 58 per ha for the different response functions considered. For rapeseed, opportunity costs did not exceed EUR 90/ha when N input was reduced up to 50 kg N/ha.

Table 9. Opportunity costs for reduced N fertilizer input (kg/ha) based on yield response data from eight years in winter rye.

	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**Average**
Linear-plateau N reduction				Opportunity cost (EUR/ha)					
−10 kg	−14	−13	−0	−13	−10	7	−12	15	−5
−20 kg	−28	−26	−1	−26	−4	15	−24	29	−8
−50 kg	139	51	−1	31	59	37	71	73	58
Quadratic N reduction				Opportunity cost (EUR/ha)					
−10 kg	12	1	n.a.	−6	2	3	−5	7	2
−20 kg	31	7	n.a.	−7	7	6	1	17	9
−50 kg	124	52	n.a.	18	42	25	82	58	57
Quadratic-plateau N reduction				Opportunity cost (EUR/ha)					
−10 kg	12	−11	n.a.	−10	0	3	−12	7	−2
−20 kg	31	−15	n.a.	−14	4	6	−14	17	2
−50 kg	124	15	n.a.	5	37	25	61	58	46

Table 10. Opportunity costs for reduced N fertilizer input (kg/ha) based on yield response data from eight years in rapeseed.

	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**Average**
Linear-plateau N reduction				Opportunity cost (EUR/ha)				
−10 kg	−14	−13	−14	−13	−10	−11	−12	−12
−20 kg	3	−26	−28	−22	−20	−22	−24	−20
−50 kg	90	−42	−16	−9	−34	11	6	1
Quadratic N reduction				Opportunity cost (EUR/ha)				
−10 kg	12	−2	5	−6	−10	−3	−5	−1
−20 kg	25	−2	15	−10	−16	−4	−7	0
−50 kg	72	12	67	−19	−14	6	8	19
Quadratic-plateau N reduction				Opportunity cost (EUR/ha)				
−10 kg	12	−11	1	−6	−10	−3	−4	−3
−20 kg	25	−19	7	−10	−17	−4	−4	−3
−50 kg	72	−22	51	−19	−18	5	15	12

Obviously, the opportunity costs depend very much on cost–price relationships. Figures 1 and 2 show the impact of different cost–price relationships on the average opportunity costs for a reduction of 10 kg, 20 kg and 50 kg N for winter rye and rapeseed, respectively. The mean value was generated from the three response functions over all the years of observation. The box plots indicate that on average the costs of N reduction of 20 kg N/ha do not result in opportunity costs at a probability of 95%. Higher reductions of N supply increase the costs, as well as the variance of the costs.

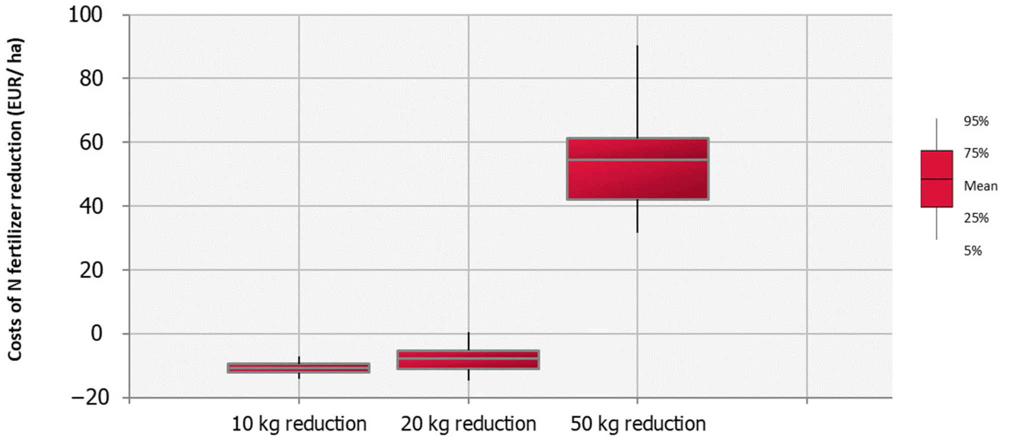

Figure 1. Simulation results of net costs of N supply reduction in winter rye production from 10,000 price–cost scenarios, all response functions.

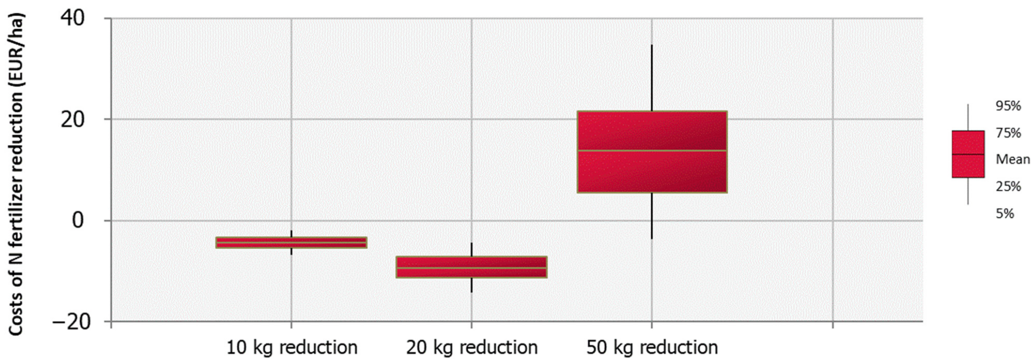

Figure 2. Simulation results of net costs of N supply reduction in rapeseed production from 10,000 price–cost scenarios, all response functions.

3.4. GHG Mitigation Costs of Reduced Fertilizer Use

The GHG mitigation costs were calculated according to the opportunity costs of reduced fertilizer application and reduced GHG emissions due to calculated changes in soil-induced emissions of N_2O and upstream emissions due to the production of N fertilizer. Furthermore, GHG emissions were taken into account in case of yield penalties for the production of the crops at other locations.

Figures 3 and 4 show the net GHG mitigation costs for a reduction of N supply for winter rye and rapeseed for the considered timespan. The cost curves differ considerably according to assumptions about the shape of the response function. For example based on different response functions, a 20 kg N reduction for winter rye resulted in GHG mitigation costs of EUR −67 to EUR 32/ton CO_2eq mitigation. For lower levels of N reduction, the selection of the linear-plateau function resulted in lower GHG mitigation costs than the quadratic and the quadratic-plateau function, whereas the mitigation costs converge toward higher fertilizer reduction. GHG mitigation with moderate N fertilizer reduction (<20 kg N/ha) from recommended rates resulted in costs below EUR 50 per ton of CO_2eq. For rapeseed, GHG mitigation costs were negative up to 40 to 50 kg N reduction indicating a win-win situation for farmers and GHG mitigation.

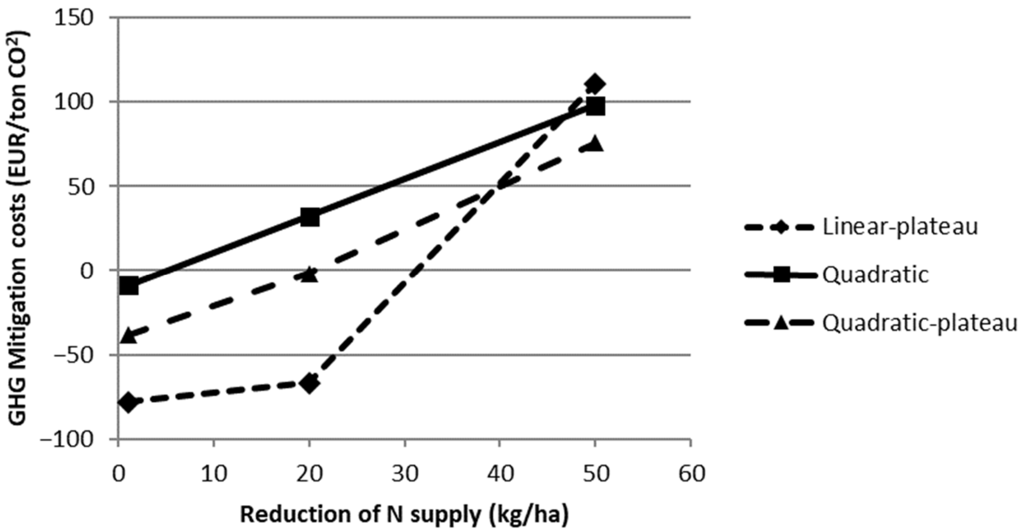

Figure 3. Average GHG mitigation costs for N fertilizer reduction on winter rye based on three different assumptions of the response function based on yield response data from eight years.

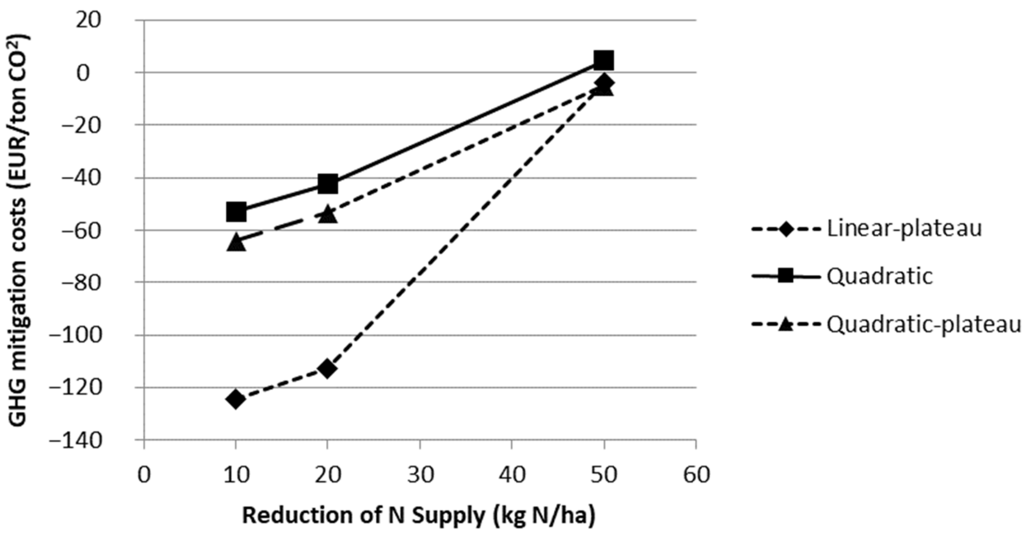

Figure 4. Average GHG mitigation costs for N fertilizer reduction on rapeseed based on three different assumptions of the response function.

4. Discussion

This study confirms that despite uncertainties in accounting for GHG mitigation costs, N fertilizer use can be an important lever for GHG mitigation at low costs [37,38]. High uncertainties in the costs are on one hand weather induced because of year-to-year variations of yield response, and on the other hand due to assumptions of the yield response function. The weather-induced uncertainties result in a very different yield response to N fertilizer from year to year, which can very well be seen from the slope (the parameter b) of the linear-plateau model. This parameter ranged from 9 to 48 kg rye per kg N fertilizer and 4 to 14 kg rapeseed per kg N fertilizer. The response was weaker compared to the yield response analyses of Henke et al., who found 9.5 to 18.6 kg rapeseed per kg N in Schleswig-Holstein [17]. Since the responsiveness of the crop is not known at the time of fertilizer application, the resulting opportunity costs for applying less fertilizer and the resulting GHG mitigation costs thereof vary in a great range. The opportunity costs for a reduction of 20 kg N per ha ranged from EUR −28 to EUR 29 per ha for winter rye and EUR −28 to EUR 3 per ha for rapeseed, based on the linear-plateau model. Apparently, for winter rye, higher opportunity costs for reduced fertilizer application are evident.

Similarly, Karatay and Meyer-Aurich found higher opportunity costs for N reduction in winter rye compared to winter wheat based on another empirical dataset [11]. Obviously, the reference fertilizer level has a strong influence on the opportunity costs. In this study, the best available knowledge from the state agency was used to determine the optimal fertilizer level. However, as the results suggest, even in the presence of the best available knowledge and the absence of profit seeking or risk mitigation strategies, the economically optimal fertilizer levels were often not met with the recommendations. The difference of recommended and economically determined N rate ranged from −40 kg to +45 kg N per ha for winter rye and −46 kg to +64 kg N per ha for winter rye. Thus, determining the economically optimal fertilizer rate at the time of fertilizer application is not a trivial task and obviously has a strong effect on the determination of opportunity costs, and thus the cost-efficiency of GHG mitigation. Thus, any efforts to increase the accuracy of yield response prediction can contribute to increase N efficiency and mitigate GHG emissions [1]. However, it is still not clear which are the right yield response functions, even from an ex post perspective [17,39]. Especially for economic considerations, the assumptions of the functional form determine the marginal response strongly at the economic optimum. While the economic response is by definition zero at the economically optimal fertilizer level for the quadratic and quadratic-plateau models, the marginal response is constant and positive for all levels of N up to the level resulting in the yield plateau. Though goodness of fit parameters and information on homoscedasticity of the errors can be taken into consideration for the choice of the functions, the limited number of observations limits the robustness of these indicators. Small variations in the data can have a great effect on the choice of the appropriate function and the associated opportunity and mitigation costs. Thus, as stated by others before (for example [17]), statistical analyses alone do not provide sufficient information for the selection of the best model.

This work investigated three potential functional forms. In addition, other functional forms, such as square root and Cobb–Douglas functions [40] could have complemented the calculations. However, the data from the experiments hardly provide sufficient information, to provide added value with more functional forms. Instead, our approach intends to show the range of possible outcomes based on a range of models. While the estimation of the quadratic and quadratic-plateau function provided reasonable results, the estimation of the linear-plateau functions was difficult to estimate in some cases and required a wise selection of initial values. Inappropriate initial values resulted sometimes in biased model results with significant heteroskedastic error structures. Thus the modelling of these models requires some experience in statistical analysis and cannot be easy implemented.

The relevance of uncertainties, ambiguity and potential risk attitudes of farmers further complicates the identification of optimal fertilizer levels from a utility perspective [41–43]. Anyhow, the flatness of the profit functions generally suggests that costs for reduced N fertilizer for arable crops, such as winter rye and rapeseed are low [44], supporting the potential of reduced fertilizer input as a GHG mitigation strategy. Farmers' perception might be different, as farmers might think that their potential loss is higher than potential savings [45,46]. Therefore, studies on the economics of fertilizer use are important to provide the arguments for cost-efficient application of fertilizer or even to convince farmers to apply less fertilizer.

5. Conclusions

GHG mitigation can be realized in crop production in rainfed winter rye and rapeseed with reduced mineral fertilizer application at costs below EUR 50/ton CO_2eq. This study has shown that GHG mitigation costs vary substantially from year to year according to the growing conditions in the respective years. Furthermore, assumptions about the yield response function highly determine the costs of fertilizer reduction. Precise ex ante estimation of yield response remains a challenge, as it heavily depends on the appropriate choice of the production function, the reference N rate, as well as price and weather-induced growing conditions. By the time of fertilization, these factors can barely be foreknown. Yet, farmers have to make continuous decisions on the level of fertilizer use every growing season. More knowledge about the response of their crops to fertilizer is a precondition to improved fertilizer use. Furthermore, knowledge about the opportunity costs of fertilizer use could provide arguments for farmers and policy makers to include reduced fertilizer in the portfolio of GHG mitigation measures. However, as it is not possible to estimate yield response in each year in advance, generalized assumptions consequently lead to under- or overestimation of GHG mitigation potential, and thus affect the cost-efficiency of mitigation for the respective year. This uncertainty may make implementation of relevant agri-environmental policies renumerating GHG mitigation by N fertilizer reduction even more difficult. Anyhow, despite uncertainties, this study has shown that policies for reduced fertilizer use can contribute to GHG mitigation at relatively low costs.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture12091438/s1, R-scripts for all models, data file with all model results.

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