# Impact of Nitrogen Rate in Conventional and Organic Production Systems on Yield and Bread Baking Quality of Soft Red Winter Wheat

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**Abstract:** Soft red winter wheat (SRW) is characterized by high yield and relatively low protein content. In Kentucky, there is growing demand from local artisan bread bakers for regionally produced flour, requiring production of grain with increased protein content and/or strength. The objective of this two-year field experiment was to evaluate the effect of nitrogen (N) management on five cultivars of winter wheat on yield and bread baking quality traits of modern and landrace SRW cultivars (*Triticum aestivum* L.). All five cultivars were evaluated using two N application rates in conventional and organic production systems. All traits measured were significantly affected by the agricultural production system and N rate, although plant height and other quality traits varied by study year. Significantly higher yields were achieved in the conventional system at a relatively low N rate (67.2 kg ha$^{-1}$) in both study years (2017–2019) ($p < 0.01$). Results were variable by cultivar and a locally bred, high-yielding cultivar (Pembroke 2014) had the highest lactic acid solvent retention capacity score and thousand kernel weight of the cultivars evaluated. In addition, a landrace cultivar (Purple Straw) had the highest grain N and plant height. A French soft wheat, Soissons, had the highest sedimentation value and Pembroke 2016 achieved the highest yield. The findings from this study suggest the possibility of attaining a desirable grain with quality traits of SRW wheat that meets the needs of local bread wheat production in Kentucky through improving the optimization of cultivar selection, N management and specific considerations for conventional and organic systems.

**Keywords:** organic agriculture; grain nitrogen; lactic acid solvent retention capacity

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## 1. Introduction

Winter wheat (*Triticum aestivum* L.) is the third most economically important grain crop in Kentucky [1] and is considered the fourth most valuable cash crop in the state [2]. Soft red winter wheat (SRW) cultivars are the most commonly grown in the state and throughout the Southeastern US due to the region's moderate winters and warm humid conditions during grain filling. The environmental conditions during grain fill result in relatively low grain nitrogen (N) [3] and, historically, SRW has been used in low-protein baking applications such as cookies, cakes, pastries and crackers. Significant effort in plant breeding and agronomic research has facilitated SRW as a profitable and high-yielding enterprise in agronomic rotations in Kentucky and regionally, where it is typically marketed through mainstream grain marketing channels and utilized in the food processing industry [4]. Recent efforts in the local food movement have emphasized the opportunities for the use of regionally produced grains, including interest from artisan bakers to use bread flour from locally grown wheat [5]. This requires increasing grain N and/or gluten strength for regionally produced wheats to be suitable for bread baking purposes. However, such increases in quality for niche markets have been shown to provide price premiums for producers. For example, by increasing the content of the protein by 1.5%, farmers can get up to 10 percent more income on their wheat [6].

There are a myriad of climatic, genetic, crop management and post-harvest factors that influence traits in grain that affect baking quality [7,8]. Recent trends promoting wheat quality and stabilizing yield have emphasized three factors—improved genetics, better management and adaptations to the environment—that significantly affect wheat yield and quality [9]. However, among these factors, management may play a greater role than genetics or environment in crop yield and baking quality [10,11]

The use of appropriate N fertilizer rates is considered to be the primary means of increasing the yield, improving N utilization and, consequently, the N harvest index [12,13]. However, the ability for N fertilizer additions to overcome effects of humid climates on protein content is unknown and is likely cultivar-specific [14]. Additionally, the quality parameters may be differently affected by N input, as greater N application rates may degrade the quality of gluten in grain by disturbing the proportion of the high molecular weight glutenin subunits [15]. As such, both gluten quality and quantity are fundamental parameters that are correlated to produce quality bread wheat [16].

Conventional and organic production systems have also been shown to produce varying effects on wheat baking quality. Work to date has shown that conventional production may result in high yields, higher grain N, higher gluten content and greater loaf volume than organically grown wheat. However, wheat grown in organic systems may exhibit greater gluten strength, although at lower gluten content [17].

In addition to lower yields and gluten content, organic and low-input systems may have greater site and year-to-year variability in soil N content due to the reliance on slow-release, biologically based fertilizers and reliance on longer-term crop rotations than in conventional managed system. Greater weed pressure in organic systems may also contribute to this heterogeneity [18]. As such, cultivars grown in organic and conventional production systems may respond differentially due to underlying nutrient cycling processes, the nature of N fertilizer additions and other management practices.

A negative correlation between yield and grain N has been widely observed in wheat [19]. Identifying agronomic practices that produce wheat with acceptable bread baking quality traits will require selecting cultivars and management practices that optimize yield and baking quality traits suitable for the artisan baking market. As a first step in screening cultivars and management techniques for this emerging market, this study investigates the interactions of cultivar selection and N fertilizer management on yield and baking quality traits in conventional and organic production systems.

## 2. Materials and Methods

### *2.1. Experimental Design and Management*

This study was conducted at the University of Kentucky, Horticulture Research Farm, (37°58′28.7″ N, −84°32.04.4″ W) in Lexington, KY, USA. The soil type was Bluegrass-Maury silt loam (fine, mixed, active, mesic oxyaquic paleudalfs, ~2.2% soil organic matter). The experiments were carried out in the 2017–2018 (Y1) and 2018–2019 (Y2) growing seasons. Winter wheat (*Triticum aestivum* L.) was planted on 27 October 2017 and 24 October 2018. The experiment was a randomized complete block design with cropping system, wheat cultivar and fertilizer N application rate as treatment factors. Treatments were arranged within fields of each cropping system (one field conventional, one field organic) with four replications. Fields were rotated each year to reduce carry-over of treatment factors between years. The crop preceding the experiment in Year 1 was pumpkin and a buckwheat (*Fagopyrum esculentum*) cover crop in Year 2. Plots measuring 5.5 $m^2$ (4.6 m × 1.2 m) were planted with six crop rows.

Three soft red winter wheat (SRW) cultivars were evaluated, including modern cultivars selected for high yield potential, lodging resistance and good test weight (Pembroke 2014, Pembroke 2016, Truman), one French baguette wheat (Soissons) and one landrace selected for regional adaptation to the eastern US (Purple Straw). Purple Straw is one of the earliest varieties in the United States and, specifically, in southeastern states that is characterized by winter hardness [20]. All seeds were untreated and planted using a Hege six-row seed drill with rows spaced 18 cm apart.

Nitrogen sources were selected based on conventional and organic management specifications. Urea (46% N) was used for all applications in the conventional (CONV) system and a granular organic fertilizer comprised of feather meal, meat and bone meal, blood meal and sulfate of potash (10% N, NaturaSafe 10-2-8, Darling Ingredients, Inc. Irving, TX, USA) in the organic (ORG) system. Nitrogen rates in each system were 67.2 kg $ha^{-1}$ and 112.08 kg $ha^{-1}$ in the low (Low N) and high (High N) N rate treatments, respectively. In the CONV treatments, N fertilizer applications were split in equal amounts at Feekes 3 and Feekes 6 growth stages [21]. In the ORG treatments, 67.2 kg $ha^{-1}$ was applied pre-plant in both N treatment rates and an additional 44.8 kg $ha^{-1}$ was added at Feekes stage 6 to the 112.08 kg $ha^{-1}$ (High N) treatment. Nitrogen application rates reflect only fertilizer application, as no N credits from the preceding crop residue, soil organic matter or other N sources were included.

Weeds were controlled in the CONV treatments at Feekes 6 in early April each year by applying a broadleaf herbicide (Harmony XP, DuPont, Wilmington, DE, USA) with a concentration of 0.04 L per hectare according to the application rate [2]. Weeds were controlled in the ORG treatments by hand cultivation utilizing stirrup hoes and hand weeding on the same date as the herbicide application in the CONV. The ORG field was managed following the USDA National Organic Program rules but was not certified organic.

### 2.2. Flag Leaf Nitrogen Analysis

Plant nitrogen (N) analysis was conducted on samples of 10 flag leaves (FL) from each plot, randomly selected at anthesis ($_{An}$) and physiological maturity ($_{PM}$) stages during both study years. Samples were dried for 48 h at 60 °C. Nitrogen concentration in flag leaves was analyzed by combustion (LECO 828 Macro Analyzer, LECO Corporation, St. Joseph, MI, USA) at the Division of Regulatory Services at the University of Kentucky. The change in flag leaf nitrogen (ΔFLN) was calculated from the difference of leaf nitrogen content at anthesis ($FLN(_{An})$) and physiological maturity ($FLN(_{PM})$) stages, where

$$\Delta FLN = FLN(_{An}) - FLN(_{PM})$$

### 2.3. Agronomic Traits and Statistical Analysis

All growth performance and grain quality data were collected from the center four rows of each plot. The Feekes scale was used to record growth stages, including heading date (HD) and plant height (PH). Heading date (HD; Julian) was determined for each cultivar in each system when more than 50% of the spikes within a plot had emerged from the flag leaf sheath. Plant height (PH; cm) was measured from the soil surface to the top of the spike, excluding awns. Thousand kernel weight (TKW) was used in combination with grain yield to estimate kernel number. Yield was calculated from plot yields, adjusted to 13.5% moisture; this trait and test weight (kg $h^{-1}$) were measured using a grain analysis computer (2100b, Dickey-John, Auburn, IL, USA). The 1000 kernel weights were measured using an electronic seed counter (ESC-1, Agriculex Inc., Guelph, ON, Canada).

Grain quality traits included grain N, sedimentation value (SV) and lactic acid solvent retention capacity (SRC, %). Sedimentation value was measured after the method of Dick and Quick (1983). Grain protein and lactic acid SRC were measured from a 50 g subsample of grain from each plot using a near infrared reflectance (NIR) analyzer (DA 7250, Perten Instrument, Hagersten, Sweden). Grain protein was converted into grain N by dividing the protein content by 5.7.

Analysis of variance (ANOVA) was performed using a linear mixed model (PROC GLIMMIX, SAS 9.4, SAS Institute, Cary, NC, USA). Data were analyzed as a split plot, with cropping system by N rate treatment as the main plot factor and cultivar as the split-plot factor. Nitrogen rate, system, cultivar and all possible interactions were fixed effects and the interaction between system, rate and replicate was a random effect, according to the model below.

$$Y_{ijkl} = Rate_j + System_i + System_i * Rate_j + Cultivar_k + Rate_i * Cultivar_k + System_i * Cultivar_k + System_i * Rate_j * Cultivar_k + \omega_{ijl} + \varepsilon_{ijkl}$$

where:

$Y_{ijkl}$ = the observation in $i$th system in the $j$th rates in the $k$th cultivars and $l$th in the rep
μ = the overall mean
System, $i$ = 1, 2
Rate, $j$ = 1, 2
Cultivar, $k$ = 1, 2, 3, 4, 5
Rep, $l$ = 1, 2, 3, 4
$\omega_{ijl}$ = main plot random effect
$\varepsilon_{ijkl}$ = residual error

Mean comparison analysis for main effect and interaction were calculated using Tukey's test (HSD) at the 0.05 level. The study was analyzed separately by year to account for differences between crop rotation and year-to-year variation in weather conditions. ANOVA tables for plant physiological, agronomic and baking quality traits are presented in Appendix A.

## 3. Results

### 3.1. Plant Height

In Y1, plants in the CONV treatments were 6.25% taller than in the ORG (Table 1), when averaged across cultivars and N rates. This trend was repeated in Y2, although the effect was modified by the system interaction with N rate ($p$ = 0.0366). Plants in the CONV system grown with the High N rate were taller by 3.2% than conventionally grown plants grown at the lower N rate. There was no difference in plant height between N rates within the ORG treatments and plants were shorter than in the CONV treatments (Table 2).

**Table 1.** Main effect for plant height (cm), 1000 kernel weight (TKW, g), yield (kg ha$^{-1}$), grain nitrogen (Grain N, %) and lactic acid (SRC, %). (Same letters within each column and main effect are not significantly different based on Tukey's honest significant difference (HSD) test performed at α = 0.05).

| Main Effect | | Plant Height (cm) | | TKW (g) | | Yield (kg ha$^{-1}$) | | Grain N (%) | | SRC (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | | 2018 | 2019 | 2018 | 2019 | 2018 | 2019 | 2018 | 2019 | 2018 | 2019 |
| System | CONV | 88.87 a | 103.5 a | 34.47 b | 34.86 b | 5012.01 a | 5296.02 a | 2.09 a | 1.81 a | 91.06 b | 98.2 a |
| | ORG | 83.64 b | 97.23 b | 36.28 a | 36.22 a | 4717.6 a | 4364.59 b | 1.81 b | 1.75 b | 99.99 a | 98.3 a |
| | $p$-value | 0.0002 | <0.0001 | <0.0002 | 0.0096 | 0.1095 | <0.0001 | <0.0001 | 0.0340 | <0.0001 | 0.9636 |
| Rate | Low N | 85.09 | 99.5 b | 35.4 a | 35.5 a | 4857.8 a | 5218.01 a | 1.89 b | 1.04 a | 97.85 a | 98.7 a |
| | High N | 87.1 | 101.21 a | 35.3 a | 35.5 a | 4871.8 a | 4442.61 b | 2.02 a | 1.2 a | 93.19 b | 97.8 a |
| | $p$-value | 0.0615 | 0.0259 | 0.8545 | 0.8809 | 0.9387 | 0.0001 | <0.0001 | 0.1148 | 0.0011 | 0.1907 |
| Cultivar | Purple Straw | 111.35 a | 135.1 a | 37.02 b | 37.32 b | 4529.64 bc | 2889.78 d | 2.02 a | 2.01 a | 94.52 bc | 97.87 b |
| | Truman | 90.65 b | 103.35 b | 31.24 d | 31.62 d | 5110.59 ab | 5539.47 b | 1.88 b | 1.67 d | 98.27 ab | 97.74 b |
| | Pembroke 2016 | 77.39 c | 85.57 d | 36.93 b | 36.38 b | 5606.3 a | 6147.42 a | 1.93 b | 1.73 bc | 91.79 c | 94.21 c |
| | Pembroke 2014 | 90.65 c | 88.59 c | 38.38 a | 38.88 a | 5214.19 ab | 5300.06 b | 1.89 b | 1.72 cd | 98.59 a | 103.06 a |
| | Soissons | 74.29 c | 89.23 c | 33.29 c | 33.51 c | 3863.38 c | 4275.82 c | 2.01 a | 1.77 b | 94.44 bc | 98.58 b |
| | $p$-value | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |

**Table 2.** Plant height (cm), 1000 kernel weight (TKW, g) and sedimentation value (SV, mL) as affected by system and fertilizer N rate. (Same letters within each column are not significantly different based on Tukey's honest significant difference (HSD) test performed at α = 0.05).

| System | Rate | Plant Height (cm) | Mean TKW (g) | Mean SV (mL) |
|---|---|---|---|---|
| | | Y2 | Y1 | Y2 |
| CONV | High N | 105.1 a | 33.59 c | 7.3 a |
| CONV | Low N | 101.8 b | 35.34 b | 5.64 b |
| ORG | High N | 79.3 c | 37.09 a | 6.2 b |
| ORG | Low N | 79.1 c | 35.47 b | 6.1 b |

In Y2, all cultivars were significantly taller when grown in the CONV system compared to the ORG system (Figure 1a). In Y1, Purple Straw was significantly taller than other cultivars, irrespective of N rate. Within cultivars, plant height did not vary significantly by N rate (Figure 1b).

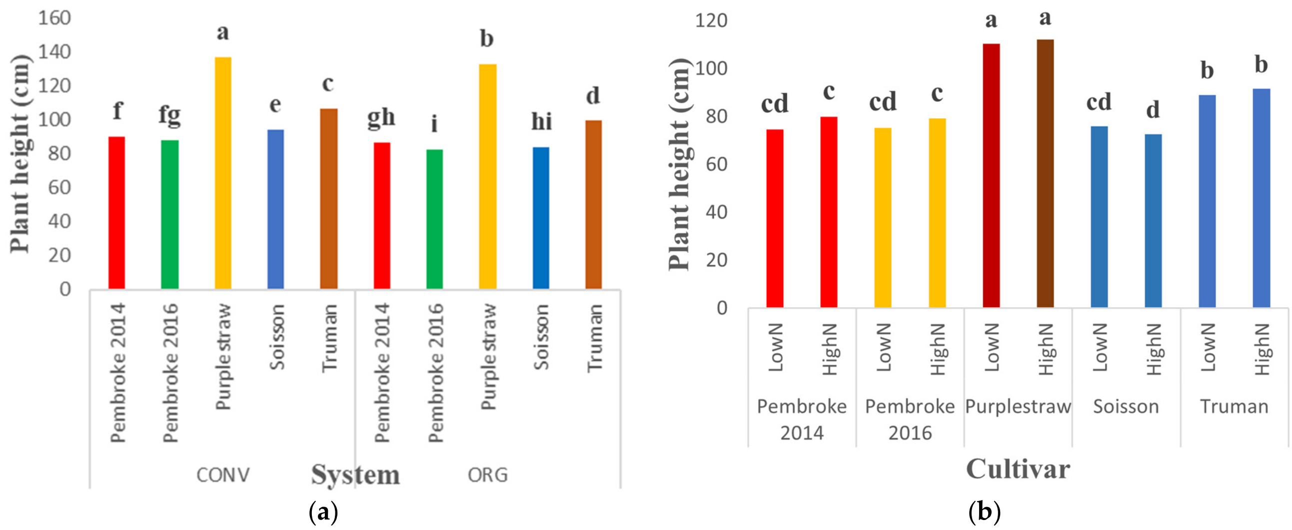


**Figure 1.** Plant height of soft red winter wheat cultivars as affected by production system in Y2 (**a**) ($p < 0.0001$) and by fertilizer nitrogen rate in Y1 (**b**) ($p = 0.0327$). Bars with the same letters within each figure are not significantly different based on Tukey's honest significant difference (HSD) test performed at α = 0.05.

### *3.2. Yield Traits*

In Y1, Pembroke 2016 in the CONV system had a significantly greater yield than Purple Straw and Soissons, while no statistical difference was observed among Pembroke 2016, Pembroke 2014 and Truman (Figure 2). Within the ORG system, yield did not vary among cultivars. When averaged across all other factors, Pembroke 2016 had the greatest yield in both years (Table 1).

In Y1, yield did not vary significantly by system (Table 1). Although yield did vary by N rate within production system ($p = 0.018$), yield did not differ between the High N treatments between systems (Table 3). The Low N ORG treatment had the lowest yield, although it did not differ significantly from the High N treatments in the CONV and ORG systems. In Y2, the Low N CONV treatment had greater yield than any other treatment combination ($p = 0.0029$).

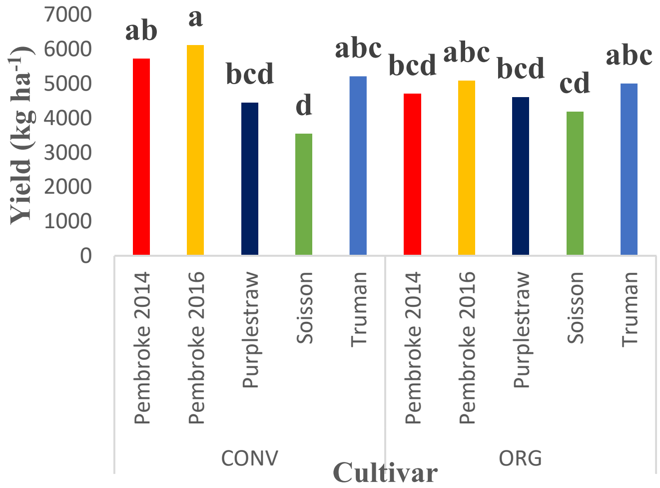


**Figure 2.** Soft red winter wheat yield (kg ha$^{-1}$) as affected by system and cultivar in Y1 ($p$ = 0.016). Bars with the same letters are not significantly different based on Tukey's honest significant difference (HSD) test performed at α = 0.05.

**Table 3.** The effect of production system and fertilizer N rate on grain yield and N content in both study years. (Same letters within each column are not significantly different based on Tukey's honest significant difference (HSD) test performed at α = 0.05).

| System | Rate | Yield (kg ha$^{-1}$) | | Grain N (%) | |
|---|---|---|---|---|---|
| | | Y1 | Y2 | Y1 | Y2 |
| CONV | High N | 4722.63 ab | 4643.70 b | 2.13 a | 1.88 a |
| CONV | Low N | 5301.39 a | 5948.30 a | 2.05 b | 1.74 b |
| ORG | High N | 5021.01 ab | 4241.50 b | 1.91 c | 1.72 b |
| ORG | Low N | 4414.25 b | 4488.30 b | 1.70 d | 1.78 ab |

In Y1, the High N ORG treatments had the greatest TKW (37.09 g) (Table 2). However, the High N CONV treatment had the lowest TKW (33.59 g). In Y2, TKW was 3.0% greater in the ORG system than that in the CONV system (Table 1).

### *3.3. Flag Leaf Nitrogen Analysis*

Fertilizer (N) rate had a significant effect on flag leaf nitrogen (FLN) content at both sample dates (anthesis and physiological maturity) in both years. In the CONV system, Truman had the greatest FLN mean within and across systems (Table 4), while other cultivars grown in the CONV system did not differ from each other. In the ORG system, Truman had significantly greater FLN than Pembroke 2016 and Purple Straw but did not differ from Pembroke 2014 and Soissons. System × rate × cultivar interactions were significant in Y1 at the anthesis sampling date ($p$ = 0.0380). When grown in the CONV system at the High N rate, Truman had greater FLN than most other treatment combinations, except for Pembroke 2016 grown at the High N rate in the CONV system and Truman grown at a low N rate in the CONV system (Table 5). Additionally, differences in FLN were not observed by N rate in any cultivar or system, except for Purple Straw grown in the CONV system.

Rate by system interactions also had a significant effect on FLN at both sampling dates in Y2. The High N CONV treatment had greater FLN than the Low N CONV treatment, but neither rate differed from the ORG treatments irrespective of N rate on the anthesis sampling date (Table 6). By the second date at physiological maturity, the High N CONV treatment had greater FLN than other treatment combinations.

**Table 4.** Flag leaf nitrogen (FLN) content as affected by cultivar and production system at anthesis (first sampling date) in Y1 ($p = 0.0166$). (Same letters within each column are not significantly different based on Tukey's honest significant difference (HSD) test performed at $\alpha = 0.05$).

| System | FLN (%) | | | | |
|---|---|---|---|---|---|
| | Cultivar | | | | |
| | Purple Straw | Truman | Pembroke 2016 | Pembroke 2014 | Soissons |
| CONV | 2.3093 bc | 2.9255 a | 2.4939 b | 2.2786 bc | 2.1634 bc |
| ORG | 1.3846 e | 1.9348 cd | 1.5349 e | 1.6152 de | 1.5909 de |

**Table 5.** Flag leaf nitrogen (FLN) by cultivar, as affected by system and rate at anthesis (first sampling date) in Y1 ($p = 0.038$). (Same letters within each column are not significantly different based on Tukey's honest significant difference (HSD) test performed at $\alpha = 0.05$).

| System | Rate | FLN (%) | | | | |
|---|---|---|---|---|---|---|
| | | Cultivar | | | | |
| | | Purple Straw | Truman | Pembroke 2016 | Pembroke 2014 | Soissons |
| CONV | High N | 2.6488 abcd | 3.0550 a | 2.7103 abc | 2.2998 bcde | 2.2793 bcde |
| CONV | Low N | 1.9698 efg | 2.7960 ab | 2.2775 bcde | 2.2575 bcde | 2.0475 def |
| ORG | High N | 1.4685 fgh | 2.1012 cde | 1.6828 efgh | 1.8472 efgh | 1.7650 efgh |
| ORG | Low N | 1.3007 h | 1.7683 efgh | 1.3870 gh | 1.3832 gh | 1.4167 fgh |

**Table 6.** Flag leaf nitrogen (FLN) content in each production system as affected by rate during anthesis (AN) and physiological maturity (PM) sampling points in Y2 ($p = 0.0064$). (Same letters within each column are not significantly different based on Tukey's honest significant difference (HSD) test performed at $\alpha = 0.05$).

| System | Rate | FLN (%) | |
|---|---|---|---|
| | | AN | PM |
| CONV | High N | 2.8488 a | 11.2309 a |
| CONV | Low N | 2.3558 b | 8.8384 b |
| ORG | High N | 2.5777 ab | 8.3375 b |
| ORG | Low N | 2.6653 ab | 8.4619 b |

Change in flag leaf nitrogen (ΔFLN) varied significantly by system in both years and by cultivar in Y1 (Table 7). In both study years, ΔFLN was greater in the ORG system than in the CONV system. The Truman cultivar had greater ΔFLN than all other cultivars, which did not differ significantly (Table 7).

### 3.4. Baking Quality Traits

In Y1, the Purple Straw and Soissons cultivars grown in the CONV system had the greatest mean grain N content (Figure 3a). In Y2, Purple Straw exceeded all other cultivars in grain N and gave the highest mean (2.01) (Table 1). In addition, Grain N in the High N treatment was numerically greater in all cultivars in Y1, although only significantly greater in the Pembroke 2014, Pembroke 2016 and Truman cultivars (Figure 3b).

**Table 7.** Flag leaf nitrogen (FLN, %) at anthesis (AN) and physiological maturity (PM), change in flag leaf nitrogen (Δ FLN, %) and sedimentation value (SV, mL). (Same letters within each column and main effect are not significantly different based on Tukey's honest significant difference (HSD) test performed at α = 0.05).

| Main Effect | FLN (%) | | | | ΔFLN (%) | | SV (mL) | |
|---|---|---|---|---|---|---|---|---|
| | Mean | | | | Mean | | Mean | |
| Year | 2018 | | 2019 | | 2018 | 2019 | 2018 | 2019 |
| | AN | PM | AN | PM | | | | |
| CONV | 2.4341 a | 1.9565 a | 2.6023 a | 1.6056 a | 0.47 b | 0.99 b | 7.86 a | 6.4 a |
| ORG | 1.6121 b | 0.9477 b | 2.6215 a | 1.3440 b | 0.66 a | 1.27 a | 6.58 b | 6.1 a |
| *p*-value | <0.0001 | <0.0001 | 0.8308 | 0.0030 | 0.0313 | 0.0137 | 0.0002 | 0.0640 |
| Low N | 1.8604 b | 1.2551 b | 2.5105 b | 1.3840 b | 0.6054 a | 1.1265 a | 7.00 a | 5.87 b |
| High N | 2.1858 a | 1.6492 a | 2.7133 a | 1.5655 a | 0.5366 a | 1.1478 a | 7.4 a | 6.75 a |
| *p*-value | 0.0009 | <0.0001 | 0.0399 | 0.0244 | 0.3869 | 0.8306 | 0.0874 | 0.0001 |
| Purple Straw | 1.8469 b | 1.5164 ab | 2.6733 a | 1.4103 a | 0.33 b | 1.2630 a | 8.68 a | 6.55 b |
| Truman | 2.4301 a | 1.5679 a | 2.7904 a | 1.4086 a | 0.86 a | 1.3818 a | 5.81 c | 4.48 c |
| Pembroke 2016 | 2.0144 b | 1.4878 ab | 2.5148 a | 1.4866 a | 0.52 b | 1.0282 a | 4.75 d | 5.13 c |
| Pembroke 2014 | 1.9469 b | 1.3859 ab | 2.4987 a | 1.5424 a | 0.56 b | 0.9563 a | 7.51 b | 6.38 b |
| Soissons | 1.8771 b | 1.3026 b | 2.5824 a | 1.5259 a | 0.57 b | 1.0565 a | 9.43 a | 9.02 a |
| *p*-value | <0.0001 | 0.0279 | 0.2389 | 0.2389 | <0.0001 | 0.1037 | <0.0001 | <0.0001 |

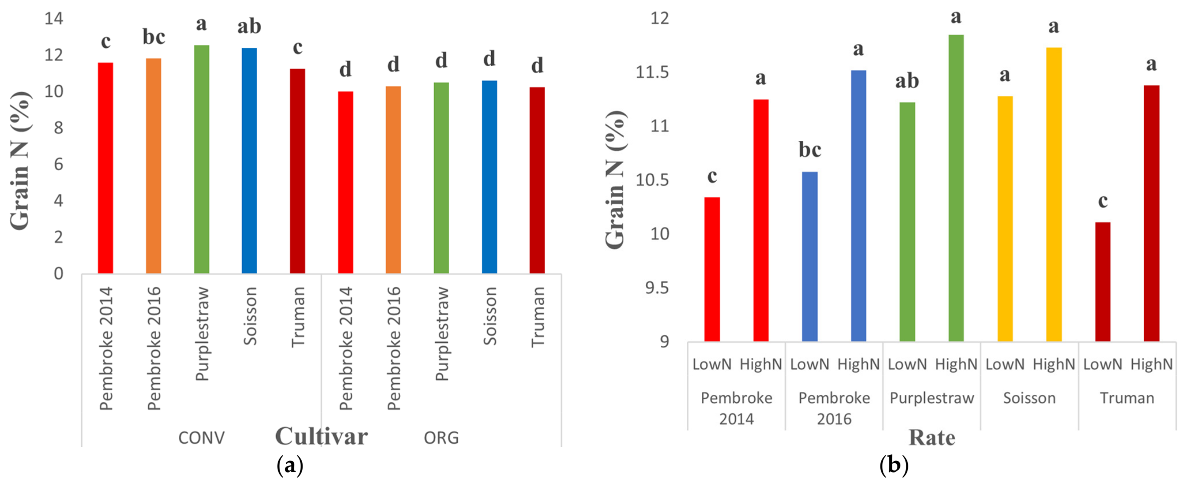


**Figure 3.** Grain N for study cultivars, as affected by system (**a**) and N rate (**b**) in Y1. Bars with the same letters within each figure are not significantly different based on Tukey's honest significant difference (HSD) test performed at α = 0.05.

The High N CONV treatments had significantly greater grain N% than any other system by N treatment combination for both years of study, although mean grain N% did not differ significantly from the Low N ORG treatments in Y2 (Table 3).

Cultivar had a significant effect in each year for predicted lactic SRC and SV. Although these main effects were modified in each year by various interactions for those two traits. Gluten strength, as measured by lactic acid SRC, was generally greater in Y1 in organically grown cultivars, although means did not significantly differ between the CONV and ORG systems in the Purple Straw and Soissons cultivars. Pembroke 2014 had the greatest mean SRC (104.9%) but was not significantly different from Truman grown in the ORG system (Figure 4a). In Y2, Pembroke 2014 also had the highest SRC (103.06%), while the lowest value was for Pembroke 2016 (94.21%, Table 1). SRC values were greater in the Low N treatments by 5%, on average (Table 1). In Y2, SRC was affected by the system interaction with N rate. The Low N CONV treatment had a greater SRC than High N CONV treatment.

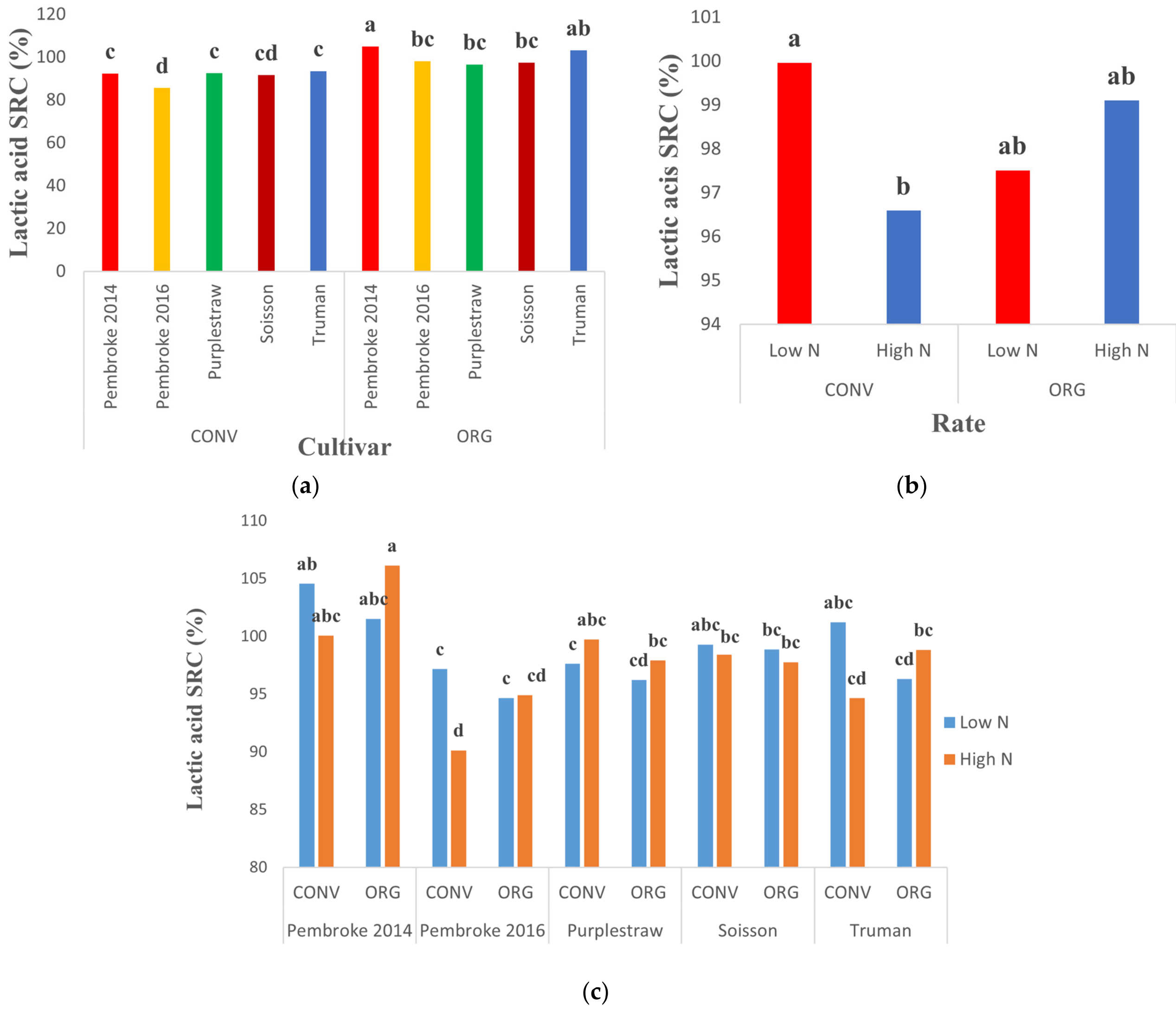


**Figure 4.** Gluten strength as measured by lactic acid solvent retention capacity (SRC) as affected by production system by cultivar in Y1(**a**), system by N fertilization rate in Y2 (**b**) and system by N fertilization rate by cultivar in Y2 (**c**). Bars with the same letters within each figure are not significantly different based on Tukey's honest significant difference (HSD) test performed at α = 0.05.

Treatments in the ORG system did not differ significantly from neither CONV N rate treatment, nor from one another (Figure 4b). However, in Y2, system by cultivar by rate interactions were significant for lactic acid SRC results (Figure 4c). Pembroke 2014 grown in the High N ORG treatment resulted in the highest SRC values, though it did not significantly differ from other Pembroke 2014 treatments, Low N CONV (Truman and Soissons) and High N CONV Purple Straw. Pembroke 2016 grown in the High N CONV treatment gave the lowest SRC values, though they did not significantly differ from several cultivars grown in the Low N ORG treatment (Truman, Purple Straw and Pembroke 2016), nor Pembroke grown in the High N ORG treatment or Truman grown in the High N CONV treatment.

The sedimentation value (SV) was 19.4% greater in the CONV system than in the ORG system in Y1. Soissons had greater mean SV than other cultivars in both years, although means were not significantly different from Purple Straw in Y1 (Table 7). Furthermore, CONV with High N had greater SV within and/or between systems in Y2 (Table 2). In the same year, when cultivars averaged across systems (Figure 5), there was no differences in SV in cultivars, regardless of what system they were grown in. Constantly, Soissons had the highest SV and Truman had the least, though, Truman did not significantly differ from Pembroke 2016 in either system, which, in turn, did not differ than Purple Straw in CONV system and Pembroke 2014 in the ORG system. Purple Straw and Pembroke 2014 followed Soissons in SV irrespective of production system.

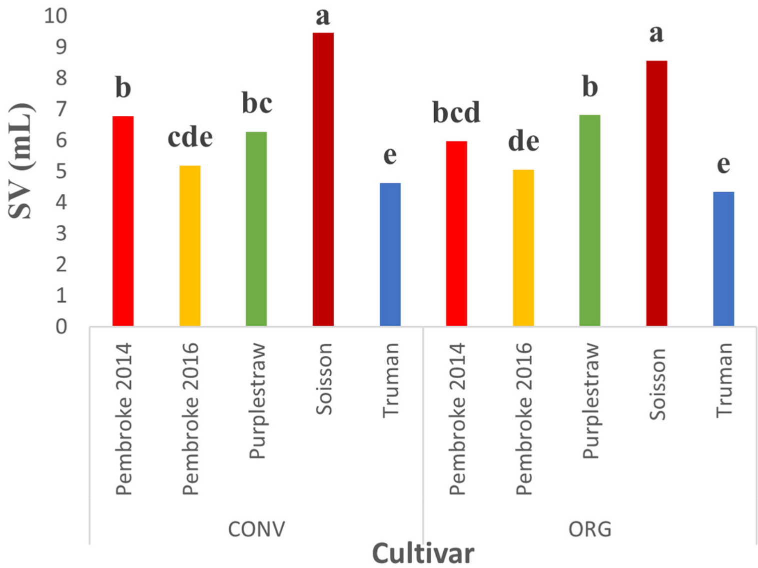


**Figure 5.** Sedimentation value (SV, mL) as affected by system and cultivar interaction in Y2 ($p$ = 0.034). Bars with the same letters within each figure are not significantly different based on Tukey's honest significant difference (HSD) test performed at $\alpha$ = 0.05.

## 4. Discussion

### 4.1. Agronomic Traits

In both study years, plant heights were significantly greater in the CONV treatments (Table 1), though, in Year 2, this effect was modified by cultivar and N rate interactions (Table 2). Conventionally managed systems are often characterized by use of high-yielding dwarf (HYD) cultivars and use of plant-available fertilizers. Not surprisingly, the HYD cultivars, which were bred, in part, to resist lodging under high N availability conditions, were significantly shorter than the landrace cultivar (Purple Straw). This trend was further pronounced at the High N rate. These results are consistent with other works comparing N fertilizer response in organic and conventional systems, which demonstrate greater plant height with use of mineral fertilizers compared to organic or biological fertilizers (e.g., manures) and with increasing N rate [22]. When averaged across systems, plant height varied by cultivar but did not vary between N rates within cultivars (Figure 1b). This may suggest that innate traits such as plant height may be more dependent upon genetic factors than management when N is not limited [23].

### 4.2. Yield Traits

In this study, the greatest yield was observed in the CONV system in the Low N treatment (Table 3). Lodging was not widely observed; thus, likely, it did not contribute to yield decrease with the High N treatments. However, a number of other factors may have contributed to greater yield with lower N application. Recent history of cover crop use in the study fields may have contributed additional N throughout the growing season and may have contributed to increased availability of soil N that was suitable for achieving high yield in the Low CONV treatment. In contrast, greater N input in the High N CONV treatment may have led to differences in N partitioning, in which the plant biomass may have reached maximum N concentration and additional partitioning to grain N, rather than overall yield. This phenomenon was observed in N rate application work by

Yue et al. [24], in which a higher input treatment resulted in lower winter wheat yield than a low input system.

The greatest yields were consistently observed in high-yield-potential cultivars, including Pembroke 2016 (Figure 2, Table 1), which has demonstrated consistently high yield potential, test weight and lodging resistance in previous cultivar trials in the region [25]. Yield differences within each cultivar did not vary based on which system they were grown in (CONV or ORG). However, in Y1, cultivars did demonstrate yield differences within the CONV system, while no yield differences were observed between cultivars in the ORG system (Figure 2). As weed pressure was nearly identical in each system, it is likely yield differences between cultivars grown in the CONV and ORG systems can be attributed to lower soil N availability in the ORG system. These results are consistent with those of by Przystalski et al. [26], who found yields were 33% lower in organic cropping systems than in conventional cropping system, when comparing winter wheat production systems in France, Switzerland and the United Kingdom. Similarly, Mäder et al. [27] attributed an average of 14% yield reduction in organic systems to a 71% reduction in soluble N input in organic systems in a long-term agroecosystem study.

Although yields were lower in the ORG system, TKW was significantly greater in the ORG system in the High N treatment in Y1 (Table 2). This may be due to N partitioning in the ORG system, which had fewer kernels per spike, likely due to limited N availability.

### *4.3. Flag Leaf Nitrogen Analysis*

The flag leaf is considered to be the principal contributor to wheat grain nitrogen due to its large protein content [28]. The cultivar had a consistent main effect on flag leaf nitrogen (FLN). Truman had greater FLN content in Y1 when grown in either CONV and ORG systems (though it did not differ from Pembroke 2014 or Soissons) (Table 4). Truman also exhibited greater ΔFLN than other cultivars in Y1 (Table 7). This may be attributed to Truman being a late maturing cultivar [29], resulting in higher flag leaf N content at anthesis. It may also be due to underlying differences in genetic background in this high-yielding, modern cultivar.

The fertilizer rate had limited effect on FLN in the ORG system, which did not differ from FLN levels in the CONV at the Low N rate in Y2. FLN was greater in the CONV system at the High N rate (Table 6). The lack of difference in the ORG treatments may be attributed to the slow-release nature of organic fertilizer. Mineralization of this biologically-based fertilizer is a function of soil microbial activity, which can be limited by low temperatures in the early growing season but may be extended as soils warm during anthesis stages [30].

The ORG system demonstrated greater ΔFLN than the CONV system in both years of study (Table 7). This may be a response to limited soil N availability and plant uptake during the grain-filling period in the ORG system, increasing remobilization of stored N to supply grain maturation. The CONV system may have experienced higher levels of soil N availability due to the use of mineral fertilizers, which resulted in less nitrogen remobilization [31].

### *4.4. Baking Quality Traits*

In general, protein content was greater in the High N treatments in each production system each year, except for in the ORG system in Y2 (Table 3). Similar to yield, wheat grain nitrogen has been shown to be dependent on the amount of soil mineral N available during plant growth and favorable growing conditions [32–35].

In addition, grain N varied between the CONV and ORG systems, as the same cultivars produced significantly different grain N when grown in different production systems. Grain from every cultivar used in this study had greater grain N content when grown in the CONV system (Figure 3a). Further, grain N content did not differ by cultivar in the ORG system, potentially indicating that soil N availability was limited at critical growth periods and cultivars did not have sufficient available N to express cultivar variability in N content as seen in the CONV system. These results are congruent with the findings of Le

Campion et al. [36], who reported cultivars grown in an organically managed system had reduced protein content from 10 to 22%, as compared to conventionally-grown cultivars.

When averaged across production systems and N rates, the landrace cultivar (Purple Straw) showed comparatively higher grain N than modern cultivars (Table 1). These results may be attributed to the genetic background, as well as timing and site N availability.

In addition to grain N content, gluten strength is a key attribute in evaluating bread baking quality. Lactic acid SRC and sedimentation value are two measures that predict gluten strength. It is commonly known that these two measurements are correlated [37], however, the results from this study are inconsistent between these two traits. Similar findings were reported by Duyvejonck, A.E., et al. [38], who found that no significant linear relation was observed between the SRC and SV when they studied the predictive value of the SRC tests for the cookie and bread-making quality of nineteen European commercial wheat flours.

Lactic acid SRC values below 85% are considered "weak" gluten soft varieties, whereas values ranging from 105 to 110% are considered "strong" gluten soft varieties [39]. Pembroke 2014 grown in ORG treatments in Y1 averaged 104.9% SRC, which indicated a strong gluten trait for this cultivar (Figure 4a). Conversely, Pembroke 2016 grown in CONV treatments for the same year averaged 85.5% SRC, which indicated a weak gluten trait. We attributed this increase to the genetic background of this cultivar. Van Sanford et al. [40] reported that Pembroke 2014 produced greater lactic acid SRC than the average values of 13 other cultivars and breeding lines. Unlike to lactic acid SRC, the SV values were greatest in the land race and bread wheat cultivars (Purple Straw and Soissons, respectively) (Table 7).

In Y2, Lactic acid SRC content did not differ between the N rate within the ORG treatments, nor did the ORG treatments vary from the CONV N rate treatments (Figure 4b). However, predicted lactic acid SRC content was significantly higher in the Low N CONV treatment than that in the High N CONV treatment. Several factors could be involved, such as better response to N level availability during production season and the favorable environmental conditions.

In contrast to the lactic acid SRC values, SV was greater in the CONV system in both study years (Tables 2 and 7). In the CONV system in Y2, the SV in the High N treatment exceeded all the other treatments. This may be due to the increase in grain N that recorded with the High N CONV treatments in the first year, because of its positive correlation. Ottman et al. [41] obtained increases in grain N, SV and wet gluten content with increasing N fertilizer rates and when using fertilizers with high N availability. Although their work utilized foliar nutrient applications, this indicates increasing N availability can be shown to increase both grain N and gluten strength. Similarly, Veselinka [42] reported greater SV and protein values in a high N treatment than those in a low N treatment (120 kg ha$^{-1}$ and 90 kg ha$^{-1}$, respectively).

The three-way interaction in lactic acid SRC in Y2 (Figure 4c) did not indicate strong differences among treatments means, although, numerically, Pembroke 2014 had a greater SRC value (106.12%). This demonstrates that cultivar played a key role in this interaction, rather than rate or system.

## 5. Conclusions

Nitrogen rate by production system interactions consistently influenced winter wheat yield. When averaged across cultivars, greater yields were observed in the CONV in crops grown with the Low N treatment. These results may indicate that reduced N rates combined with a conventional system may achieve adequate yield and avoid excessive N fertilizer usage. However, grain N—an important trait for bread baking quality—was increased, with the CONV High N treatment producing the highest grain N content in both years of the study. However, generalizable trends were not observed in this work, as the majority of other observed agronomic and grain quality traits varied by year, with inconsistent treatment interactions. Several consistent main effects were observed, including that cultivar had a constant and distinctive response across both study years. For example, Purple Straw had a higher plant height and grain N, due to its genetic characteristic as a landrace cultivar that may be adapted to lower soil N conditions. Pembroke 2014 had consistently greater lactic acid SRC and TKW, indicating greater potential gluten strength that may allow for the cultivar to be utilized on its own or in combination with a hard wheat for bread production. Similarly, Soissons, a modern soft bread wheat cultivar, had greater sedimentation value in both years of study, indicating that, despite relatively low protein content, it may make suitable bread. This work indicates that the addition of N applications, in combination with responsive cultivars, may allow for production of SRW suitable for bread baking. However, additional work is needed to optimize organic production systems and achieve consistent outcomes. Specifically, additional research to improve understanding of the interactions between soil N availability and plant response by cultivar and N management regime would inform improved production in organic farming systems. Additionally, research conducted in the context of region-specific crop rotations and that includes an economic analysis of the impacts and potential opportunities of production for local, artisan baking markets for both organic and conventional production systems is needed.

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## Appendix A

**Table A1.** ANOVA values for plant height (cm), 1000 kernel weight (TKW, g), yield (kg ha$^{-1}$), grain nitrogen (Grain N, %) and lactic acid (SRC, %). Values were considered significant at the $\alpha \leq 0.05$ level, with non-significant effects indicated by annotation as "ns".

| | | **Plant Height (cm)** | | **Yield (kg ha$^{-1}$)** | | **TKW (g)** | | **Grain N (%)** | | **SRC (%)** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Source of Variance** | **DF** | ***p*-Value** | | ***p*-Value** | | ***p*-Value** | | ***p*-Value** | | ***p*-Value** | |
| **Year** | | **2018** | **2019** | **2018** | **2019** | **2018** | **2019** | **2018** | **2019** | **2018** | **2019** |
| Rate | 1 | 0.0615ns | 0.0259 | 0.9387ns | 0.0001 | 0.8545ns | 0.8809ns | ≤0.0001 | 0.1148ns | 0.0011 | 0.1907ns |
| System | 1 | 0.0002 | ≤0.0001 | 0.1095ns | ≤0.0001 | ≤0.0001 | 0.0096 | ≤0.0001 | 0.0340 | ≤0.0001 | 0.9636ns |
| Cultivar | 4 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 |
| Rate × System | 1 | 0.8766ns | 0.0366 | 0.0018 | 0.0029 | 0.0004 | 0.2767ns | ≤0.0001 | 0.0014 | 0.6739ns | 0.0023 |
| Rate × Cultivar | 4 | 0.0327 | 0.2403 ns | 0.4789 ns | 0.0722 ns | 0.368 0 ns | 0.6515 ns | 0.0475 | 0.1894 ns | 0.1139 ns | 0.0587 ns |
| System × Cultivar | 4 | 0.2554 ns | ≤0.0001 | 0.0165 | 0.7852 ns | 0.0016 | 0.1884 ns | 0.0081 | 0.7450 ns | 0.0085 | 0.4196 ns |
| Rate × System × Cultivar | 4 | 0.4496 ns | 0.1651 ns | 0.7476 ns | 0.0714 ns | 0.3755 ns | 0.2198 ns | 0.3096 ns | 0.6436 ns | 0.0597 ns | 0.0125 |

**Table A2.** ANOVA values for flag leaf nitrogen (FLN, %) at anthesis (AN) and physiological maturity (PM), change in flag leaf nitrogen (ΔFLN, %) and sedimentation value (SV, mL). Values were considered significant of the $\alpha \leq 0.05$ level, with non-significant effects indicated by annotation as "ns".

| | | FLN (%) | | | | ΔFLN (%) | | SV (mL) | |
|---|---|---|---|---|---|---|---|---|---|
| Source of Variance | DF | *p*-Value | | | | *p*-Value | | *p*-Value | |
| Year | | 2018 | | 2019 | | 2018 | 2019 | 2018 | 2019 |
| | | AN | PM | AN | PM | | | | |
| Rate | 1 | 0.0009 | ≤0.0001 | 0.0399 | 0.0244 | 0.3869 ns | 0.8306 ns | 0.0874 ns | 0.0001 |
| System | 1 | ≤0.0001 | ≤0.0001 | 0.8308 ns | 0.0030 | 0.0313 | 0.0137 | 0.0002 | 0.0640 ns |
| Cultivar | 4 | ≤0.0001 | 0.0279 | 0.2389 ns | 0.8111 ns | ≤0.0001 | 0.3789 ns | ≤0.0001 | ≤0.0001 |
| Rate × System | 1 | 0.9624 ns | 0.3307 ns | 0.0064 | 0.0145 | 0.5350 ns | 0.1037 ns | 0.1995 ns | 0.0003 |
| Rate × Cultivar | 4 | 0.7879 ns | 0.7151 ns | 0.9688 ns | 0.3814 ns | 0.8125 ns | 0.4218 ns | 0.5763 ns | 0.2417 ns |
| System × Cultivar | 4 | 0.0166 | 0.2514 ns | 0.4151 ns | 0.5365 ns | 0.1867 ns | 0.6446 ns | 0.2030 ns | 0.0348 |
| System × Rate × Cultivar | 4 | 0.0380 | 0.7765 ns | 0.9419 ns | 0.9008 ns | 0.1147 ns | 0.9011 ns | 0.0614 ns | 0.9961 ns |

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