

Article

Using the Haney Soil Test to Predict Nitrogen Requirements in Winter Wheat (*Triticum aestivum* L.)

Debankur Sanyal ¹  and Christopher Graham ^{2,*}

¹ Department of Environmental Science, College of Agriculture and Life Science, University of Arizona, Tucson, AZ 85721, USA; dsanyal@arizona.edu

² Department of Agronomy, Horticulture and Plant Science, South Dakota State University Extension West River Ag Center, Rapid City, SD 57703, USA

* Correspondence: christopher.graham@sdstate.edu

Abstract: Managing nitrogen (N) is one of the of the biggest challenges in achieving environmental and economic sustainability in the agroecosystem. As N fertilizer prices have increased significantly, farmers are considering a revised N recommendation to optimize crop production, while addressing negative environmental impacts of excess N in water bodies. This study analyzes the accuracy of using the Haney Soil Test (HST) to predict the N requirement (HSTNR) of winter wheat (*Triticum aestivum* L.) in a semi-arid climate. The accuracy of the HST to predict the economically optimum N rate (EONR) was dependent on in-season precipitation. In drought conditions, the HSTNR was 33 kg N ha⁻¹ lower on average than the EONR. Conversely, in wetter years, the HSTNR was 35 kg N ha⁻¹ higher than the EONR. Net return was approximately USD 19 ha⁻¹ lower than that with the EONR under both precipitation scenarios. Similar differences were found for protein content. There was a strong correlation between soil respiration and the soil health calculation, within the HST, and the difference between the net return on yield from the HSTNR and the EONR yield. These indicators may serve as useful metrics for formulating soil health-based N recommendations in winter wheat. However, in drought-prone areas, the HSTNR may significantly underpredict the EONR in many years due to an overestimation of N mineralization.

Keywords: nitrogen recommendation; economically optimum nitrogen rate (EONR); Haney soil test nitrogen requirement (HSTNR); protein content; soil health



Citation: Sanyal, D.; Graham, C. Using the Haney Soil Test to Predict Nitrogen Requirements in Winter Wheat (*Triticum aestivum* L.). *Nitrogen* **2022**, *3*, 376–386. <https://doi.org/10.3390/nitrogen3020024>

Academic Editor: Francisco M. Padilla

Received: 31 March 2022

Accepted: 6 June 2022

Published: 9 June 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Mitigating agricultural nitrogen (N) pollution is one of the major environmental concerns in the twenty-first century [1,2]. Additionally, as N fertilizer prices increase, growers are considering a revision of their current N recommendations to use an optimum N rate to enhance N use efficiency [3]. N fertilizer recommendations must bridge the shortfall between N provided by the soil and that required by the plant. To be most effective in improving current N recommendations, new methodologies need to accurately incorporate N provided by the soil and optimize economic profits. Some current N fertilizer recommendations incorporate economics to calculate an economically optimal N rate (EONR) by including the cost of fertilizer, the price of the commodity, and the response curve of the crop to N additions into a rate recommendation—independent of soil conditions [4,5].

Conversely, the Haney Soil Test (HST) was developed to include a suite of lab-based methods to predict the amount of N supplied to the crop from the soil, which could improve the accuracy of N fertilizer recommendations [6–8]. Traditional soil testing uses potassium chloride (KCl) to extract plant-available N from the soil, while the HST utilizes an extractant comprising organic acids designed to mimic the mechanisms used by plant roots to acquire nutrients at a solution pH similar to that observed in the soil [8]. Additionally, the HST approach assesses water-extractable organic carbon and organic N in the soil along

with soil respiration as a 1-day CO₂ evolution to estimate the microbial contribution to plant-available N [7,9,10].

Initial evaluations of the HST have primarily focused on the southern and central United States, with a particular focus on corn (*Zea mays* L.) production [11,12]. It is less clear how well the HST predicts N supply in more northern climates with small grains. Wheat (*Triticum aestivum* L.) differs from many other commodity crops in that protein content is measured along with yield. Because wheat protein is well correlated with N fertility, one concern from producers is that reducing N fertilizer will reduce protein, even if yields remain adequate. The objective of the current study was to compare two approaches in estimating the N requirement of wheat: an economics-based approach that does not consider soil N mineralization with the HST method that specifically measures soil N supply. Thus, our study evaluated the accuracy of the HST for N recommendations in winter wheat in a semi-arid climate where N limitations often reduce yield and protein content due to slow rates of mineralization.

2. Materials and Methods

2.1. Experimental Design and Setup

This study took place over three growing seasons (2017–2019) at three locations (Sturgis, Vivian and Wall) in western South Dakota. However, the field sites where experimental plots were laid out were different for different years, but had similar soil types and were managed similarly. Initial soil test information is given in Table 1. Two site-years (Vivian, 2018 and Sturgis, 2019) were omitted from the study due to unresponsiveness to N and flooding, respectively. As excess precipitation coupled with soil texture created an anaerobic condition, it impacted the N dynamics; therefore, the research dataset could not be used to maintain a logical interpretation of the overall research outcomes. Hard red winter wheat (HRW) was planted in the Fall on 25 cm row spacing with a no-till grain drill (Model 750, John Deere Co., Moline, IL, USA) at a population of 297 pure live seeds m⁻². In 2017, urea granules were broadcast at rates of 0, 45, 90, 134, 180 and 224 kg N ha⁻¹ at planting. In 2018 and 2019, urea was applied at the ‘Feekes 4’ growth stage of wheat, also known as ‘green-up’ when active tiller formation occurs [13]. These differences in N application dates are assumed to be negligible, as previous research suggests insignificant differences in wheat production due to early-season application timing in semi-arid climates [14].

Table 1. Initial values for soil organic matter (SOM), pH, electrical conductivity (EC), organic nitrogen released (ON release), total Haney available nitrogen (N), and soil health calculations (SHC) using Haney Soil Test protocols.

| Site | SOM % | pH | EC | ON Release | ON Release | Total Haney Available N | SHC 0–15 cm | SHC 15–60 cm |
|--------------|-------|-----|--------------------|-----------------------|------------|-------------------------|-------------|--------------|
| | | | | 0–15 cm | 15–60 cm | | | |
| | | | dS m ⁻¹ | Kg N ha ⁻¹ | | | | |
| Sturgis 2017 | 3.1 | 6.8 | 0.5 | 22 | - | 33 | 16.5 | - |
| Vivian 2017 | 4.4 | 7.3 | 0.8 | 7 | - | 33 | 5.5 | - |
| Wall 2017 | 1.8 | 6.4 | 0.3 | 21 | - | 63 | 11.9 | - |
| Sturgis 2018 | 3.6 | 6.1 | 0.3 | 30 | 25 | 67 | 15.4 | 10.7 |
| Wall 2018 | 2.7 | 6.9 | 1.0 | 50 | 27 | 92 | 15.6 | 7.9 |
| Vivian 2019 | 2.6 | 6.5 | 0.3 | 25 | 22 | 56 | 7.6 | 6.1 |
| Wall 2019 | 5.2 | 7.8 | 0.7 | 36 | 35 | 116 | 22.4 | 20.4 |

All sites used the same randomized complete block design with four replications. Plots consisted of six planted rows with a total area of 14 m². At harvest maturity, the front and back of each plot were trimmed back and only the middle four rows were harvested to avoid edge effects (total harvested area = 11.6 m²). Plots were harvested with a small plot combine (Wintersteiger, Salt Lake City, UT, USA), and yield was adjusted to 130 g H₂O kg-grain⁻¹. A subsample from each replication was taken for further protein analysis using whole grain near-infrared transmittance (Foss, Eden Prairie, MN, USA). Each protein

value was a composite of the measured light transmittance through the grain from ten sub-samples.

2.2. Soil Sampling and Haney N Recommendations

Soil samples for N analysis were gathered in early spring prior to urea application. Each sample consisted of a composite of 8–12 samples per plot. In 2017, N recommendations were based on a 0–15 cm sample only per HST recommendations. In 2018 and 2019, samples were taken from 0–15 cm and 15–60 cm depths to align more closely with standard N testing for wheat in South Dakota [15].

Haney soil test protocols were conducted at the USDA-ARS Grassland Soil and Water Research Laboratory on air-dried samples previously passed through a 2-mm sieve. All analyses in the HST protocol were based on previously described methods, which together were combined to create a N recommendation (HSTNR) based on estimated plant-available N [6–8,16–18]. The final HSTNR was determined using guidelines established by the South Dakota State Experiment Station [15]:

$$\text{Haney Soil Test Fertilizer Recommendation (HSTNR)} = 2.5 \times \text{YG} - \text{HSTN}$$

where YG is the yield goal in bu ac⁻¹ (where 1 bushel of wheat weighs 60 lbs.; therefore, 1 bu acre⁻¹ is equal to 67.25 kg ha⁻¹; we converted YG to kg ha⁻¹), '2.5' is a numeric factor, derived from N rate studies in South Dakota [15]; HSTN is the estimated HST plant-available N (kg ha⁻¹) from either a 0–15 cm or 0–60 cm soil sample.

To determine how well the HSTNR approximates the EONR, the YG was determined as the yield corresponding to the EONR of each site and year. The maximum return to N (MRTN) approach (the N rate that maximizes the economic return to N application) was used to determine the EONR and corresponding yield [4,19,20]. This approach predicts N rates based on replicated N response trials, independent of starting soil N values. However, the maximum grain accumulation is the same with or without accounting for soil N, hence the validity of using this value as the YG. Based on the similarity of fit statistics but significantly different join point, both a quadratic plateau and a linear plateau curve were used to fit the yield response for each N trial conducted (Table 2). The linear plateau model is defined by Equations (1) and (2):

$$Y = a + bX \text{ if } X < J \quad (1)$$

$$Y = P \text{ if } X \geq J \quad (2)$$

where Y is the yield of grain (kg ha⁻¹) and X is the N application rate (kg ha⁻¹); a (intercept), b (linear coefficient), J (join point, occurring at the intersection of the linear and the plateau lines), and P (plateau yield) are constants obtained by fitting the model to the data. The quadratic-plus-plateau model is defined by Equations (3) and (4):

$$Y = a + bX + cX^2 \text{ if } X < J \quad (3)$$

$$Y = P \text{ if } X \geq J \quad (4)$$

where Y is the yield of grain (kg ha⁻¹) and X is the N application rate (kg ha⁻¹); a (intercept), b (linear coefficient), c (quadratic coefficient), J (join point, occurring at the intersection of the quadratic and the plateau lines), and P (plateau yield) are constants obtained by fitting the model to the data [21]. The join point (J) is considered to be the point at which increasing the fertilizer rate is no longer effective at increasing yield. The plateau (P) is the value at which yield is maximized for the site.

Table 2. Regression statistics for the linear plateau (LP) and quadratic plateau (QP) models and plateau N rate and corresponding grain yield at the hinge point, where R^2 is the coefficient of determination, RMSE is root mean square error, and AIC is Akaike information criterion.

| Location | Year | LP R^2 | QP R^2 | LP RMSE | QP RMSE | LP AIC | QP AIC | LP Plateau N | QP Plateau N | LP Plateau Grain Yield | QP Plateau Grain Yield |
|----------|------|----------|----------|---------|---------|--------|--------|--------------|--------------|------------------------|------------------------|
| | | | | | | | | | | kg ha ⁻¹ | |
| Sturgis | 2017 | 0.81 | 0.80 | 241 | 248 | 339 | 341 | 134 | 204 | 2481 | 2523 |
| Sturgis | 2018 | 0.60 | 0.60 | 424 | 425 | 366 | 367 | 72 | 109 | 3481 | 3487 |
| Vivian | 2017 | 0.81 | 0.81 | 322 | 324 | 353 | 354 | 101 | 155 | 3531 | 3558 |
| Vivian | 2019 | 0.80 | 0.81 | 218 | 212 | 335 | 333 | 106 | 159 | 4304 | 4318 |
| Wall | 2017 | 0.50 | 0.51 | 495 | 495 | 375 | 374 | 95 | 120 | 3278 | 3267 |
| Wall | 2018 | 0.70 | 0.71 | 414 | 410 | 336 | 335 | 111 | 162 | 5446 | 5458 |
| Wall | 2019 | 0.87 | 0.89 | 402 | 372 | 364 | 360 | 101 | 136 | 4641 | 4624 |
| Average | | 0.73 | 0.73 | 359 | 355 | 353 | 352 | 103 | 149 | 3880 | 3891 |

Using the equation derived from fitting each model (i.e., site) (Figure 1), the net return can be calculated and plotted as the increase in yield multiplied by the grain price at a given N rate, minus the cost of that same amount of N. In this paper, we used a ratio of 5.55 for cost of fertilizer N: price of wheat grain (equivalent to USD 1.11 kg N⁻¹ (USD 0.50 lb N⁻¹) and USD 0.202 kg grain⁻¹ (USD 5.50 bu grain⁻¹)). The EONR is the N rate at which this return is maximized.

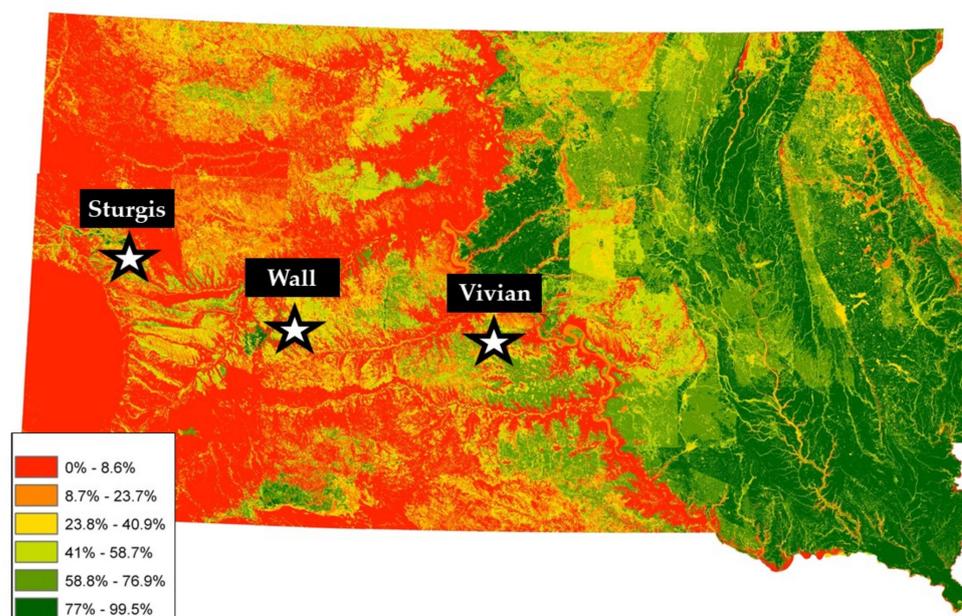


Figure 1. Study locations in South Dakota on a map depicting predicted cropland intensities by soil units in 2017 as proposed by the United States Department of Agriculture (USDA).

All statistical analyses were conducted in the R statistical package (R Core Development Team, 2014). Analysis examined both differences between the HSTNR and EONR using either the plant-available N estimated from 0–15 cm soil depth or as the total plant-available N from the 0–60 cm soil depth where available (2018 and 2019).

3. Results and Discussion

Precipitation during the three growing seasons strongly influenced the differences between HSTNR and MRTN (Figures 2 and 3). The 2017 growing season experienced severe drought, receiving 60–70% of the long-term average precipitation (<https://climate.sdstate.edu/>: accessed on 1 July 2021). During this year, the HSTNR was underestimated by an average of 35 kg ha⁻¹ for the quadratic plateau yield curve and 30 kg ha⁻¹ for the linear plateau estimation using a 0–15 cm soil sample. Conversely, in wetter years (2018 and 2019, <https://climate.sdstate.edu/>: accessed on 1 June 2021), the HSTNR was

on average 29 kg ha^{-1} and 41 kg ha^{-1} higher than the MRTN for the quadratic plateau and linear plateau curves, respectively (Table 3). It is important to note that the HST is a lab-based method that measures the CO_2 flux following soil rewetting to predict the potential availability of N to the plant through mineralization [11]. This is due in large part to the strong correlation between soil respiration and water-soluble organic N [7]. Further, soils in more arid environments tend to exhibit a lower CO_2 burst upon rewetting, which is presumed to be due to a higher frequency of drying/rewetting cycles and an increasing trend of available carbon depletion [22]. However, where the rewetting cycle is limited (e.g., drought), so too is respiration, which presumes a decreased rate of N mineralization and an overprediction of N available to the plant.

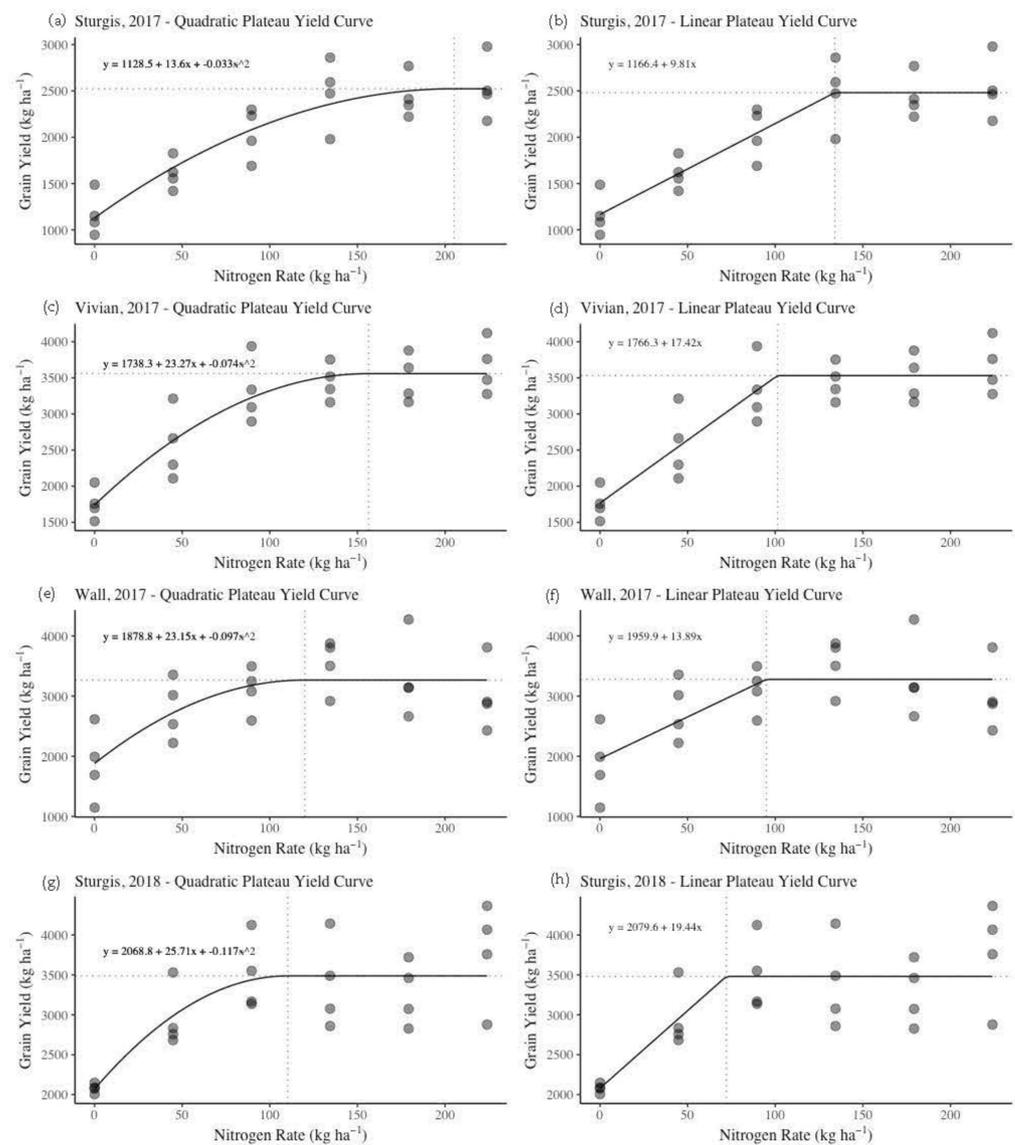


Figure 2. Cont.

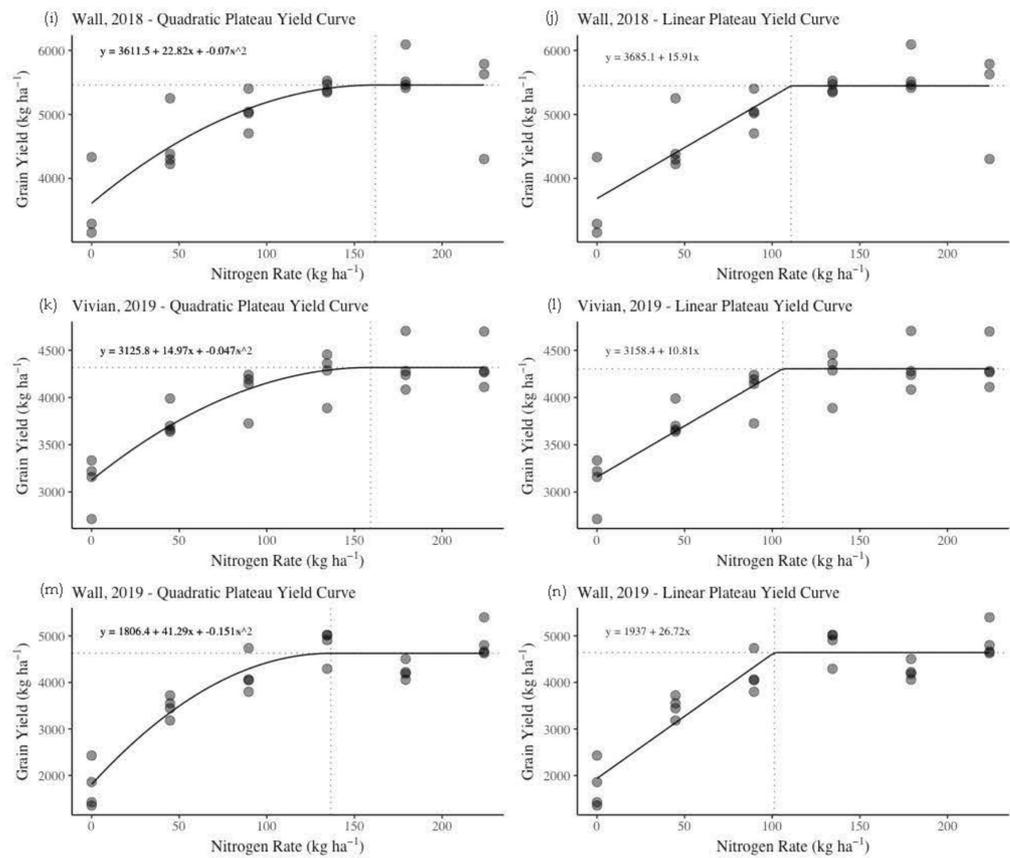


Figure 2. Graphical representation of quadratic plateau yield curve (left column) and linear plateau yield curve (right column) depicting relationships between grain yield (kg ha^{-1}) on the Y-axis and nitrogen rate (kg ha^{-1}) on the X-axis at the three study locations over three years between 2017–2019. The circles in each graph represent the yield measurements (replications) for each N rate. The dotted horizontal and vertical lines represent the joint point (N rate) for each site/year and plateau (grain yield). Equations in each graph represent Equations (1) and (3) depicting each site’s unique coefficients.

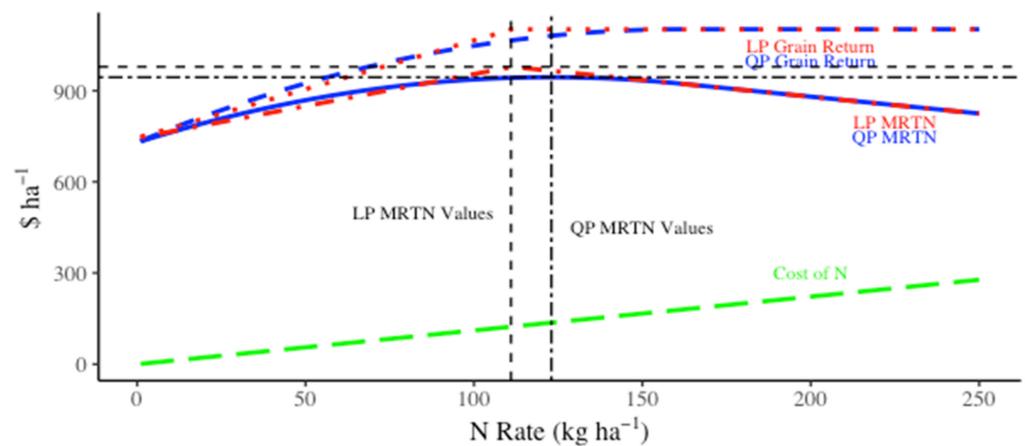


Figure 3. A graphical representation of the maximum return to N (MRTN) approach. The dotted red line and dashed blue line represent a typical linear plateau (LP) and quadratic plateau (QP) grain yield, respectively. The dot-dash red line and solid blue line represent the LP and QP MRTN. The MRTN curve

is derived from the difference between the respective yield curve and the cost of N fertilizer (represented as a green dashed line). The MRTN curve peaks, as represented by the dotted and dot-dash black lines, and then declines with increasing N rate due to the additional cost of N without additional return on grain. The corresponding peak values for each curve represent the most economically efficient N rate (i.e., MRTN).

Table 3. Estimated nitrogen rate (kg ha^{-1}) for the linear plateau (LP) and quadratic plateau (QP) models at the estimated Haney Soil Test (HST) and MRTN values.

| Site | Estimated Available N (0–15 cm) | Estimated Available N (0–60 cm) | HSTNR QP (0–15 cm) | HSTNR LP (0–15 cm) | HSTNR QP (0–60 cm) | HSTNR LP (0–60 cm) | QP MRTN | LP MRTN |
|--------------|---------------------------------|---------------------------------|--------------------|--------------------|--------------------|--------------------|---------|---------|
| | | | | | | | | |
| Sturgis 2017 | 37 | - | 58 | 66 | - | - | 122 | 134 |
| Vivian 2017 | 37 | - | 106 | 109 | - | - | 119 | 101 |
| Wall 2017 | 71 | - | 61 | 65 | - | - | 91 | 95 |
| Sturgis 2018 | 39 | 75 | 103 | 105 | 67 | 69 | 87 | 72 |
| Wall 2018 | 31 | 63 | 191 | 195 | 159 | 163 | 123 | 111 |
| Vivian 2019 | 62 | 130 | 110 | 117 | 42 | 49 | 101 | 106 |
| Wall 2019 | 27 | 41 | 163 | 166 | 149 | 152 | 118 | 101 |
| Average | | | 113 | 118 | 104 | 108 | 109 | 103 |

Moreover, using a 0–60 cm soil sample will always decrease the HSTNR over a 0–15 cm soil sample because it incorporates a larger soil volume and accounts for more soil N. This means that differences between the HSTNR and MRTN will likely be exacerbated during dry years but may be closer to the optimum in wetter years/climates. Overall, incorrect estimation of N mineralization can be attributed to its dependency on climatic variables, specifically rainfall [23–25].

Because the HSTNR varied by weather, wheat yields were similarly affected. During the dry 2017 growing season, the estimated HST yield was 276 kg ha^{-1} lower than the MRTN using a quadratic plateau curve and was 361 kg ha^{-1} lower when a linear plateau curve was used (Table 4). This was largely due to two of the three sites having HSTNR values significantly lower than the MRTN rate (Table 3). Ironically, the Vivian site's 2017 HSTNR was very close to the MRTN rate, but this was due to the low soil health score from the Haney test, which resulted in a low predicted N mineralization (hence, higher predicted HSTNR). During more conducive growing conditions, the HST yield using a linear plateau estimation generally fell beyond the curve join point, resulting in N being applied without returning an increase in grain yield. Using a quadratic plateau also resulted in yields beyond the MRTN yield but to a lesser extent, averaging 66 kg ha^{-1} more than the MRTN (Table 4).

Table 4. Estimated grain yield (kg ha^{-1}) for the linear plateau (LP) and quadratic plateau (QP) models at the estimated Haney soil test (HST) and MRTN values.

| Site | HST QP Yield (0–15 cm) | HST LP Yield (0–15 cm) | HST QP Yield (0–60 cm) | HST LP Yield (0–60 cm) | QP MRTN Yield | LP MRTN Yield |
|--------------|------------------------|------------------------|------------------------|------------------------|---------------|---------------|
| | | | | | | |
| Sturgis 2017 | 1806 | 1814 | - | - | 2294 | 2481 |
| Vivian 2017 | 3369 | 3531 | - | - | 3454 | 3531 |
| Wall 2017 | 2932 | 2863 | - | - | 3186 | 3278 |
| Sturgis 2018 | 3481 | 3481 | 3268 | 3421 | 3424 | 3481 |
| Wall 2018 | 5458 | 5456 | 5450 | 5456 | 5352 | 5446 |
| Vivian 2019 | 4204 | 4304 | 3672 | 3688 | 4158 | 4304 |
| Wall 2019 | 4625 | 4641 | 4625 | 4641 | 4572 | 4641 |
| Average | 3696 | 3727 | 4254 | 4302 | 3777 | 3880 |

From an economic perspective, the quadratic plateau estimation of the MRTN was always lower than the linear plateau model (Table 5). By definition, the MRTN value will always equal the plateau/join point, whereas with the quadratic plateau model, the MRTN value is generally significantly lower than the plateau join point. As a result, net return is more volatile in the linear plateau estimation and, in general, the net HSTN return was closer to the MRTN in the quadratic model. On average, the quadratic plateau model HSTN return was USD 21.27 ha⁻¹ less than the MRTN, whereas the linear plateau model HSTN was USD 45.34 less than the MRTN. These differences were roughly 97% and 93% of the MRTN for the quadratic plateau and linear plateau models, respectively (Table 5).

Table 5. Estimated returns (USD ha⁻¹) for the linear plateau (LP) and quadratic plateau (QP) model parameters at the estimated Haney soil test (HST) and MRTN values.

| Site | HSTN QP Return (0–15 cm) | HSTN LP Return (0–15 cm) | HSTN QP Return (0–60 cm) | HSTN LP Return (0–60 cm) | QP MRTN Return | LP MRTN Return |
|--------------|-----------------------------|--------------------------------|-----------------------------|--------------------------------|-------------------|-------------------|
| | USD ha ⁻¹ | | | | | |
| Sturgis 2017 | 300.38 | 293.14 | - | - | 328.01 | 352.42 |
| Vivian 2017 | 562.87 | 592.27 | - | - | 565.59 | 601.15 |
| Wall 2017 | 524.49 | 506.13 | - | - | 542.57 | 556.71 |
| Sturgis 2018 | 588.85 | 586.61 | 585.86 | 614.44 | 595.05 | 623.24 |
| Wall 2018 | 890.51 | 885.66 | 933.28 | 921.18 | 944.54 | 978.90 |
| Vivian 2019 | 727.03 | 739.54 | 695.04 | 690.6 | 727.84 | 751.75 |
| Wall 2019 | 753.26 | 768.8 | 753.22 | 768.76 | 792.66 | 825.37 |
| Average | 621.06 | 624.59 | 741.85 | 748.75 | 642.32 | 669.93 |

Components of the HST have been shown to be moderately correlated to the EONR of corn [12]. While the data are limited, our study supports this finding in wheat as a strong correlation was found in the difference between net return from the HSTN and the EONR return and either the soil health calculation (SHC) or the 1-day CO₂ burst (Figure 4). The SHC is a relative measure of soil health, which incorporates the 1-day CO₂ burst (hence autocorrelation) along with measures of soil organic C and N. While not used explicitly in the HSTNR, it appears to offer a potential guide for estimating N recommendations along with CO₂ evolution. The negative correlation in average or above average precipitation growing seasons suggests that a higher SHC or CO₂ burst value indicates that the HSTNR was a more accurate approximation of the EONR in this study. Additionally, the positive correlation in the drier year corroborates our inference that the HST is overestimating the N supplying abilities of the soil with the implicit assumption that a high SHC (i.e., a healthier soil) equates to more N mineralization and a lower HSTNR. Another report from South Dakota also recommended CO₂ burst (soil respiration) as a potential tool for N recommendation in corn [26,27]. Further study should be directed toward the influence of rainfall on the estimation of the HSTNR to ensure that the effect is directly related to rainfall and not confounded by other site-specific factors such as soil texture and land use history.

The flush of CO₂ is a measure of microbial biomass and well-correlated with N mineralization, but this is a simulated measure under idealized conditions [17]. Our results suggest that the efficacy of the ‘CO₂ burst’ would be maximized by incorporating as much in-season weather as possible. Hence, the later the soil test is taken into the growing season, the closer it is likely to approximate the EONR, which may necessitate a split N application in wheat; similar reports are available for corn [26–28].

Likewise, protein content is a critical measure of wheat quality and is positively correlated with timing and concentration of plant-available N [29,30]. Hence, protein content at the HSTNR was not significantly different between the quadratic plateau and linear plateau models (Table 6). During the drier 2017 growing season, the HSTNR estimated protein trended much lower, which could be problematic in years where protein discounts and premiums are in effect. Winter wheat typically requires a protein content of 12%. Where

nitrogen mineralization does not meet expectations (i.e., dry growing conditions), a protein shortfall is more likely. Therefore, a split application of N towards reproductive growth stages can provide additional benefit by improving wheat quality; a recent report indicated similar findings in wheat [14,31].

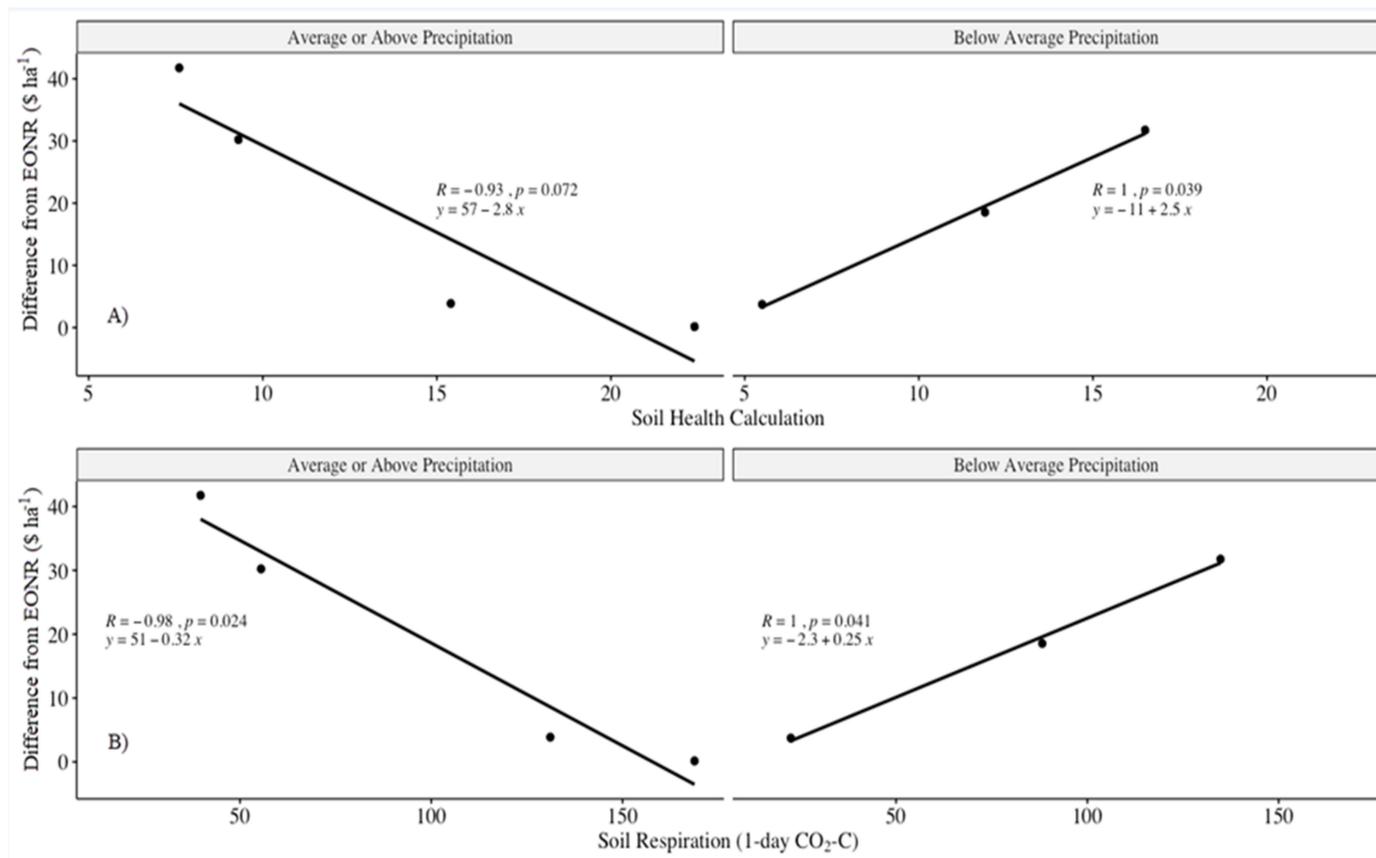


Figure 4. Regression of the difference in return from the HSTN and EONR (EONR – HSTN) on soil health calculation (A) and soil respiration (1-day CO₂ burst) (B) based on precipitation level.

Table 6. Estimated parameterized percent protein values based on the regression of applied fertilizer N on protein content for each site-year.

| Site-year | Regression Equation | R ² | HSTN QP | HSTN LP | HSTN QP | HSTN LP | EONR QP | EONR LP |
|--------------|----------------------|----------------|---------|---------|---------|---------|---------|---------|
| | | | 0–15 cm | | 0–60 cm | | | |
| Sturgis 2017 | $y = 0.016x + 11.26$ | 0.80 | 12.2 | 12.3 | - | - | 13.2 | 13.4 |
| Vivian 2017 | $y = 0.017x + 11.15$ | 0.78 | 13.0 | 13.0 | - | - | 13.2 | 12.9 |
| Wall 2017 | $y = 0.024x + 9.55$ | 0.87 | 11.0 | 11.1 | - | - | 11.7 | 11.8 |
| Sturgis 2018 | $y = 0.013x + 12.13$ | 0.61 | 13.5 | 13.5 | 13.0 | 13.0 | 13.3 | 13.1 |
| Wall 2018 | $y = 0.021x + 9.05$ | 0.92 | 13.1 | 13.1 | 12.4 | 12.5 | 11.6 | 11.4 |
| Vivian 2019 | $y = 0.010x + 11.99$ | 0.89 | 13.1 | 13.2 | 12.4 | 12.5 | 13.0 | 13.1 |
| Wall 2019 | $y = 0.011x + 10.49$ | 0.65 | 12.3 | 12.3 | 12.1 | 12.2 | 11.8 | 11.6 |
| Average | $y = 0.016x + 10.80$ | 0.79 | 12.6 | 12.7 | 12.5 | 12.5 | 12.5 | 12.4 |

4. Conclusions

Devising efficient N recommendations is difficult because historically it has been largely based on available N (generally nitrate N) in soil before/at the time of planting and does not consider N mineralization during crop growth. The HST attempts to account for N mineralization in its recommended N rate, which offers the prospect of reducing overall N

rates. The SHC and 1-day CO₂ burst provide useful indicators of the potential for the soil to supply N to the plant. However, in-season precipitation plays a critical role in the efficacy of this test, especially in dryland ecosystems, where plant-available water is primarily dependent on in-season precipitation, ultimately influencing N mineralization. In our study, the HST appeared to underestimate N mineralization under dry conditions. Since N mineralization is a microbially mediated process and water limitations severely reduce microbial metabolism and growth, drought effectively ‘penalized’ the soils with higher mineralization potential (i.e., ‘healthy soils’ with higher SOM, mineralizable N, soil protein content or microbial activities), where that potential was not realized in-season due to an assumed limitation on N mineralization during critical plant growth stages. In semi-arid climates, where adequate protein concentration is of concern, a 0–15 cm soil sample for HSTNR, rather than a 0–60 cm sample, likely approximates the EONR more closely with adequate protein in drought years or when N is applied as a single application. However, under wetter conditions, a 0–60 cm soil sample may perform similarly, particularly where a split application is utilized for protein content.

Designing N recommendations that incorporate N mineralization during crop growth is critical to improving N recommendations overall. Under dryland conditions in particular, attaining accuracy in estimating N mineralization is difficult. However, split N application provides an opportunity to incorporate more weather information during the wheat growing season to better optimize N use efficiency. Our study provides valuable information regarding the impact of in-season precipitation on HST-based N recommendation that necessitates a revision of the parameters used in the estimation of model parameters. In spite of other limitations in the scope of this study due to limited numbers of years and locations, it indicates an important knowledge gap to improve N recommendation. Future studies should incorporate more diverse locations in terms of soil characteristics, climate, etc. over multiple years to develop a more effective model for N recommendation to optimize N use efficiency.

Author Contributions: Conceptualization, C.G.; methodology, C.G.; formal analysis, C.G.; investigation, C.G. and D.S.; resources, C.G.; data curation, C.G. and D.S.; writing—original draft preparation, C.G.; writing—review and editing, D.S.; visualization, C.G. and D.S.; supervision, C.G.; project administration, C.G.; funding acquisition, C.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by a Conservation Innovation Grant funded by USDA-NRCS.

Institutional Review Board Statement: Not available.

Informed Consent Statement: Not available.

Data Availability Statement: Research data can be made available by contacting Christopher Graham at christopher.graham@sdstate.edu.

Acknowledgments: The authors acknowledge all technicians and research interns that helped in conducting field experiments successfully.

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

References

1. Gu, B.; van Grinsven, H.J.; Lam, S.K.; Oenema, O.; Sutton, M.A.; Mosier, A.; Chen, D. A credit system to solve agricultural nitrogen pollution. *Innovation* **2021**, *2*, 100079. [[CrossRef](#)] [[PubMed](#)]
2. Harindintwali, J.D.; Zhou, J.; Muhoza, B.; Wang, F.; Herzberger, A.; Yu, X. Integrated eco-strategies towards sustainable carbon and nitrogen cycling in agriculture. *J. Environ. Manag.* **2021**, *293*, 112856. [[CrossRef](#)] [[PubMed](#)]
3. Wan, X.; Wu, W.; Shah, F. Nitrogen fertilizer management for mitigating ammonia emission and increasing nitrogen use efficiencies by 15N stable isotopes in winter wheat. *Sci. Tot. Environ.* **2021**, *790*, 147587. [[CrossRef](#)] [[PubMed](#)]
4. Sawyer, J.; Nafziger, E.; Randall, G.; Bundy, L.; Rehm, G.; Joern, B. Concepts and rationale for regional nitrogen rate guidelines for corn. PM 2015. *Iowa State Univ. -Univ. Ext. Ames Iowa* **2006**, *28*.
5. Yost, M.A.; Pound, C.A.; Creech, J.E.; Cardon, G.E.; Pace, M.G.; Kitchen, B.; Nelson, M.; Russell, K. Nitrogen requirements of first-year small grains after alfalfa. *Soil Sci. Soc. Am. J.* **2021**, *85*, 1698–1709. [[CrossRef](#)]

6. Haney, R.L.; Hons, F.M.; Sanderson, M.A.; Franzluebbers, A.J. A rapid procedure for estimating nitrogen mineralization in manured soil. *Biol. Fert. Soils* **2001**, *33*, 100–104. [[CrossRef](#)]
7. Haney, R.; Brinton, W.; Evans, E. Estimating soil carbon, nitrogen, and phosphorus mineralization from short-term CO₂ respiration. *Commun. Soil Sci. Plant Anal.* **2008**, *39*, 2706–2720. [[CrossRef](#)]
8. Haney, R.L.; Haney, E.B.; Hossner, L.H.; Arnold, J.G. Modifications to the new soil extractant H3A-1: A multinutrient extractant. *Commun. Soil Sci. Plant Anal.* **2010**, *41*, 1513–1523. [[CrossRef](#)]
9. Haney, R.L.; Franzluebbers, A.J.; Jin, V.L.; Johnson, M.V.; Haney, E.B.; White, M.J.; Harmel, R.L. Soil organic C:N vs. water-extractable organic C:N. *Open J. Soil Sci.* **2012**, *2*, 269–274. [[CrossRef](#)]
10. Franzluebbers, A.J. Short-term C mineralization (aka the flush of CO₂) as an indicator of soil biological health. *CAB Reviews: Pers Agric. Vet. Sci. Nutr. Nat. Res.* **2018**, *13*, 14. [[CrossRef](#)]
11. Harmel, R.D.; Haney, R.L. Initial field evaluation of the agro-economic effects of determining nitrogen fertilizer rates with a recently-developed soil test methodology. *Open J. Soil Sci.* **2013**, *3*, 91–99. [[CrossRef](#)]
12. Yost, M.A.; Veum, K.S.; Kitchen, N.R.; Sawyer, J.E.; Camberato, J.J.; Carter, P.R.; Ferguson, R.B.; Fernández, F.G.; Franzen, D.W.; Laboski, C.A.; et al. Evaluation of the Haney Soil Health Tool for corn nitrogen recommendations across eight Midwest states. *J. Soil Water Conserv.* **2018**, *73*, 587–592. [[CrossRef](#)]
13. Large, E.C. Growth stages in cereals. *Plant Patholog.* **1954**, *3*, 128–129. [[CrossRef](#)]
14. Graham, C.J.; Stockton, M. Winter wheat response to fertilizer type and timing in western South Dakota. *Agron. J.* **2019**, *11*, 1433–1440. [[CrossRef](#)]
15. Gerwing, J.; Gelderman, R. *Fertilizer Recommendations Guide—EC 750*; United States Department of Agriculture: Brookings, SD, USA. Available online: <http://agbiopubs.sdstate.edu/articles/EC750.pdf>.
16. Haney, R.L.; Haney, E.B.; Smith, D.R.; White, M.J. Estimating potential nitrogen mineralisation using the Solvita soil respiration system. *Open J. Soil Sci.* **2015**, *5*, 319–323. [[CrossRef](#)]
17. Franzluebbers, A.J. Should soil testing services measure soil biological activity? *Agric. Environ. Lett.* **2016**, *1*, 150009. [[CrossRef](#)]
18. Singh, S.; Jagadamma, S.; Yoder, D.; Yin, X.; Walker, F. Agroecosystem management responses to Haney soil health test in the southeastern United States. *Soil Sci. Soc. Am. J.* **2020**, *84*, 1705–1721. [[CrossRef](#)]
19. Pan, W.L.; Kidwell, K.K.; McCracken, V.A.; Bolton, R.P.; Allen, M. Economically optimal wheat yield, protein and nitrogen use component responses to varying N supply and genotype. *Front. Plant Sci.* **2020**, *10*, 1790. [[CrossRef](#)]
20. Schwalbert, R.A.; Amado, T.J.C.; Reimche, G.B.; Gebert, F. Fine-tuning of wheat (*Triticum aestivum*, L.) variable nitrogen rate by combining crop sensing and management zones approaches in southern Brazil. *Precis. Agric.* **2019**, *20*, 56–77. [[CrossRef](#)]
21. Cerrato, M.E.; Blackmer, A.M. Comparison of Models for Describing Corn Yield Response to Nitrogen Fertilizer. *Agron. J.* **1990**, *82*, 132–143. [[CrossRef](#)]
22. Fierer, N.; Schimel, J.P. A proposed mechanism for the pulse in carbon dioxide production commonly observed following the rapid rewetting of a dry soil. *Soil Sci. Soc. Am. J.* **2003**, *67*, 798–805. [[CrossRef](#)]
23. Maithani, K.; Arunachalam, A.; Tripathi, R.S.; Pandey, H.N. Nitrogen mineralization as influenced by climate, soil and vegetation in a subtropical humid forest in northeast India. *For. Ecol. Manag.* **1998**, *109*, 91–101. [[CrossRef](#)]
24. Song, W.; Chen, S.; Zhou, Y.; Lin, G. Rainfall amount and timing jointly regulate the responses of soil nitrogen transformation processes to rainfall increase in an arid desert ecosystem. *Geoderma* **2020**, *364*, 114197. [[CrossRef](#)]
25. Zhang, X.Y.; Li, Q.W.; Gao, J.Q.; Hu, Y.H.; Song, M.H.; Yue, Y. Effects of rainfall amount and frequency on soil nitrogen mineralization in Zoigê alpine wetland. *Eur. J. Soil Biol.* **2020**, *97*, 103170. [[CrossRef](#)]
26. Bean, G.M.; Kitchen, N.R.; Veum, K.S.; Camberato, J.J.; Ferguson, R.B.; Fernandez, F.G.; Franzen, D.W.; Laboski, C.A.; Nafziger, E.D.; Sawyer, J.E.; et al. Relating four-day soil respiration to corn nitrogen fertilizer needs across 49 US Midwest fields. *Soil Sci. Soc. Am. J.* **2020**, *84*, 1195–1208. [[CrossRef](#)]
27. Sanyal, D.; Wolthuizen, J.; Bly, A. Influence of Nitrogen Fertilization Rate on Soil Respiration: A Study Using a Rapid Soil Respiration Assay. *Nitrogen* **2021**, *2*, 218. [[CrossRef](#)]
28. Liang, G.; Cai, A.; Wu, H.; Wu, X.; Houssou, A.A.; Ren, C.; Wang, Z.; Gao, L.; Wang, B.; Li, S.; et al. Soil biochemical parameters in the rhizosphere contribute more to changes in soil respiration and its components than those in the bulk soil under nitrogen application in croplands. *Plant Soil* **2019**, *435*, 111–125. [[CrossRef](#)]
29. Bly, A.; Woodard, H.J. Nitrogen management: Foliar nitrogen application timing influence on grain yield and protein concentration of hard red winter and spring wheat. *Agron. J.* **2003**, *95*, 335–338. [[CrossRef](#)]
30. Wilson, T.L.; Guttieri, M.J.; Nelson, N.O.; Fritz, A.; Tilley, M. Nitrogen and sulfur effects on hard winter wheat quality and asparagine concentration. *J. Cereal Sci.* **2020**, *93*, 102969. [[CrossRef](#)]
31. Xue, C.; Matros, A.; Mock, H.P.; Mühlhling, K.H. Protein composition and baking quality of wheat flour as affected by split nitrogen application. *Front. Plant Sci.* **2019**, *10*, 642. [[CrossRef](#)]