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Optimizing Nitrogen Use Efficiency and Yield in Winter Barley: A Three-Year Study of Fertilization Systems in Southern Germany

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Abstract: Various fertilization systems have been developed to optimize nitrogen (N) application, yet their effectiveness remains a topic of debate in both science and practice. This study evaluates the effects of 28 N fertilization treatments on yield, quality, nitrogen use efficiency (NUE), N surplus, and economic optima in two winter barley (*Hordeum vulgare* L.) varieties—a multi-row and a two-row type—across a three-year field trial (2021–2023). Specifically, it compares the performance of fertilizer requirement calculations based on the German Fertilizer Application Ordinance (GFO), multispectral sensor-based fertilization systems, and fixed N input treatments. Under the trial conditions (highly productive fields without organic fertilization for decades), the GFO system consistently achieved high yields ($>10 \text{ t ha}^{-1}$) and NUE (up to 88%) for both barley varieties, often near economically optimal N rates and with minimal N surpluses. Sensor-based systems demonstrated promising potential for yield optimization and reducing N input; however, they did not result in significantly higher yields. Further research is needed to assess the performance of these fertilization systems under different conditions, such as sandy soils in regions with early-summer droughts or in systems involving organic fertilization.

Keywords: N fertilization; fertilizer application regression models; nitrogen application strategies; German Fertilizer Application Ordinance; multispectral sensor; *Hordeum vulgare* L.



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1. Introduction

Barley (*Hordeum vulgare* L.) is the second most grown cereal after wheat in Germany, with about 10% of the total cropland [1]. In Germany, multi-row varieties (mostly for feed) dominate at 70%, and are generally higher yielding, more stress-tolerant during early growth, and more winter-hardy [2]. In contrast, two-row varieties (mostly for malting) typically offer better grain quality, are more resistant to lodging, and have stronger straw [3]. Two-row and multi-row winter barley varieties differ less in total nitrogen (N) fertilization but more in the distribution of the N fertilizer applications [4]. Various fertilization systems have been developed to optimize N application, including: (a) basic fertilization methods using static factors like crop type, target yield, and soil mineral N content, (b) dynamic methods that consider static factors, crop development, and N uptake at crop growth stages, and (c) multi-spectral sensor technologies for site-specific N fertilization [5,6]. Basic fertilization methods, as defined in the German Fertilizer Application Ordinance

(GFO), calculate N application rates before the growing season starts, making them easy to implement [7].

In contrast, multi-spectral sensors can record the spectral reflectance of the cultivated crops during the growing season [8]. These sensors calculate vegetation indices, which correlate with plant parameters like biomass and N uptake [9–12]. By redistributing or even reducing the amount of mineral N fertilizer applied depending on weather and soil conditions, an increase in N use efficiency (NUE) can be achieved by using multi-spectral sensors and fertilization algorithms [13,14]. Despite their positive aspects, the efficiency of these systems remains unclear [15] and their practical implementation is still limited and not widespread in some agricultural areas [16,17], partly because the benefits for farmers have not been sufficiently researched. Furthermore, errors can still occur. Hagn et al. [18] note that variable rate application is not always superior to uniform application, as issues such as physiological leaf yellowing during measurements can lead to inaccuracies.

Recent studies with multi-year field trials and crop rotation with winter barley have examined the impact of N fertilization on grain yield. N fertilization enhances winter barley yield, with modern cultivars showing improved efficiency and greater response to higher N levels compared to older varieties [7,19,20], though the potential for sensor-based methods to enhance yield remains a subject of active research. In a multi-year fertilization trial, Mittermayer et al. [7] found high NUE with multispectral sensor-based fertilization, but could not determine a clear yield advantage over the basic fertilization method (GFO). Similarly, Wendland et al. [21] reported comparable yields between GFO and sensor-based systems, with the latter showing the potential to save N and reduce N surplus. In other field trials, where sensor-based N fertilization was applied using the ‘Online + Map-overlay’ principle [5], high NUE was achieved and often the need for the last N application was reduced, often without any clear yield effects compared to uniform fertilization [22]. While NUE and yield are critical, economic considerations also play a central role [23]. Efficiency analysis must evaluate not only whether site-specific yield potential is fully utilized but also whether the economic optimum—defined as the fertilization level yielding the highest net N return—is achieved. This optimum, based on standard mineral N and grain prices, can be estimated using various response functions, including quadratic and linear models [23–25]. In multi-year trials, Mittermayer et al. [7] found that quadratic regression functions provided a more accurate estimation of the economic optimum for winter barley compared to linear models, as they better captured the non-linear relationship between N fertilization and yield. Due to the high yield and environmental relevance of N fertilization, the partly unclear or contradictory results of previous fertilization experiments, and many open questions regarding fertilization efficiency, further comparative analyses of the different fertilization systems are required. These should include different site and management conditions, as well as different crops. The investigations were carried out at the Roggenstein research station in southern Germany, where only mineral N has been used as N fertilizer for decades (no organic fertilization, no cultivation of legumes). The aim of this study is to analyze the effects of different N fertilization systems on yield, protein content, and N balance. The large number of treatments (28) allows us to determine the yield optima exactly by increasing N applications. By N additions and N reductions, it is examined whether the yield potential is achieved with N fertilization according to GFO. Various sensor-based fertilization treatments are being tested to assess the fine-tuning capabilities of this method, focusing on aspects not commonly addressed in other studies. Experimental approaches include varying target yields, initial N applications, total N supply, and sensor-determined N rates. Furthermore, the study investigated how different distributions of N fertilizer during the growing season affect these parameters. While the GFO mandates N limits for all farms, the effects of reduced N fertilization,

particularly when comparing GFO strategies with sensor-based systems, remain under examination [12,26,27]. This study addresses these gaps by providing innovative insights into the comparative performance of fertilization systems. By leveraging a large number of treatments (28), the study precisely determines yield optima and explores the potential of different N fertilization systems to refine N application.

2. Materials and Methods

2.1. Site and Weather Conditions

The research was conducted at the Roggenstein Research Station (48°10'47" N, 11°19'11" E), situated 35 km west of Munich at an elevation of 520 m above sea level. The arable land at this experimental site has a history of intensive mineral (non-organic) fertilization and a structured crop rotation system comprising maize, wheat, barley, and sugar beet, with no inclusion of forage or grain legumes (Table 1). The 30-year climatic baseline (1991–2020) reveals an average annual precipitation of 954 mm and a mean annual air temperature of 8.9 °C (Appendix A Table A1). In 2021, air temperatures closely aligned with this long-term average. However, both 2022 and 2023 experienced notably higher air temperatures, diverging from the historical mean. Precipitation patterns also varied, with a deficit recorded in 2022 and an above-average increase observed in 2023 (Appendix A Table A1). Pre-trial soil analyses confirmed that nutrient levels were adequate to support optimal plant growth, ensuring reliable experimental conditions.

Table 1. Characterization of the study fields.

Field	Unit	2021	2022	2023
Size of the plot trial	ha	0.9 ha	0.9 ha	0.9 ha
Name of the field		U 3–4	U 5	M 2–3
Soil		silty loam	silty loam	silty loam
Soil type		Cambisol	Cambisol	Cambisol
German soil evaluation ¹		54	55	54
pH		6.7	6.8	6.8
Phosphorus (P ₂ O ₅)	mg 100 g ^{−1}	13.1	10.9	6.7
Potassium (K ₂ O)	mg 100 g ^{−1}	18.0	21.3	19.9
SMN (0–60 cm) ²	kg ha ^{−1}	35.1	40.2	29.1
SMN (0–60 cm) ³	kg ha ^{−1}	28.2	38.1	22.2

¹ 100 = best possible soil quality, Blume et al., 2016 [28]; ² experimental area with the variety Meridian (multi-row type); ³ experimental area with the variety Sandra (two-row type); SMN = soil mineral N.

2.2. Experimental Design

The fertilization trial comprised 28 fertilization treatments (Table 2), each with four replicates (112 plots). To obtain representative results for winter barley, a two-row variety (Sandra) and a multi-row variety (Meridian) were equally subjected to the different fertilization treatments. The total number of plots was 224 each year (112 per variety), with individual plots measuring 10 m in length and 2.25 m in width (Appendix A Figure A1). The width was determined by 18 seed rows. However, for the harvest, only the 12 central rows were used to avoid edge effects on the experimental results.

The first N application was conducted at the beginning of the growing season (March), the second N application took place at BBCH 32 growth stage [29], and the final N application was at the BBCH 37/39 growth stage. Calcium ammonium nitrate (CAN, 27% N) was used as fertilizer. Plant protection measures were carried out according to local practices.

Table 2. Explanation of N Fertilization treatments in trials 2021–2023.

Treatment	Explanation
N 1	0/0/0 = 0 Control (no N fertilization)
N 2	40/30/0 = 70 Fixed N application
N 3	40/30/40 = 110 Fixed N application
N 4	40/60/40 = 140 Fixed N application
N 5	70/30/40 = 140 Fixed N application
N 6	160/0/0 = 160 Fixed N application
N 7	70/90/0 = 160 Fixed N application
N 8	40/90/40 = 170 Fixed N application
N 9	70/60/40 = 170 Fixed N application
N 10	70/90/40 = 200 Fixed N application
N 11	70/120/40 = 230 Fixed N application
N 12	GFO Determination of the N fertilizer requirement according to GFO ¹
N 13	GFO – 10% Adjustments of the N fertilizer requirement according to GFO ¹
N 14	GFO – 20% Adjustments of the N fertilizer requirement according to GFO ¹
N 15	GFO – 30% Adjustments of the N fertilizer requirement according to GFO ¹
N 16	GFO + 10% Adjustments of the N fertilizer requirement according to GFO ¹
N 17	BESyD + Yara N-Tester Model BESyD (consideration of the N content of the crop stand using a chlorophyll-meter.
N 18	Sensor 10 t ha ^{−1} Sensor method ² , target yield 10 t ha ^{−1}
N 19	Sensor – 10% Sensor method ² (according to treatment 18) – 10% targeted N uptake
N 20	Sensor – 20% Sensor method ² (according to treatment 18) – 20% targeted N uptake
N 21	Sensor – 30% Sensor method ² (according to treatment 18) – 30% targeted N uptake
N 22	Sensor + 10% Sensor method ² (according to treatment 18) + 10% targeted N uptake
N 23	Sensor 10 t ha ^{−1} VB + 30% Sensor method ² , 30% more N fertilization at the beginning of vegetation, target yield 10 ha ^{−1}
N 24	Sensor 10 t ha ^{−1} VB – 30% Sensor method ² , 30% less N fertilization at the beginning of vegetation, target yield 10 ha ^{−1}
N 25	Sensor 11 t ha ^{−1} Sensor method ² , target yield 11 t ha ^{−1}
N 26	Sensor 8 t ha ^{−1} Sensor method ² , target yield 8 t ha ^{−1}
N 27	Sensor balance Sensor method ² , the mean N uptake ha ^{−1} with a target yield of 10 ha ^{−1} is the upper limit of fertilization
N 28	Sensor GFO Sensor method ² , the fertilizer requirement according to GFO is the upper limit of fertilization

¹ GFO = German Fertilizer Application Ordinance, ² Determination of the N fertilizer requirement based on multispectral sensor data and algorithm according to Maidl (2011) [12].

2.3. Experimental Treatments

The 28 fertilization treatments include fixed fertilization levels, legally required fertilization systems (with adjustments), and sensor-based fertilization (with adjustments) (Table 2):

- N 1–N 11: Fixed fertilization application including control plots,
- N 12–N 17: Official fertilization systems including adjustments,
- N 18–N 28: Sensor-based fertilization systems including adjustments [12,30].

2.3.1. Fixed Fertilization Levels (N 1–N 11)

In addition to the control plot (N 1), where no N was applied, 10 different fixed N levels (N 2–N 11) were tested for both varieties. The N inputs covered a total N fertilization range from 70 kg ha^{−1} to 230 kg ha^{−1} and included different distributions of N inputs between the first, second, and third applications. The initial N fertilization involved either 40 kg ha^{−1}, 70 kg ha^{−1}, or 160 kg ha^{−1}. The second application includes N doses from 0 to 120 kg ha^{−1}, and the third application includes 0 or 40 kg ha^{−1}.

2.3.2. Official Fertilization Systems (N 12–N 17)

The GFO method [27] and its adjustments were used in this study (N 12–N 16). The methodology for determining N fertilizer requirements according to the GFO [27] is described in Mittermayer et al. [7]. In this trial, several treatments of the GFO system were tested, covering a range of deviations from the calculated total N input of plus 10% to minus 30%. The BESyD fertilization system (N 17) incorporates more factors than the GFO, such as crop development and N content of the biomass at the second and third fertilization stages [31]. BESyD provides a fixed recommendation for the first application, with the subsequent applications being controlled by a handheld chlorophyll meter [32] to optimize N fertilization. The total N fertilizer requirement determined by BESyD does not exceed the permissible N input according to the GFO (in accordance with the legal regulations).

2.3.3. Sensor-Based N Fertilization (N 18–N 28)

Eleven sensor-based treatments (N 18–N 28) were tested, differing in target yields and N application adjustments. The core sensor-based treatment (N 18) followed the N fertilization algorithm exactly as it is intended for practical application [12,30]. The other treatments were designed to evaluate the performance of this core algorithm—specifically, whether it achieves the full yield potential or requires adjustments. For the second and third applications (BBCH 32 and BBCH 39), a handheld multispectral sensor was used to calculate the vegetation index REIP (Red Edge Inflection Point), and the application of an N fertilization algorithm according to Maidl [12,30] (see Mittermayer et al. for more details [7]). To test different scenarios, variations were introduced as follows:

- Sensor-determined N applications were adjusted (N 19 to N 22) to explore the flexibility of the system.
- The first N application was varied (N 23, N 24) to test the sensitivity of the algorithm to initial fertilization levels.
- Target yields were adjusted (N 25, N 26) to evaluate performance under modified yield expectations.
- The total N supply was limited (N 27, N 28) to assess efficiency under reduced N availability.

For reduced N treatments, target yields were adjusted based on the assumption that a 2% N reduction decreases yield by 1%. The new target yield was calculated as follows: New target yield = Original target yield × (1 − (% N reduction ÷ 2)).

2.4. Crop Yield, Protein Concentrations, N Uptake and N Balancing

Grain yield for each experimental plot was precisely measured using a plot combine harvester. Laboratory analyses were performed to determine the grain's dry matter (DM) content after drying at 60 °C. Fresh matter (FM) yields, expressed in t ha⁻¹, were standardized to a dry matter content of 86%. Grain N content was quantified using a C/N Analyzer [33] and N uptake was calculated by multiplying the grain DM yield by the N content determined through laboratory analysis. By-products, including straw, were excluded from harvesting and were not factored into the calculation of N output.

The N surplus (kg ha⁻¹) was calculated:

$$N_{\text{surplus}} = N_{\text{input}} - N_{\text{output}}$$

The NUE (%) was determined using the difference method:

$$NUE = (N_{\text{output_fertilized}} - N_{\text{output_unfertilized}}) / N_{\text{input}}$$

N_{input} is defined as the amount of mineral N fertilizer applied to each plot.

N_{output} is represented as the grain N uptake in the fertilized treatment and unfertilized treatment, respectively.

2.5. Statistical Analyses

Statistical analysis and data processing were conducted using the “R” software (R version 4.2.2) [34]. The Shapiro–Wilk test (shapiro.test) was used to assess normality, and ANOVA (aov()) was applied to evaluate the effects of N fertilization on variables such as yield, protein concentration, N uptake, N surplus, and NUE. Post hoc analysis was performed using the Student–Newman–Keuls test, with significant differences ($p < 0.05$) marked by different letters.

To evaluate the fertilizer systems, N response functions were fitted to predict crop fresh matter yield standardized to 86% dry matter content as a function of N fertilization. Three models—quadratic, quadratic-plateau, and linear-plateau—were parameterized, as described in detail by Mittermayer et al. [7]. These models were used to estimate maximum and economically optimum fertilizer levels, as well as their corresponding N surplus values, based on standard assumptions for fertilizer and product prices. For further details, refer to Mittermayer et al. [7]. These models estimated maximum (N_{max} , Y_{max}) and economically optimum (N_{opt} , Y_{opt}) fertilizer levels and their associated N surplus values under standard price assumptions. Model evaluation metrics included mean absolute error (MAE), root mean square error (RMSE), and the coefficient of determination (R^2), alongside yield-related parameters).

3. Results

3.1. Multi-Row Variety ‘Meridian’ in 2021

The unfertilized control treatment (N 1) achieved a significantly low yield of 3.5 t ha⁻¹, which corresponds to approximately 32% of the maximum yield (Table 3). N application of 160 kg ha⁻¹ (N 6) was sufficient to achieve the maximum yield. Notably, this single application, likely influenced by the year's weather conditions, produced results comparable to other strategies. Both GFO (N 12) and Sensor 10 t ha⁻¹ (N 18) achieved the maximum yield of 10.9 t ha⁻¹, while BESyD (N 17) was slightly lower with (10.7 t ha⁻¹). Significantly reduced N applications, such as GFO – 30% (N 15) and Sensor – 30% (N 21), as well as increased N applications such as Sensor + 10% (N 22), resulted in a significantly lower yield. However, the highest N uptake achieved Sensor + 10% (N22) with 207 kg ha⁻¹, because of high protein contents. The N balances were generally at a low level, with a maximum of

28 kg ha⁻¹ (N 11). Many treatments, including GFO (N 12) and BESyD (N 17), resulted in negative N balances.

Table 3. Yields and N balances of variety Meridian in the year 2021.

	Treatment	N Fertilization [kg ha ⁻¹]	FM Yield [t ha ⁻¹]	Protein [%]	N Uptake [kg ha ⁻¹]	N Surplus [kg ha ⁻¹]	NUE [%]
N 1	0/0/0 = 0	0/0/0 = 0	3.5 j	10.3 op	49.3 n	−49.3 k	
N 2	40/30/0 = 70	40/30/0 = 70	7.7 i	10.0 P	106.2 m	−36.2 j	81.2 abcd
N 3	40/30/40 = 110	40/30/40 = 110	8.8 h	11.1 no	134.2 l	−24.2 hij	77.2 abcdef
N 4	40/60/40 = 140	40/60/40 = 140	9.9 defg	11.9 ijklm	162.3 hij	−22.3 ghij	80.7 abcde
N 5	70/30/40 = 140	70/30/40 = 140	10.1 bcdef	11.3 lmn	157.2 ijk	−17.2 ghi	77.0 abcdef
N 6	160/0/0 = 160	160/0/0 = 160	10.8 ab	11.7 klmn	172.6 fghi	−12.6 efghi	77.1 abcdef
N 7	70/90/0 = 160	70/90/0 = 160	10.6 abcde	12.2 hijk	176.6 efgh	−16.6 fghi	79.6 abcde
N 8	40/90/40 = 170	40/90/40 = 170	10.0 cdefg	13.2 efg	181.6 defg	−11.6 efghi	77.8 abcde
N 9	70/60/40 = 170	70/60/40 = 170	10.5 abcdef	12.6 ghi	182.1 cdefg	−12.1 efghi	78.1 abcde
N 10	70/90/40 = 200	70/90/40 = 200	10.6 abcd	13.6 def	197.2 abc	2.8 bcde	74.0 cdefg
N 11	70/120/40 = 230	70/120/40 = 230	10.0 cdefg	14.7 ab	201.7 a	28.3 a	66.3 g
N 12	GFO	60/55/50 = 175	10.9 a	12.9 fgh	193.7 abcd	−18.7 ghij	82.5 abc
N 13	GFO − 10%	54/50/54 = 158	10.4 abcdef	12.5 ghij	178.1 efg	−20.1 ghij	81.5 abc
N 14	GFO − 20%	48/44/48 = 140	10.5 abcdef	11.7 jklmn	168.4 ghij	−28.4 ij	85.1 ab
N 15	GFO − 30%	42/39/42 = 123	9.4 gh	11.2 mn	145.6 kl	−22.6 ghij	78.3 abcde
N 16	GFO + 10%	66/61/66 = 193	10.9 a	13.3 efg	198.8 ab	−5.8 cdefg	77.4 abcdef
N 17	BESyD + Yara N-Tester	55/60/50 = 165	10.7 ab	12.1 ijkl	177.3 efgh	−12.3 efghi	77.5 abcdef
N 18	Sensor 10 t ha ⁻¹	60/77/68 = 205	10.9 a	13.7 def	204.7 a	0.9 bcdef	75.7 bcdefg
N 19	Sensor − 10%	57/68/57 = 182	10.6 abc	13.1 efg	191.4 abcde	−10.2 defgh	78.4 abcde
N 20	Sensor − 20%	54/54/40 = 148	10.6 abc	12.1 hijk	177.2 efgh	−28.7 ij	86.5 a
N 21	Sensor − 30%	51/49/33 = 133	9.9 efg	11.5 klmn	155.9 jk	−23.6 hij	80.7 abcde
N 22	Sensor + 10%	63/89/82 = 234	9.8 fg	15.3 a	206.8 a	26.9 a	67.4 fg
N 23	Sensor 10 t ha ⁻¹ VB + 30%	60/81/72 = 213	10.5 abcdef	14.2 bcd	205.6 a	6.7 bcd	73.7 cdefg
N 24	Sensor 10 t ha ⁻¹ VB − 30%	60/78/70 = 208	10.3 abcdef	13.9 cde	196.3 abcd	11.8 abc	70.7 efg
N 25	Sensor 11 t ha ⁻¹	66/72/82 = 220	10.4 abcdef	14.5 bc	206.1 a	14.0 ab	71.2 defg
N 26	Sensor 8 t ha ⁻¹	48/73/38 = 159	10.1 bcdefg	12.6 ghi	174.8 fgh	−15.8 fghi	79.0 abcde
N 27	Sensor balance	60/80/49 = 189	11.0 a	13.0 fg	196.6 abcd	−7.6 defgh	78.0 abcde
N 28	Sensor GFO	60/82/33 = 175	10.6 abcde	12.7 ghi	184.0 bcdef	−9.0 defgh	77.0 abcdef

Letters following the values (e.g., “abcd”) indicate statistical groupings based on the post-hoc test.

The quadratic yield response function indicates that the GFO (N 12), BESyD (N 17), and Sensor 10 t ha⁻¹ (N 18) align closely with the economic optimum (Figure 1). Positive N balances occur only at applications above 200 kg ha⁻¹. Exceeding the yield optimum marks the transition into the surplus range of N balances.

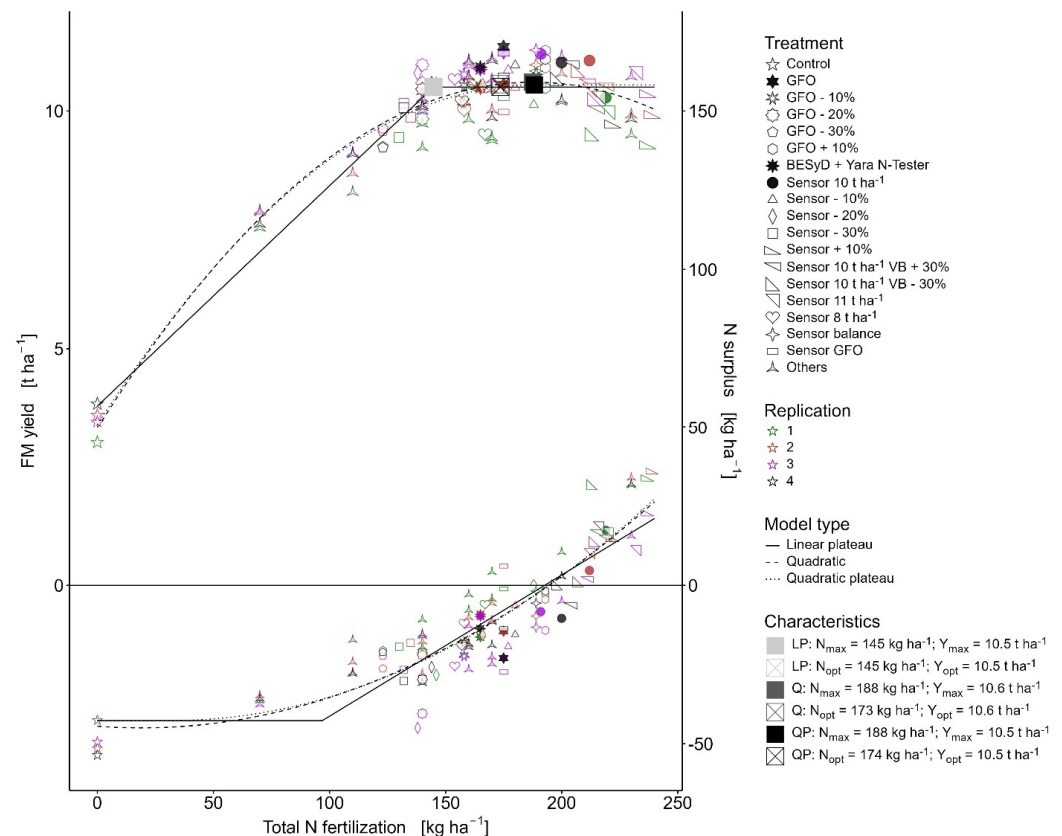


Figure 1. Relationships between N fertilization and yield and between N fertilization and N surplus for the year 2021 (Meridian). Yield is expressed as fresh matter, standardized to a dry matter content of 86%. The upper lines depict the relationship between N fertilization and yield, whereas the lower lines represent the relationship between N fertilization and N surplus.

3.2. Two-Row Variety ‘Sandra’ in 2021

The yields of the two-row barley variety Sandra were slightly lower than those of the six-row variety Meridian, and the N fertilization requirement was higher (Table 4). The theoretical optimal yield (Y_{opt}) of the quadratic function for Sandra was 10.1 t ha^{-1} , achieved with an optimal N application (N_{opt}) of 197 kg ha^{-1} (Figure 2). In comparison, Meridian achieved a higher Y_{opt} of 10.6 t ha^{-1} with a lower N_{opt} of 173 kg ha^{-1} . The yield of the unfertilized control plot (N 1) (2.9 t ha^{-1}) and N uptake (35 kg ha^{-1}) were very low and even lower than those observed with Meridian. Treatments GFO (N 12) and Sensor 10 t ha^{-1} (N 18) achieved maximum yields for Sandra, while BESyD (N 17) did not reach this level. Adjustments to the N 18 treatment, whether through reductions or increases in N application, resulted in yield reductions, indicating the high precision of the original Sensor 10 t ha^{-1} (N 18) treatment. Similarly, reductions in N application for GFO led to lower yields, while increases, as seen in GFO + 10% (N 16), maintained optimal performance.

Protein contents declined significantly under reduced N application, such as in GFO – 30% (N 15), and were generally lower for Sandra than for Meridian. N uptake was lower for Sandra, while N surpluses were slightly higher than those for Meridian. Consequently, NUE was lower for Sandra compared to Meridian.

Table 4. Yields and N balances of variety Sandra in the year 2021.

	Treatment	N Fertilization [kg ha ⁻¹]	FM Yield [t ha ⁻¹]	Protein [%]	N Uptake [kg ha ⁻¹]	N Surplus [kg ha ⁻¹]	NUE [%]
N 1	0/0/0 = 0	0/0/0 = 0	2.9 ^k	8.6 ^l	35.4 ^p	−35.4 ^l	
N 2	40/30/0 = 70	40/30/0 = 70	7.0 ^j	8.7 ^l	84.3 ^o	−14.3 ^k	69.8 ^a
N 3	40/30/40 = 110	40/30/40 = 110	8.1 ⁱ	9.8 ^k	109.6 ⁿ	0.4 ^{jk}	67.4 ^a
N 4	40/60/40 = 140	40/60/40 = 140	8.9 ^h	10.6 ^{ghijk}	130.4 ^{klm}	9.7 ^{ghij}	67.8 ^a
N 5	70/30/40 = 140	70/30/40 = 140	9.2 ^{fgh}	10.2 ^{ijk}	128.7 ^{klm}	11.4 ^{ghij}	66.6 ^a
N 6	160/0/0 = 160	160/0/0 = 160	9.9 ^{abcde}	10.1 ^{jk}	137.3 ^{ijk}	22.7 ^{cdefghi}	63.7 ^a
N 7	70/90/0 = 160	70/90/0 = 160	9.6 ^{cdef}	11.1 ^{efghi}	148.4 ^{ghij}	11.7 ^{ghij}	70.6 ^a
N 8	40/90/40 = 170	40/90/40 = 170	9.2 ^{fgh}	11.8 ^{def}	148.7 ^{ghij}	21.3 ^{cdefghi}	66.6 ^a
N 9	70/60/40 = 170	70/60/40 = 170	9.7 ^{bcdef}	11.5 ^{defg}	154.3 ^{fgh}	15.8 ^{efghij}	69.9 ^a
N 10	70/90/40 = 200	70/90/40 = 200	10.1 ^{abcde}	12.2 ^{cd}	170.2 ^{bcde}	29.8 ^{cdef}	67.4 ^a
N 11	70/120/40 = 230	70/120/40 = 230	9.9 ^{abcde}	13.4 ^{ab}	182.2 ^{ab}	47.9 ^{ab}	63.8 ^a
N 12	GFO	80/62/40 = 182	10.1 ^{abcde}	11.7 ^{def}	162.7 ^{defg}	19.3 ^{cdefghi}	69.9 ^a
N 13	GFO − 10%	72/56/36 = 164	9.6 ^{cdef}	11.2 ^{efgh}	148.8 ^{ghij}	15.2 ^{efghij}	69.1 ^a
N 14	GFO − 20%	64/50/32 = 146	9.6 ^{def}	10.5 ^{hijk}	138.6 ^{hijk}	7.4 ^{hij}	70.7 ^a
N 15	GFO − 30%	56/43/28 = 127	8.7 ^h	9.6 ^{kl}	115.8 ^{mn}	11.2 ^{ghij}	63.3 ^a
N 16	GFO + 10%	88/68/44 = 200	10.2 ^{abc}	12.1 ^{cde}	169.1 ^{bcdef}	30.9 ^{bcde}	66.8 ^a
N 17	BESyD + Yara N-Tester	55/65/50 = 170	9.5 ^{efg}	11.4 ^{defgh}	150.1 ^{ghi}	20.0 ^{cdefghi}	67.4 ^a
N 18	Sensor 10 t ha ⁻¹	80/69/60 = 209	10.4 ^a	12.8 ^{bc}	183.1 ^{ab}	26.2 ^{cdefg}	70.8 ^a
N 19	Sensor − 10%	76/65/48 = 189	9.9 ^{abcde}	12.0 ^{cde}	164.2 ^{cdefg}	24.4 ^{cdefgh}	68.3 ^a
N 20	Sensor − 20%	72/47/30 = 149	9.7 ^{bcde}	10.5 ^{ghijk}	141.5 ^{hijk}	7.5 ^{hij}	71.2 ^a
N 21	Sensor − 30%	68/39/18 = 125	9.0 ^h	9.6 ^{kl}	118.8 ^{lmn}	6.0 ^{ij}	66.9 ^a
N 22	Sensor + 10%	84/84/80 = 248	9.8 ^{bcde}	14.0 ^a	189.2 ^a	57.8 ^a	62.2 ^a
N 23	Sensor 10 t ha ⁻¹ VB + 30%	80/71/64 = 215	10.0 ^{abcd}	12.9 ^{bc}	179.9 ^{abc}	35.4 ^{bcd}	67.2 ^a
N 24	Sensor 10 t ha ⁻¹ VB − 30%	80/72/64 = 216	10.1 ^{abcde}	12.8 ^{bc}	178.1 ^{abcd}	37.7 ^{bc}	66.1 ^a
N 25	Sensor 11 t ha ⁻¹	88/64/61 = 213	10.2 ^{abc}	12.8 ^{bc}	179.2 ^{abc}	34.3 ^{bcd}	67.4 ^a
N 26	Sensor 8 t ha ⁻¹	56/23/68 = 147	9.0 ^{gh}	10.8 ^{fghij}	134.2 ^{kl}	13.1 ^{fghij}	67.1 ^a
N 27	Sensor balance	80/73/36 = 189	10.3 ^{ab}	11.9 ^{cde}	168.0 ^{bcdef}	21.0 ^{cdefghi}	70.1 ^a
N 28	Sensor GFO	80/73/29 = 182	10.0 ^{abcde}	11.5 ^{defg}	157.9 ^{efg}	24.1 ^{cdefgh}	67.3 ^a

Letters following the values (e.g., “abcd”) indicate statistical groupings based on the post-hoc test.

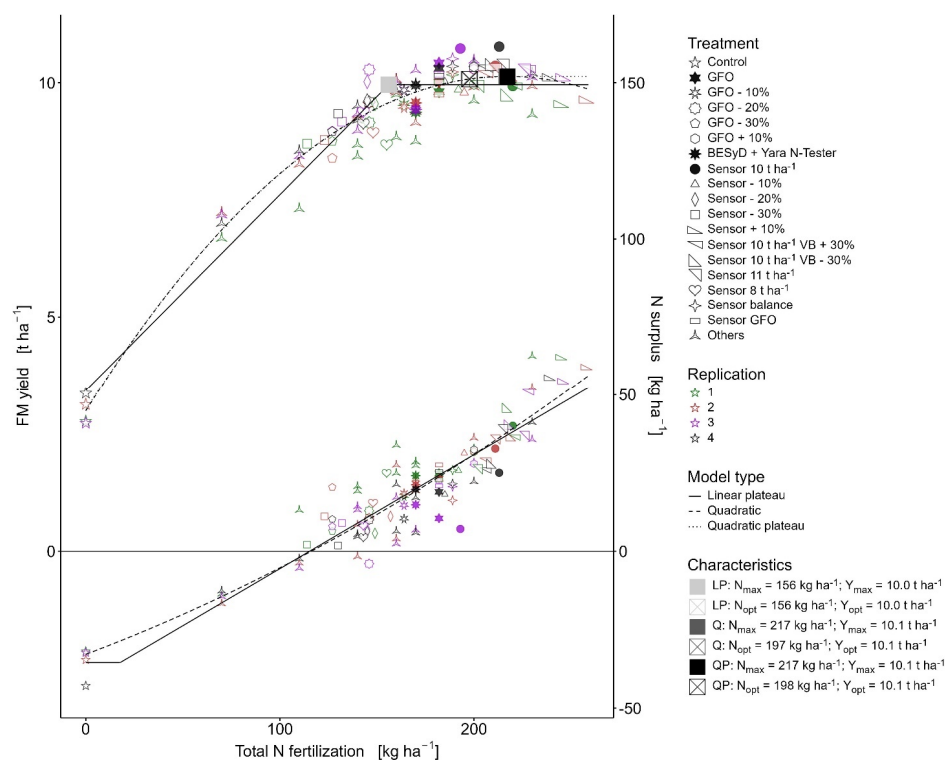


Figure 2. Relationships between N fertilization and yield and between N fertilization and N surplus for the year 2021 (Sandra). Yield is expressed as fresh matter, standardized to a dry matter content of 86%. The upper lines depict the relationship between N fertilization and yield, whereas the lower lines represent the relationship between N fertilization and N surplus.

3.3. Multi-Row Variety ‘Meridian’ in 2022

In 2022, the variety Meridian achieved high yields, significantly exceeding the target yield (10 t ha^{-1}) (Table 5). According to the quadratic regression, the theoretical optimal yield (Y_{opt}) was 11.6 t ha^{-1} , reached with an optimal N application (N_{opt}) of 213 kg ha^{-1} (Figure 3). Both the GFO (N_{12}) and Sensor 10 t ha^{-1} (N_{18}) achieved the maximum yield, with sensor-based fertilization showing higher protein contents and N uptakes compared to GFO. The Sensor 10 t ha^{-1} (N_{18}) applied 40 kg ha^{-1} more N than GFO but remained slightly below N_{opt} . Notably, in this year, only negative N balances were observed, except for Sensor + 10% (N_{22}), which achieved a balanced N surplus (0 kg ha^{-1}). NUE was very high across all treatments. Additionally, treatment N 6, characterized by a single N application at the beginning of the growing season, performed very well in 2022.

Table 5. Yields and N balances of variety Meridian in the year 2022.

	Treatment	N Fertilization [kg ha^{-1}]	FM Yield [t ha^{-1}]	Protein [%]	N Uptake [kg ha^{-1}]	N Surplus [kg ha^{-1}]	NUE [%]
N 1	0/0/0 = 0	0/0/0 = 0	3.9 ^j	10.0 ^k	54.5 ⁿ	−54.5 ^g	
N 2	40/30/0 = 70	40/30/0 = 70	7.8 ⁱ	9.9 ^k	106.3 ^m	−36.3 ^{fg}	74.0 ^c
N 3	40/30/40 = 110	40/30/40 = 110	9.3 ^h	11.0 ^{jk}	141.6 ^l	−31.6 ^f	79.2 ^{abc}
N 4	40/60/40 = 140	40/60/40 = 140	10.5 ^{defg}	12.1 ^{ghij}	173.9 ^{ghij}	−33.9 ^{fg}	85.3 ^{abc}
N 5	70/30/40 = 140	70/30/40 = 140	10.4 ^{defg}	11.7 ^{ghij}	167.6 ^{ijk}	−27.6 ^{def}	80.8 ^{abc}
N 6	160/0/0 = 160	160/0/0 = 160	11.2 ^{abcd}	11.6 ^{hij}	178.8 ^{fghi}	−18.8 ^{abcdef}	77.7 ^{abc}
N 7	70/90/0 = 160	70/90/0 = 160	11.1 ^{abcde}	12.5 ^{defghi}	192.1 ^{defgh}	−32.1 ^f	86.0 ^{ab}
N 8	40/90/40 = 170	40/90/40 = 170	10.9 ^{bcde}	13.0 ^{bcdefg}	195.0 ^{defg}	−25.0 ^{cdef}	82.6 ^{abc}
N 9	70/60/40 = 170	70/60/40 = 170	11.2 ^{abcd}	12.9 ^{cdefgh}	198.7 ^{cdef}	−28.7 ^{def}	84.9 ^{abc}
N 10	70/90/40 = 200	70/90/40 = 200	11.7 ^{ab}	13.5 ^{abcde}	218.5 ^{abc}	−18.5 ^{abcdef}	82.0 ^{abc}
N 11	70/120/40 = 230	70/120/40 = 230	11.9 ^a	14.2 ^{ab}	233.9 ^a	−3.9 ^{ab}	78.0 ^{abc}
N 12	GFO	60/50/60 = 170	11.4 ^{abc}	13.0 ^{bcdefg}	205.2 ^{bcde}	−35.2 ^{fg}	88.7 ^a
N 13	GFO − 10%	54/45/54 = 153	10.4 ^{defg}	12.5 ^{defghi}	180.2 ^{fghi}	−27.2 ^{def}	82.2 ^{abc}
N 14	GFO − 20%	48/40/48 = 136	10.2 ^{efgh}	11.8 ^{ghij}	166.2 ^{ijk}	−30.2 ^{ef}	82.2 ^{abc}
N 15	GFO − 30%	42/35/42 = 119	9.7 ^{gh}	11.4 ^{ij}	153.3 ^{jkl}	−34.3 ^{fg}	83.0 ^{abc}
N 16	GFO + 10%	66/55/66 = 187	11.1 ^{abcde}	13.5 ^{abcde}	206.3 ^{bcde}	−19.3 ^{abcdef}	81.2 ^{abc}
N 17	BESyD + Yara N-Tester	60/55/50 = 165	11.1 ^{abcde}	12.6 ^{defghi}	192.7 ^{defg}	−27.7 ^{def}	83.8 ^{abc}
N 18	Sensor 10 t ha^{-1}	60/86/64 = 210	11.4 ^{abc}	13.9 ^{abc}	219.3 ^{abc}	−10.3 ^{abcde}	78.9 ^{abc}
N 19	Sensor − 10%	57/70/43 = 170	11.2 ^{abcd}	12.8 ^{cdefgh}	198.9 ^{cdef}	−28.9 ^{ef}	85.6 ^{ab}
N 20	Sensor − 20%	54/56/29 = 139	10.6 ^{cdef}	11.6 ^{hij}	170.1 ^{hijk}	−31.1 ^f	83.6 ^{abc}
N 21	Sensor − 30%	51/46/18 = 115	9.7 ^{gh}	11.1 ^{jk}	148.5 ^{kl}	−33.0 ^f	81.8 ^{abc}
N 22	Sensor + 10%	63/96/69 = 228	11.5 ^{abc}	14.3 ^{ab}	227.0 ^{ab}	0.0 ^a	76.7 ^{bc}
N 23	Sensor 10 t ha^{-1} VB + 30%	78/77/43 = 198	11.6 ^{ab}	13.7 ^{abcd}	219.0 ^{abc}	−21.3 ^{bcdef}	83.3 ^{abc}
N 24	Sensor 10 t ha^{-1} VB − 30%	42/94/76 = 212	11.0 ^{abcde}	14.4 ^a	219.2 ^{abc}	−8.0 ^{abcd}	78.0 ^{abc}
N 25	Sensor 11 t ha^{-1}	66/96/68 = 230	11.8 ^{ab}	14.4 ^a	233.9 ^a	−4.9 ^{abc}	78.8 ^{abc}
N 26	Sensor 8 t ha^{-1}	48/53/31 = 132	9.8 ^{fgh}	12.2 ^{efghij}	165.0 ^{ijk}	−33.3 ^f	84.3 ^{abc}
N 27	Sensor balance	60/85/44 = 189	11.6 ^{ab}	13.4 ^{abcdef}	213.7 ^{abcd}	−24.7 ^{bcdef}	84.2 ^{abc}
N 28	Sensor GFO	60/83/27 = 170	10.6 ^{cdef}	13.0 ^{bcdefg}	190.8 ^{efgh}	−20.8 ^{bcdef}	80.2 ^{abc}

Letters following the values (e.g., “abcd”) indicate statistical groupings based on the post-hoc test.

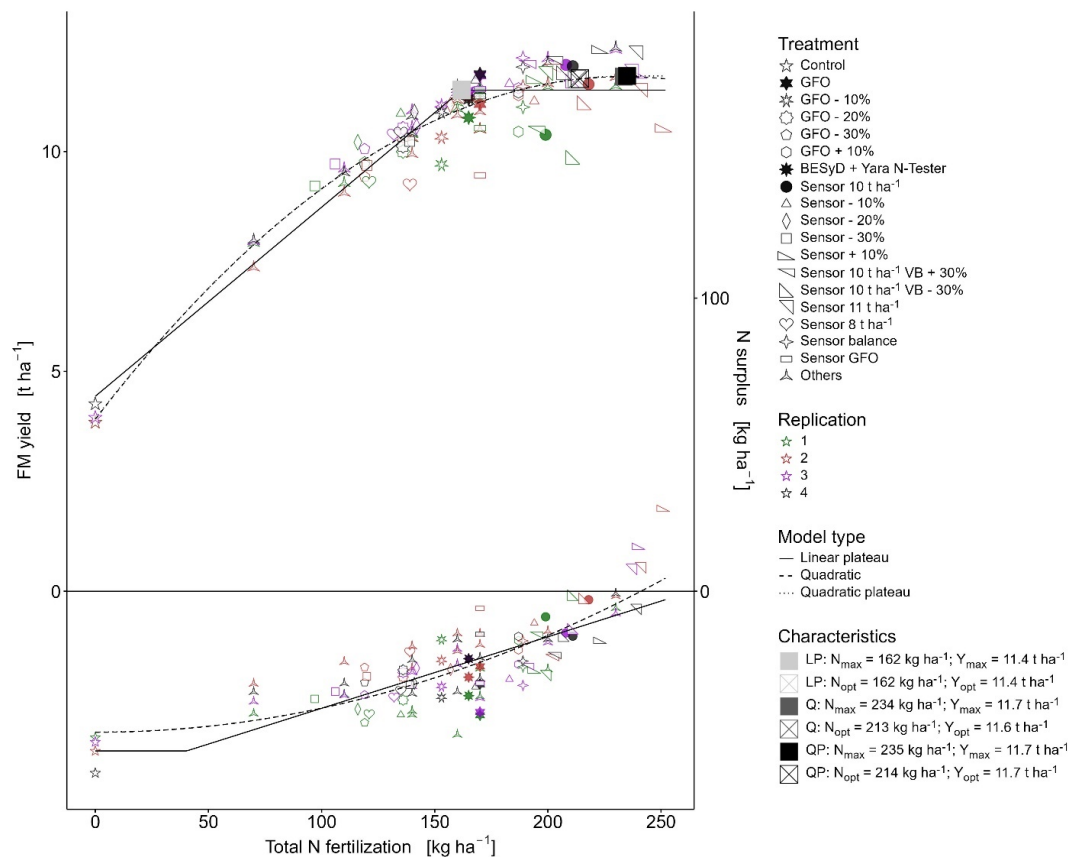


Figure 3. Relationships between N fertilization and yield and between N fertilization and N surplus for the year 2022 (Meridian). Yield is expressed as fresh matter, standardized to a dry matter content of 86%. The upper lines depict the relationship between N fertilization and yield, whereas the lower lines represent the relationship between N fertilization and N surplus.

3.4. Two-Row Variety ‘Sandra’ in 2022

In 2022, the yields for the two-row barley variety Sandra were again slightly lower (Appendix A Table A2) than those for the six-row variety Meridian, despite having a nearly identical N requirement (N_{opt}). The theoretical optimal yield (Y_{opt}) for Sandra was 10.4 t ha^{-1} , achieved with an N_{opt} of 209 kg ha^{-1} (Appendix A Figure A2). Both GFO (N_{12}) and Sensor 10 t ha^{-1} (N_{18}) produced nearly the same yield for Sandra (10.3 t ha^{-1}), but the sensor-based treatment needed 54 kg ha^{-1} more N fertilizer. BESyD (N_{17}) achieved a slightly lower yield (9.8 t ha^{-1}). N surpluses for Sandra in 2022 were significantly higher than those for Meridian, reaching values above 40 kg ha^{-1} in treatments such as N_{22} and N_{24} . NUE was lower for Sandra compared to Meridian, with Sandra achieving 76.6% under GFO (N_{12}) compared to 88.7% for Meridian.

3.5. Performance of Multi-Row Variety ‘Meridian’ in 2023

In 2023, the yield optima for the six-row barley variety Meridian confirmed the trends observed in previous years (Table 6). The theoretical optimal yield (Y_{opt}) was 11.0 t ha^{-1} , achieved with an optimal N application (N_{opt}) of 217 kg ha^{-1} (Figure 4). Over the three years of the study, Meridian consistently reached very high yields, ranging from 10.6 t ha^{-1} in 2021 to 11.6 t ha^{-1} in 2022, with N requirements increasing from 173 kg ha^{-1} in 2021 to 217 kg ha^{-1} in 2023. The unfertilized control plot (N_1) showed very low performance, with a yield of only 3.1 t ha^{-1} and an N uptake of 33 kg ha^{-1} . The highest yield in 2023, 11.1 t ha^{-1} , was recorded in treatment N_{10} with 200 kg ha^{-1} . The GFO treatment (N_{12}) achieved a statistically similar yield but with 29 kg ha^{-1} less N applied. The Sensor

10 t ha^{−1} treatment (N 18) also delivered a comparable yield of 10.1 t ha^{−1} with significantly less N input, requiring only 145 kg ha^{−1}, which is 55 kg ha^{−1} less than N 10. However, sensor-based treatments with further reduced N input (N 19 to N 21) resulted in significant reductions in yield, protein content, and N uptake. These treatments also slightly increased N surpluses compared to N 18, although the differences were not statistically significant. Similarly, GFO treatments with reduced N application (N 13 to N 15) led to significant reductions in yield, protein content, and N uptake. Higher N applications in GFO and sensor-based treatments (e.g., N 16 and N 22) did not increase yields but had a positive effect on protein content.

Table 6. Yields and N balances of variety Meridian in the year 2023.

	Treatment	N Fertilization [kg ha ^{−1}]	FM Yield [t ha ^{−1}]	Protein [%]	N Uptake [kg ha ^{−1}]	N Surplus [kg ha ^{−1}]	NUE [%]
N 1	0/0/0 = 0	0/0/0 = 0	3.1 j	7.4 m	32.6 m	−32.5 d	
N 2	40/30/0 = 70	40/30/0 = 70	7.1 i	8.4 lm	83.7 l	−13.7 c	73.1 ab
N 3	40/30/40 = 110	40/30/40 = 110	8.7 fgh	9.4 ijkl	112.6 jk	−2.6 bc	72.8 ab
N 4	40/60/40 = 140	40/60/40 = 140	10.1 abcde	9.9 ghijkl	136.7 ghij	3.3 bc	74.4 ab
N 5	70/30/40 = 140	70/30/40 = 140	9.6 bcdefg	10.1 fghijk	134.4 ghij	5.6 bc	74.5 ab
N 6	160/0/0 = 160	160/0/0 = 160	9.7 bcdefg	10.5 efghijk	139.7 fghi	20.3 ab	67.0 ab
N 7	70/90/0 = 160	70/90/0 = 160	10.3 abc	11.1 cdefg	158.9 cdefg	1.1 bc	79.0 ab
N 8	40/90/40 = 170	40/90/40 = 170	9.9 abcdef	12.2 abcd	167.0 bcde	3.0 bc	79.1 ab
N 9	70/60/40 = 170	70/60/40 = 170	10.0 ab	11.6 bcdef	173.3 bcd	−3.3 bc	82.8 a
N 10	70/90/40 = 200	70/90/40 = 200	11.1 a	12.4 abc	189.4 ab	10.6 bc	78.4 ab
N 11	70/120/40 = 230	70/120/40 = 230	10.6 ab	13.6 a	199.6 a	30.4 a	72.6 ab
N 12	GFO	60/56/55 = 171	10.8 ab	11.8 bcde	174.7 abcd	−3.7 bc	83.2 a
N 13	GFO − 10%	54/50/50 = 154	10.3 abc	10.9 cdefgh	156.0 defgh	−2.0 bc	80.1 ab
N 14	GFO − 20%	48/45/44 = 137	9.7 bcdefg	10.0 ghijk	133.1 hij	3.9 bc	73.4 ab
N 15	GFO − 30%	42/39/39 = 120	9.1 cdefg	9.9 ghijkl	125.0 ij	−5.0 bc	77.0 ab
N 16	GFO + 10%	66/62/61 = 189	10.7 ab	12.4 abc	182.7 abc	6.3 bc	79.4 ab
N 17	BESyD + Yara N-Tester	65/50/50 = 165	10.4 abc	11.1 cdefg	159.0 cdefg	6.1 bc	76.6 ab
N 18	Sensor 10 t ha ^{−1}	60/43/42 = 145	10.1 abcde	10.5 efghijk	146.2 efghi	−1.2 bc	78.4 ab
N 19	Sensor − 10%	57/36/32 = 125	9.0 defg	9.8 ghijkl	122.3 ij	2.7 bc	71.8 ab
N 20	Sensor − 20%	54/43/16 = 113	8.9 efgh	9.1 jkl	112.1 jk	0.9 bc	70.4 ab
N 21	Sensor − 30%	51/17/36 = 104	7.6 hi	9.0 kl	95.6 kl	8.4 bc	60.6 b
N 22	Sensor + 10%	63/57/49 = 169	10.1 abcde	11.6 bcdef	162.1 cdefg	6.9 bc	76.6 ab
N 23	Sensor 10 t ha ^{−1} VB + 30%	78/35/36 = 149	9.9 abcdefg	10.3 fghijk	139.7 fghi	9.3 bc	71.9 ab
N 24	Sensor 10 t ha ^{−1} VB − 30%	42/55/55 = 152	10.3 abcd	11.5 bcdef	163.6 cdef	−11.6 c	86.2 a
N 25	Sensor 11 t ha ^{−1}	66/89/47 = 202	10.8 ab	12.8 ab	191.0 ab	11.1 bc	78.4 ab
N 26	Sensor 8 t ha ^{−1}	48/43/20 = 111	8.6 gh	9.4 hijkl	111.5 jk	−0.5 bc	71.1 ab
N 27	Sensor balance	60/44/46 = 150	9.9 abcdef	10.6 efghij	145.7 efghi	4.3 bc	75.4 ab
N 28	Sensor GFO	60/46/47 = 153	9.7 bcdefg	10.8 defghi	144.9 efghi	8.1 bc	73.4 ab

Letters following the values (e.g., “abcd”) indicate statistical groupings based on the post-hoc test.

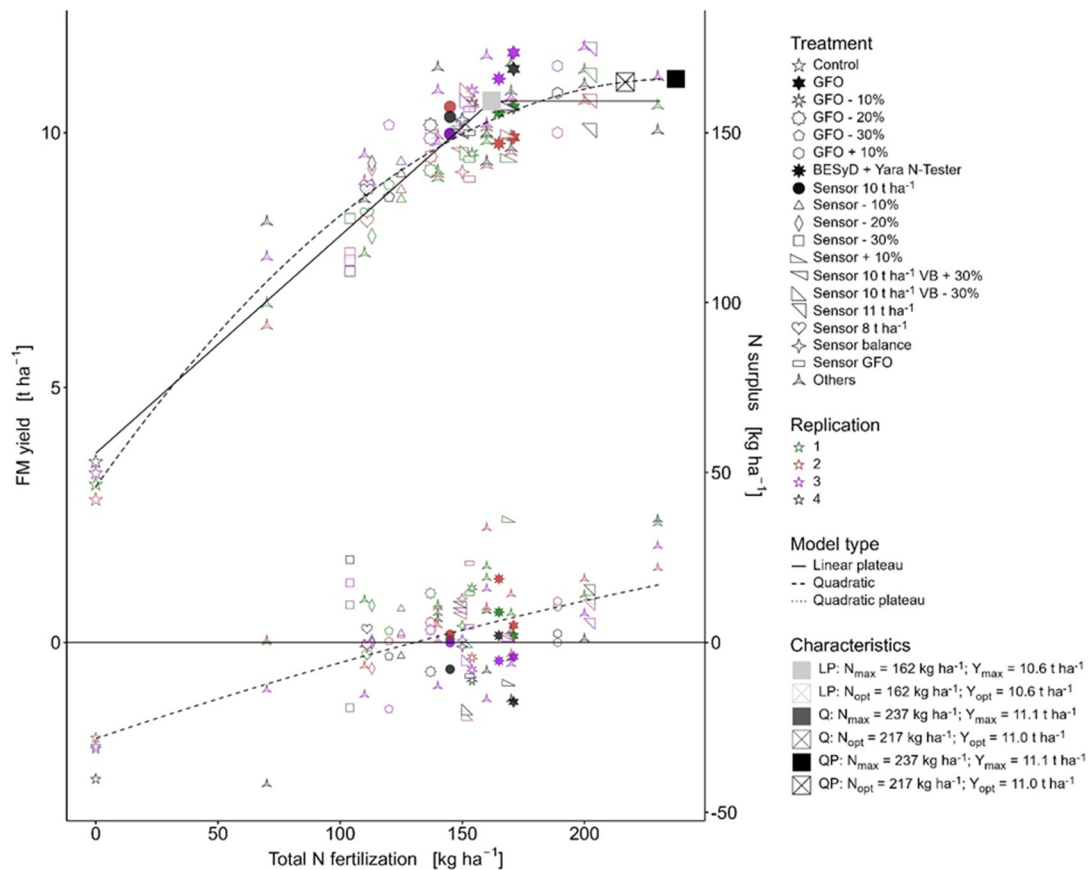


Figure 4. Relationships between N fertilization and yield and between N fertilization and N surplus for the year 2023 (Meridian). Yield is expressed as fresh matter, standardized to a dry matter content of 86%. The upper lines depict the relationship between N fertilization and yield, whereas the lower lines represent the relationship between N fertilization and N surplus.

In particular, varying assumptions about yield levels in the sensor-based treatments (N 25 and N 26) had a clear impact on the N application rates, which ranged from 111 to 202 kg ha⁻¹. N surpluses in 2023 were largely balanced, with the exception of extreme treatments. The unfertilized control plot (N 1) had a negative balance of −32 kg ha⁻¹, while the highest fertilized treatment (N 11) had a surplus of 30 kg ha⁻¹.

3.6. Two-Row Variety ‘Sandra’ in 2023

In 2023, the economic yield optima for the two-row barley variety Sandra were slightly lower than those for Meridian, with a theoretical optimal yield (Y_{opt}) of 9.7 t ha⁻¹ and an optimal N application (N_{opt}) of 193 kg ha⁻¹ (Appendix A Figure A3). The single-application strategy N 6 (160 kg ha⁻¹ applied at the first timing) performed worse in 2023 compared to previous years, resulting in a relatively high N surplus of 45 kg ha⁻¹ (Appendix A Table A3). Overall, N surpluses for Sandra were at a higher level compared to Meridian in the same year, reaching a maximum of 51 kg ha⁻¹ in the highest fertilized treatment (N 11). This can be attributed to the relatively low protein contents and N uptakes observed in Sandra this year. Both GFO (N 12) and Sensor 10 t ha⁻¹ (N 18) strategies largely exploited the yield potential of Sandra, with N applications slightly below the calculated N_{opt} . However, reduced N treatments for both GFO and Sensor resulted in significant decreases in yield, protein content, and N uptake.

Additional N inputs beyond N 12 (GFO) or N 18 (Sensor 10 t ha⁻¹) did not result in significant yield increases, while gradual reductions led to increasingly pronounced yield

losses. Higher N applications compared to N 12 and N 18 almost always resulted in higher protein contents.

3.7. Evaluation of the Regression Models

The quadratic function (Q-model) demonstrated the best fit quality across all parameters (MAE, RMSE, R^2) (Table 7). The quadratic-plateau model (QP-model) delivered similar results in terms of fit parameters and the calculated optima (N_{opt} and Y_{opt}). In contrast, the linear-plateau model (LP-model) showed a poorer fit to the observed data. The differences in N_{opt} values between the LP- and Q-/QP-models were sometimes greater than 50 kg ha⁻¹. The Q-model highlighted very small differences between Y_{max} and Y_{opt} , whereas the difference between N_{max} and N_{opt} was approximately 20 kg ha⁻¹. In all three years studied, the optimal and maximum yields (Y_{opt} and Y_{max}) of the six-row variety Meridian were consistently higher than those of the two-row variety Sandra. Regarding N optima (N_{max} and N_{opt}), the comparison varied: Sandra required higher values than Meridian in 2021 but lower values in 2022 and 2023.

Table 7. Evaluation of model performance for the regression functions across different years and varieties. N_{max} is the minimum N fertilizer needed to achieve the highest yield. Y_{max} is the peak yield, N_{opt} is the optimal N fertilizer for maximum economic return, and Y_{opt} is the yield corresponding to N_{opt} .

Group Name	Model Type	MAE	RMSE	R^2	N_{max}	Y_{max}	N_{opt}	Y_{opt}
Meridian 2021	LP	0.39	0.49	0.89	144.8	10.5	144.8	10.5
Meridian 2021	Q	0.37	0.45	0.91	187.5	10.6	173.3	10.5
Meridian 2021	QP	0.39	0.48	0.89	188.2	10.5	173.6	10.5
Meridian 2022	LP	0.39	0.52	0.89	161.9	11.4	161.9	11.4
Meridian 2022	Q	0.35	0.47	0.91	233.5	11.7	213.0	11.6
Meridian 2022	QP	0.35	0.47	0.91	235.0	11.7	214.2	11.6
Meridian 2023	LP	0.49	0.61	0.86	162.0	10.6	162.0	10.6
Meridian 2023	Q	0.46	0.58	0.87	237.5	11.0	216.7	10.9
Meridian 2023	QP	0.46	0.58	0.87	237.5	11.0	216.7	10.9
Sandra 2021	LP	0.33	0.43	0.91	156.1	9.9	156.1	9.9
Sandra 2021	Q	0.28	0.36	0.94	216.7	10.1	197.4	10.0
Sandra 2021	QP	0.29	0.36	0.94	217.4	10.1	197.9	10.0
Sandra 2022	LP	0.41	0.53	0.86	172.6	10.3	172.6	10.3
Sandra 2022	Q	0.36	0.46	0.90	231.9	10.4	208.8	10.4
Sandra 2022	QP	0.36	0.46	0.90	228.0	10.4	205.7	10.3
Sandra 2023	LP	0.28	0.36	0.92	149.6	9.5	149.6	9.5
Sandra 2023	Q	0.23	0.30	0.94	215.0	9.7	192.9	9.6
Sandra 2023	QP	0.23	0.30	0.94	213.0	9.7	191.3	9.6

There are also clear differences when comparing the model types for the calculated N surpluses at the corresponding N_{opt} ($N_{surplus_{opt}}$) and N_{max} ($N_{surplus_{max}}$) fertilizer rates (Appendix A Table A4). The LP-model demonstrated consistently lower N surplus values compared to the quadratic (Q-model) and quadratic-plateau (QP-model) across most scenarios (Appendix A Table A4). This observation applies to both $N_{surplus_{max}}$ and $N_{surplus_{opt}}$. For the six-row variety Meridian, the LP-model estimated minimal or even negative N surplus values at both N_{max} and N_{opt} . For example, in 2021 and 2022, the LP-model recorded $N_{surplus_{opt}}$ values of −21.3 kg ha⁻¹ and −24.8 kg ha⁻¹, respectively, while the Q-model and QP-model showed smaller reductions, such as −10.2 kg ha⁻¹ and −10.6 kg ha⁻¹, respectively. In 2023, the LP-model estimated a positive surplus of 5.7 kg ha⁻¹ for Meridian, significantly lower than the Q-model (14.9 kg ha⁻¹) and QP-model (14.8 kg ha⁻¹) at $N_{surplus_{opt}}$. For the two-row variety Sandra, the LP-model similarly showed consistently lower N surpluses compared to the Q and QP models. In 2021,

the LP-model recorded an $N_{surplus_{opt}}$ of 1.8 kg ha^{-1} , whereas the Q-model and QP-model estimated much higher values of 29.8 kg ha^{-1} and 30.0 kg ha^{-1} , respectively.

4. Discussion

4.1. Discussion of Methods

The conditions of the study field result in a low soil N mineralization potential, as demonstrated by analyses in field experiments [7,30]. The results presented in this paper also show low N mineralization from the soil N pool, which is reflected in the low grain yield and low N uptake in the unfertilized treatment (N 1). This means that the results obtained here regarding the suitability and performance of fertilization systems also apply to these conditions but cannot be transferred to farms with animal husbandry and long-term organic fertilization without further testing. The trial size was relatively small (0.9 ha) to ensure uniform conditions, in contrast to N fertilization experiments in agricultural practice, in which much larger and more heterogeneous arable fields are investigated [18]. In field experiments (such as the present one) with homogeneous soils, it can be determined how accurately a fertilization system determines the correct N fertilization rate for the expected yield. However, this does not prove that the same N fertilization system also performs well in situations with small-scale variations in soil properties and yield potential. The fundamental problem of uniform fertilization systems—overfertilization in low-yield zones and underfertilization in high-yield zones [35,36]—cannot be analyzed in experiments with homogeneous soils. This means that the potential of systems that apply fertilizer uniformly across the field (e.g., according to GFO) may be overestimated and that of site-specific, sensor-controlled systems underestimated. Nevertheless, the results obtained in the Roggenstein trial are relevant because they show that the tested GFO, BESyD, and sensor-based fertilizer systems are very well adapted to the site conditions and provide very good fertilizer recommendations.

With the revision of the GFO in 2020, calculating N fertilizer requirements became mandatory in Germany, whereby the amount determined according to the GFO must not be exceeded [27]. Even if sensor measurements indicate a higher N requirement, fertilization with sensors must comply with the GFO limit in agricultural practice. In this trial, various sensor methods were employed, such as treatment N 28 (sensor with GFO upper limit), which applies sensor-based fertilization but does not exceed the limit defined by the GFO. In other sensor-based treatments, this limit was not applied to test the systems independently. Besides the GFO fertilization system, the BESyD system, which is widely used in farming practice, particularly in eastern Germany with larger farms, was tested. A special feature of the BESyD system is its consideration of crop development and the N content of the biomass in the second and third applications for winter barley using a sensor measuring the plant stand reflectance (e.g., yara N tester) [32,37]. Also, with the BESyD application, the upper limit of fertilization according to GFO must not be exceeded. However, the N doses determined with BESyD are often considerably lower than according to the GFO [22].

For the sensor-based treatments (N18–N28) in this study, a handheld multispectral sensor was used in combination with fertilization algorithms that were derived and validated in other field trials [7]. In contrast to static methods such as GFO, the sensor-based approach enables real-time adjustments based on plant growth. While handheld sensors have limited practical applications, tractor-mounted sensors, satellites, and drones with multispectral or hyperspectral cameras offer scalable solutions for continuous, large-scale crop monitoring, enhancing N application accuracy over larger areas [38,39]. An essential prerequisite for the application of sensor-based systems for N fertilization, regardless of the specific technology, is the accurate estimation of the site-specific yield potential, which forms the basis for determining realistic target yields and corresponding N requirements.

Errors in estimating the site-specific yield potential can lead to suboptimal fertilization decisions (over- or underfertilization) that algorithms based on sensor systems cannot fully correct [18]. Even when using static fertilization systems such as GFO, the precise determination of the target plant yield (almost always as an average for the area, e.g., using a weighing bridge) is crucial for the accuracy of the fertilizer requirement calculation. Even better results could be achieved if the GFO were also applied with site-specific target yields, but this is not common practice at present due to the high effort involved. To identify the optimal yield potential, various sensor-based N treatments were implemented, each aligned with a specific target yield and corresponding N application rate: N 18 (Sensor 10 t ha⁻¹), N 25 (Sensor 11 t ha⁻¹), and N 26 (Sensor 8 t ha⁻¹).

4.2. Discussion of Results

The results demonstrate the reliable yield performance of the GFO fertilization system for both the multi-row winter barley variety (Meridian) and the two-row variety (Sandra) under the given trial conditions. The GFO fertilization system almost achieved the optimum yield (Y_{opt}), and the optimum N-fertilizer quantity (N_{opt}) was also well matched. The frequently expressed criticism of the GFO system for ecological reasons—overestimation of fertilizer requirements, resulting in N over-fertilization [25]—cannot be confirmed for the present trial with winter barley. N fertilization of the GFO treatments was slightly above N_{opt} only for Meridian in 2021, whereas for all other years, and for variety Sandra, it was below N_{opt} . Goulding [40] identified N fertilizer doses above the economic optimum as particularly susceptible to nitrate leaching. Yield losses compared to N_{opt} were quite low. Styczen et al. [41] observed significant reductions in crude protein contents in Denmark because of strong fertilizer regulations. Crude protein contents in our trial were on average 12.1%, and therefore in range with standard crude protein contents in winter barley. Rather, at least for the experimental conditions applied here, it can be concluded that the GFO system is very well-adjusted and enables high yields without leading to excessive N surpluses. Therefore, there is no need to correct the fertilization algorithm.

Quadratic regression models estimating the economic optimum showed that GFO performed close to the theoretical optimum. However, the LP model consistently recommends significantly lower N_{opt} , with differences of up to 55 kg ha⁻¹ for two-row barley and up to 43 kg ha⁻¹ for multi-row barley, depending on the year. The findings of this study highlight sensor-based fertilization systems [12,42,43] and BESyD as valuable alternatives to the established GFO strategy for N management. While the GFO remains a robust approach for achieving high yields and NUE, the sensor-based N 18 treatment performed comparably, achieving yields near the economic optimum and largely balanced N surpluses, demonstrating both environmental and agronomic benefits. Over the three-year period, GFO consistently outperformed BESyD and sensor-based systems in terms of NUE and N surplus reduction, particularly for the multi-row variety, Meridian. For instance, the sensor-based treatment Sensor 10 t ha⁻¹ achieved 92–94% of GFO's efficiency in certain years, while BESyD displayed even lower NUE values. The high NUE performance of GFO is further supported by its minimal or negative N surpluses, indicating a balanced N application approach.

An important aspect of the sensor-based approach is its flexibility. The N 18 (Sensor 10 t ha⁻¹) treatment, unrestricted by the GFO's N application ceiling, applied higher N rates in some cases and significantly lower rates in others. This dynamic adjustment highlights the potential of sensor-based systems to optimize NUE more precisely than GFO. In practical applications, however, GFO-compliant limits are legally binding, meaning that a sensor-based fertilization system operating within these limits (e.g., the N 28 treatment) could still lead to overall reductions in mineral N use while maintaining high yields.

The study also tested fine-tuning adjustments to sensor-based fertilization (e.g., N 19 to N 22), but these variations did not improve performance. These findings align with observations from previous research, which frequently reported that sensor-based fertilization systems lead to reduced N application rates, higher NUE, and lower N surpluses, but rarely to significant yield increases compared to uniform field-level fertilization or GFO recommendations [18,22,30].

Despite their promise, sensor-based systems are not without challenges. Their effectiveness depends on the accuracy of sensor algorithms, which must be calibrated to reflect site-specific and temporal variability in crop N demand. Furthermore, the legal and practical constraints of applying sensor-based systems under GFO limits warrant further investigation.

5. Conclusions and Outlook

The present fertilization trials evaluated various systems and their variations, demonstrating the high performance of both GFO and sensor-based fertilization strategies. This was evident in the high yields achieved (yields > 10 t ha⁻¹), the excellent NUE (up to 88%), and the low N surpluses (mostly balanced) observed under the controlled conditions of the trials. In contrast, N surpluses in agricultural practice in Germany remain significantly higher, ranging between 70 and 100 kg ha⁻¹ over the past decade. The consistent implementation of GFO and sensor-based fertilization in practice could lead to a substantial reduction in N surpluses without compromising yields. However, challenges remain, particularly in regions with intensive organic fertilization, where the highest N surpluses are observed. The trials conducted at the Roggenstein research station benefited from excellent soil and climatic conditions, achieving very high yields and NUE. It is essential to investigate how these systems perform under less favorable conditions, such as sandy soils in arid regions with pronounced early-summer droughts, which are becoming more common due to climate change. Further studies should also explore the long-term impact of integrating sensor-based systems with organic fertilization to address N surpluses in mixed farming systems. Additionally, scaling these systems for larger heterogeneous fields could offer new insights into their practical applications across diverse agricultural landscapes.

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Appendix A

Table A1. Mean temperature (°C) and precipitation (mm), research station Roggenstein.

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Year
2021													
Temperature $\bar{x}$	−0.6	2.6	4.1	6.4	10.4	18.4	17.6	16.4	14.8	8.4	2.8	2.3	8.6
Precipitation Σ	63	43	48	25	147	155	114	159	53	29	33	75	945
2022													
Temperature $\bar{x}$	1.4	3.9	4.5	7.6	15.1	18.7	19.5	19.1	13.0	12.5	5.5	1.6	10.2
Precipitation Σ	24	28	6	59	98	106	72	116	80	81	59	66	794
2023													
Temperature $\bar{x}$	2.6	2.5	6.1	7.3	12.9	18.5	19.7	19.2	16.9	12.0	5.3	3.2	9.9
Precipitation Σ	16	33	43	86	111	46	85	185	45	50	166	123	1005
1991–2020													
Temperature $\bar{x}$	−1.3	0	3.6	7.8	12.3	15.4	17.5	16.8	13.6	8.6	3.3	−0.1	8.1
Precipitation Σ	50	48	54	75	107	127	120	118	84	57	63	56	958

Table A2. Yields and N balances of variety Sandra in the year 2022.

	Treatment	N Fertilization [kg ha ^{−1}]	FM Yield [t ha ^{−1}]	Protein [%]	N Uptake [kg ha ^{−1}]	N Surplus [kg ha ^{−1}]	NUE [%]
N 1	0/0/0=0	0/0/0 = 0	3.6 ^m	8.2 ^l	40.7 ⁿ	−40.7 ^j	
N 2	40/30/0 = 70	40/30/0 = 70	7.0 ^l	8.4 ^l	81.8 ^m	−11.8 ⁱ	58.7 ^b
N 3	40/30/40 = 110	40/30/40 = 110	8.4 ^k	10.0 ^k	116.9 ^l	−6.9 ^{hi}	69.3 ^{ab}
N 4	40/60/40 = 140	40/60/40 = 140	9.3 ^{hij}	10.8 ^{hijk}	140.0 ^{ijk}	0.1 ^{ghi}	70.9 ^{ab}
N 5	70/30/40 = 140	70/30/40 = 140	9.4 ^{ghij}	10.9 ^{hijk}	141.2 ^{hijk}	−1.2 ^{ghi}	71.7 ^a
N 6	160/0/0 = 160	160/0/0 = 160	9.8 ^{abcdefghi}	10.8 ^{ijk}	145.9 ^{ghijk}	14.1 ^{cdefgh}	65.7 ^{ab}
N 7	70/90/0 = 160	70/90/0 = 160	10.0 ^{abcdefghi}	11.4 ^{ghij}	157.3 ^{efghi}	2.8 ^{ghi}	72.8 ^a
N 8	40/90/40 = 170	40/90/40 = 170	9.7 ^{defghij}	12.3 ^{defg}	164.0 ^{efgh}	6.0 ^{fghi}	72.5 ^a
N 9	70/60/40 = 170	70/60/40 = 170	10.1 ^{abcdefgh}	12.1 ^{efgh}	167.8 ^{defg}	2.2 ^{ghi}	74.8 ^a
N 10	70/90/40 = 200	70/90/40 = 200	10.5 ^{abcd}	13.0 ^{bcdef}	187.2 ^{abcd}	12.8 ^{cdefgh}	73.3 ^a
N 11	70/120/40 = 230	70/120/40 = 230	10.2 ^{abcdefg}	14.1 ^{abc}	198.9 ^{ab}	31.1 ^{abcde}	68.8 ^{ab}
N 12	GFO	80/52/40 = 172	10.3 ^{abcdef}	12.1 ^{efgh}	172.5 ^{cde}	−0.5 ^{ghi}	76.6 ^a
N 13	GFO − 10%	72/47/36 = 155	9.5 ^{fghij}	11.4 ^{ghij}	149.4 ^{fghij}	5.6 ^{fghi}	70.1 ^{ab}
N 14	GFO − 20%	64/42/32 = 138	9.2 ^{hijk}	10.3 ^{jk}	131.7 ^{jkl}	6.4 ^{fghi}	65.9 ^{ab}
N 15	GFO − 30%	56/36/28 = 120	8.9 ^{jk}	10.0 ^k	123.3 ^{kl}	−3.3 ^{ghi}	68.8 ^{ab}
N 16	GFO + 10%	88/57/44 = 189	10.0 ^{abcdefgh}	12.4 ^{defg}	171.1 ^{cdef}	17.9 ^{bcdefg}	69.0 ^{ab}
N 17	BESyD + Yara N-Tester	60/55/50 = 165	9.8 ^{bcdefghi}	11.7 ^{fghi}	158.8 ^{efghi}	6.2 ^{fghi}	71.5 ^a
N 18	Sensor 10 t ha ^{−1}	80/94/52 = 226	10.3 ^{abcdef}	13.4 ^{abcde}	191.4 ^{abc}	34.7 ^{abcd}	66.5 ^{ab}
N 19	Sensor − 10%	76/77/30 = 183	10.3 ^{abcdef}	12.1 ^{efgh}	172.8 ^{cde}	10.8 ^{defghi}	72.4 ^a
N 20	Sensor − 20%	72/64/13 = 149	9.9 ^{abcdefghi}	10.8 ^{hijk}	148.2 ^{fghij}	0.6 ^{ghi}	73.0 ^a
N 21	Sensor − 30%	68/53/7 = 128	9.1 ^{ijk}	9.8 ^k	124.3 ^{kl}	3.5 ^{ghi}	65.4 ^{ab}
N 22	Sensor + 10%	84/106/61 = 251	10.7 ^{ab}	14.2 ^{ab}	209.7 ^a	41.1 ^{ab}	67.8 ^{ab}
N 23	Sensor 10 t ha ^{−1} VB + 30%	104/92/37 = 233	10.6 ^{abc}	13.5 ^{abcd}	196.2 ^{ab}	36.1 ^{abc}	66.9 ^{ab}
N 24	Sensor 10 t ha ^{−1} VB − 30%	56/107/77 = 240	9.9 ^{abcdefghi}	14.5 ^a	197.5 ^{ab}	42.5 ^a	65.4 ^{ab}
N 25	Sensor 11 t ha ^{−1}	88/80/50 = 218	10.7 ^a	12.8 ^{cdef}	188.9 ^{abcd}	28.4 ^{abcdef}	68.4 ^{ab}
N 26	Sensor 8 t ha ^{−1}	64/62/46 = 172	9.6 ^{efghij}	12.0 ^{fghi}	158.7 ^{efghi}	13.1 ^{cdefgh}	68.4 ^{ab}
N 27	Sensor balance	80/92/17 = 189	10.4 ^{abcde}	12.3 ^{defg}	177.2 ^{bcde}	11.8 ^{cdefghi}	72.2 ^a
N 28	Sensor GFO	80/91/1 = 172	9.8 ^{cdefghi}	12.1 ^{efgh}	163.4 ^{efgh}	8.7 ^{efghi}	71.3 ^a

Letters following the values (e.g., “abcd”) indicate statistical groupings based on the post-hoc test.

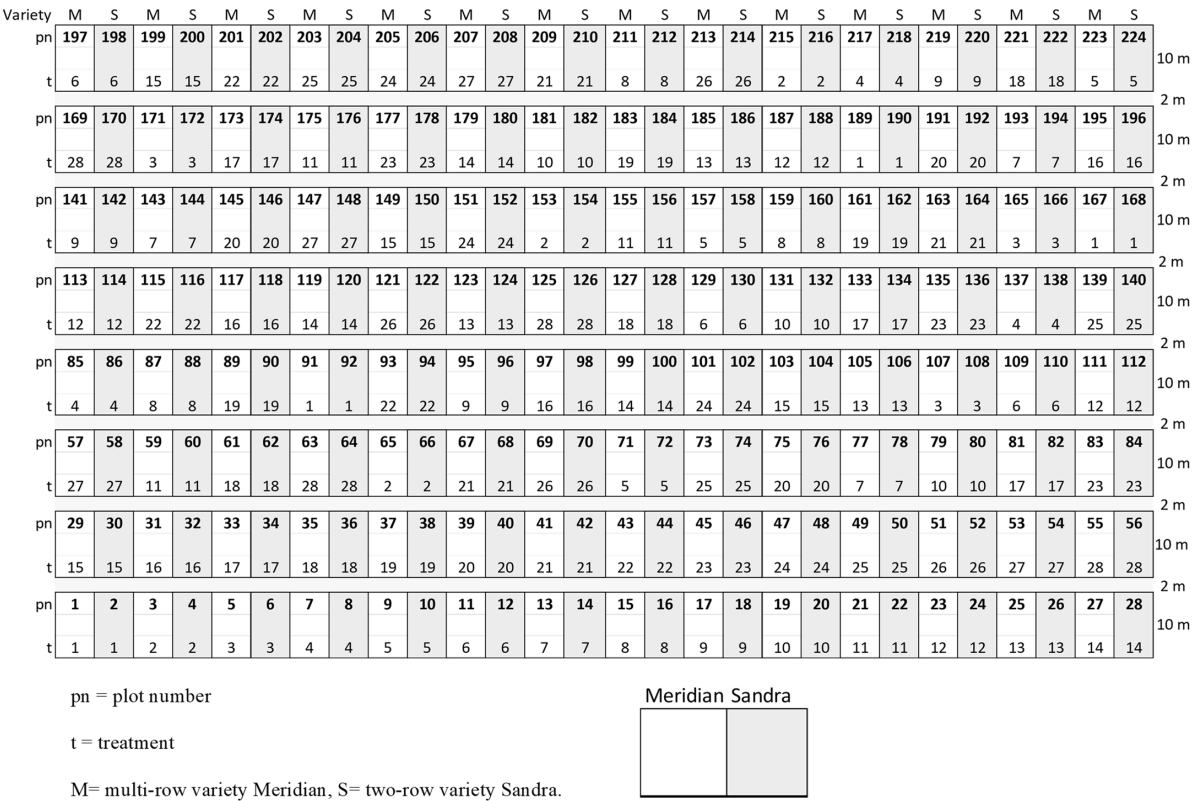


Figure A1. Design of the plot trial. The trials were consistent in each study year (2021–2023).

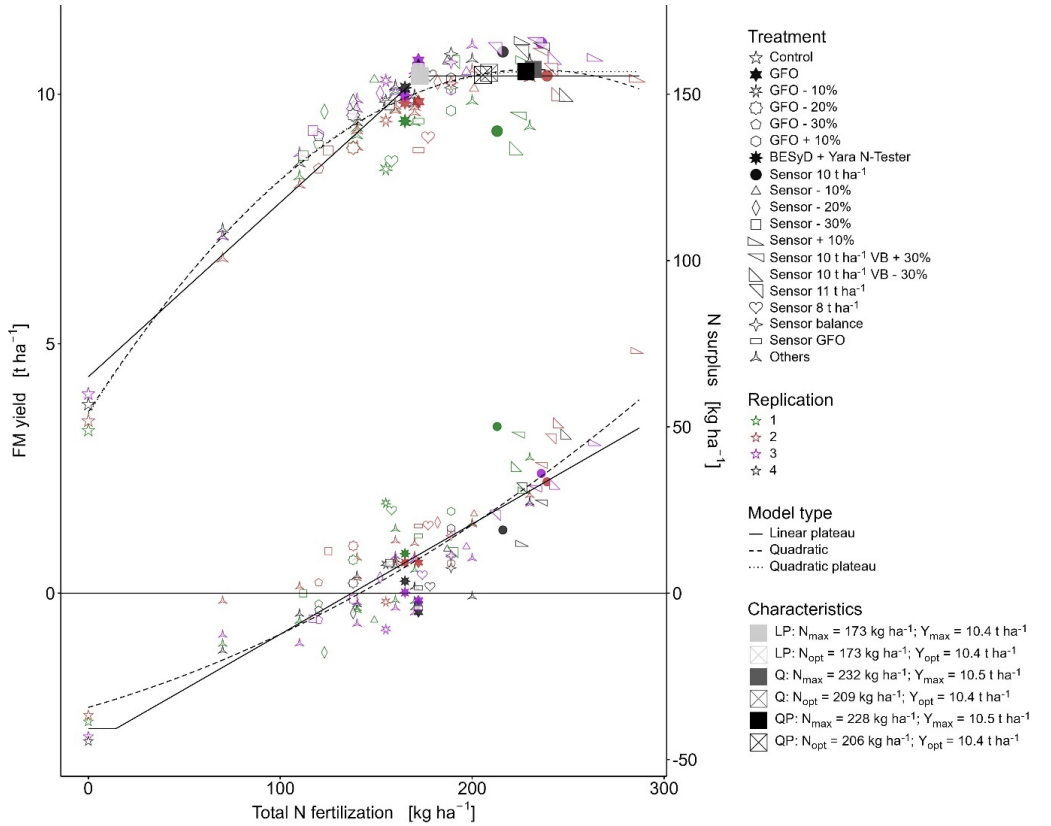


Figure A2. Relationships between N fertilization, yield, and nitrogen surplus for the year 2022 (Sandra). Yield is given in fresh matter with a dry matter content of 86%. The lines above describe the relationship between N fertilization and yield, while the lines below illustrate the relationship between N fertilization and N surplus.

Table A3. Yields and N balances of variety Sandra in the year 2023.

	Treatment	N Fertilization [kg ha ⁻¹]	FM Yield [t ha ⁻¹]	Protein [%]	N Uptake [kg ha ⁻¹]	N Surplus [kg ha ⁻¹]	NUE [%]
N 1	0/0/0=0	0/0/0 = 0	3.5 j	7.4 no	35.5 p	−35.5 l	
N 2	40/30/0 = 70	40/30/0 = 70	7.1 i	6.9 o	67.7 o	2.3 k	46.0 de
N 3	40/30/40 = 110	40/30/40 = 110	8.2 gh	8.5 lmn	96.4 mn	13.6 j	55.4 abcd
N 4	40/60/40 = 140	40/60/40 = 140	8.9 cdefg	9.7 ghijkl	119.7 hijkl	20.3 hij	60.1 ab
N 5	70/30/40 = 140	70/30/40 = 140	9.0 abcdef	9.2 ijklm	114.4 jkl	25.7 ghij	56.3 abcd
N 6	160/0/0 = 160	160/0/0 = 160	9.3 abcde	9.0 jklm	115.1 ijkl	44.9 abcde	49.7 bcde
N 7	70/90/0 = 160	70/90/0 = 160	9.4 abcd	10.0 fghijk	130.3 efghij	29.7 efghi	59.2 abc
N 8	40/90/40 = 170	40/90/40 = 170	9.0 bcdef	11.5 bc	142.8 bcdef	27.3 fghij	63.1 a
N 9	70/60/40 = 170	70/60/40 = 170	9.5 abcd	10.6 cdefgh	138.9 cdefg	31.1 defghi	60.8 ab
N 10	70/90/40 = 200	70/90/40 = 200	9.7 abc	11.4 bcd	153.3 bc	46.7 abc	58.9 abc
N 11	70/120/40 = 230	70/120/40 = 230	9.8 a	13.2 a	178.7 a	51.3 a	62.3 a
N 12	GFO	80/63/35 = 178	9.6 abcd	10.9 bcdefg	145.2 bcde	32.8 cdefghi	61.6 a
N 13	GFO − 10%	72/57/32 = 161	9.4 abcd	10.2 efghij	132.1 efghi	29.0 fghi	60.0 ab
N 14	GFO − 20%	64/50/28 = 142	8.9 cdefg	9.1 ijklm	111.6 klm	30.5 efghi	53.6 abcde
N 15	GFO − 30%	56/44/25 = 125	8.6 efgh	8.8 klm	104.3 lmn	20.7 hij	55.0 abcd
N 16	GFO + 10%	88/69/39 = 196	9.6 abcd	11.4 bcde	150.0 bcd	46.0 abcd	58.4 abc
N 17	BESyD + Yara N-Tester	65/50/50 = 165	9.3 abcde	10.2 efghij	130.9 efghij	34.1 bcdefgh	57.8 abc
N 18	Sensor 10 t ha ⁻¹	80/51/29 = 160	9.4 abcd	9.6 hijkl	125.4 fghijk	34.6 bcdefgh	56.2 abcd
N 19	Sensor − 10%	76/41/38 = 155	9.2 abcdef	9.6 hijkl	122.1 ghijk	32.9 cdefghi	55.9 abcd
N 20	Sensor − 20%	72/33/17 = 122	8.5 fgh	8.0 mno	93.8 n	28.2 fghi	47.8 cde
N 21	Sensor − 30%	68/24/1 = 93	7.8 hi	7.0 o	75.5 o	17.5 ij	43.0 e
N 22	Sensor + 10%	84/68/54 = 206	9.5 abcd	12.0 ab	157.8 b	48.2 ab	59.4 abc
N 23	Sensor 10 t ha ⁻¹ VB + 30%	104/40/18 = 162	9.4 abcd	9.5 hijkl	123.1 ghijk	38.9 abcdefg	54.1 abcde
N 24	Sensor 10 t ha ⁻¹ VB − 30%	56/67/52 = 175	9.3 abcde	11.0 bcdef	141.2 bcdef	33.9 bcdefgh	60.4 ab
N 25	Sensor 11 t ha ⁻¹	88/81/29 = 198	9.7 ab	11.6 bc	156.0 bc	42.1 abcdef	60.8 ab
N 26	Sensor 8 t ha ⁻¹	64/35/40 = 139	8.9 defg	9.5 hijkl	116.6 hijkl	22.4 hij	58.4 abc
N 27	Sensor balance	80/53/36 = 169	9.4 abcd	10.0 fghijk	129.9 efghij	39.1 abcdefg	55.9 abcd
N 28	Sensor GFO	80/56/32 = 168	9.5 abcd	10.2 defghi	133.8 defgh	34.2 bcdefgh	58.5 abc

Letters following the values (e.g., “abcd”) indicate statistical groupings based on the post-hoc test.

Table A4. N-balance: evaluation of the model quality of the quadratic, the quadratic-plateau, and the linear plateau function and resulting nitrogen surpluses when fertilizing according to N_{max} and N_{opt}.

Group Name	Model Type	Nsurplus _{max}	Nsurplus _{opt}
Meridian 2021	LP	−21.3	−21.3
Meridian 2021	Q	−3.5	−10.2
Meridian 2021	QP	−3.3	−10.3
Meridian 2022	LP	−24.8	−24.8
Meridian 2022	Q	−3.0	−10.6
Meridian 2022	QP	−2.4	−10.2
Meridian 2023	LP ¹	5.7	5.7
Meridian 2023	Q	18.0	14.9
Meridian 2023	QP ¹	17.9	14.8
Sandra 2021	LP	1.8	14.8
Sandra 2021	Q	37.7	29.8
Sandra 2021	QP	38.0	30.0
Sandra 2022	LP	11.7	11.7
Sandra 2022	Q	33.4	24.0
Sandra 2022	QP	31.7	22.8
Sandra 2023	LP ¹	30.0	30.0
Sandra 2023	Q	47.1	42.0
Sandra 2023	QP ¹	46.6	41.6

¹ N surplus values were determined using the parameters of the Q function, as the LP and QP functions could not be estimated for these data sets.

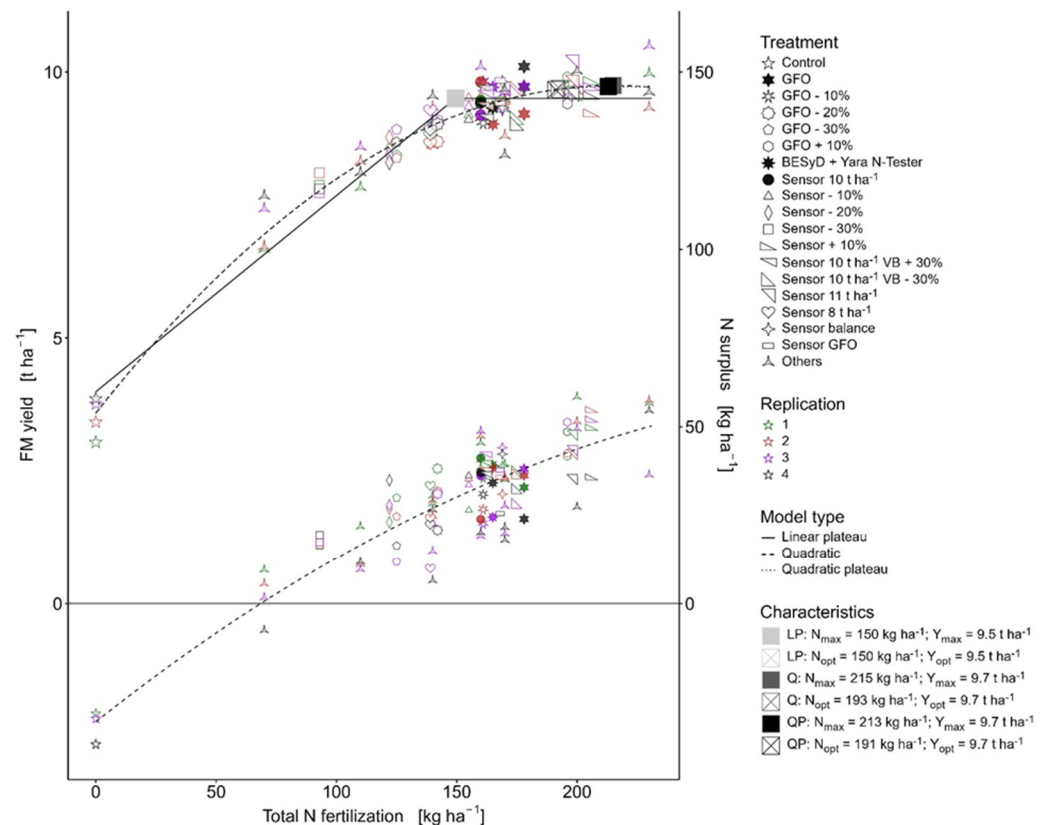


Figure A3. Relationships between N fertilization, yield, and nitrogen surplus for the year 2023 (Sandra) Yield is given in fresh matter with a dry matter content of 86%. The lines above describe the relationship between N fertilization and yield, while the lines below illustrate the relationship between N fertilization and N surplus.

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