

## Article

# Post-Harvest Management Practices Impact on Light Penetration and Kernza Intermediate Wheatgrass Yield Components

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**Abstract:** Kernza intermediate wheatgrass (*Thinopyrum intermedium*) is the first commercially developed perennial grain crop in North America, with multiple environmental and economic benefits. One of the major challenges for adoption of this dual-use forage and grain crop is the decline in grain yield in subsequent harvest years. Post-harvest management practices (e.g., chopping, burning, chemical, and mechanical thinning) could reduce the intraspecific competition for light and maintain Kernza grain yields over time. We aimed to identify management practices that improve light penetration and propose a conceptual model to explain the mechanisms contributing to Kernza grain yield. We applied 10 management practices after the first Kernza grain harvest in a randomized complete block design experiment with three replications, at two different locations in Wisconsin, USA. Light penetration increased when post-harvest management practices were applied. Mechanical or chemical thinning had relatively lower lodging and increased yield components per row, but not per area due to a reduction in the number of productive rows. Threshed grain yield per area in the second year of Kernza was similar among the treatments despite the differences in vegetative biomass generated. Further research is needed to optimize management practices to maintain Kernza grain yield over time.

**Keywords:** perennial grain; dual-use; forage; grass; yield components

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## 1. Introduction

Improving environmental quality and resilience to climate change demands rethinking current agricultural systems. Annual monoculture croplands are a source of ecosystem disservices (e.g., soil erosion, soil carbon loss, nutrient leaching) mainly due to soil tillage and the lack of vegetation cover for prolonged periods [1]. These disservices have been mitigated in part with cover crops and conservation tillage, but the annual monoculture paradigm is the root of the problem [2,3]. Perennial grain crops may be part of the solution to the dual challenge of promoting human nutritional security while protecting environmental quality and resilience to climate change [4,5]. In particular, intermediate wheatgrass [*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey], marketed under the tradename Kernza [2], has garnered the interests of scientists, farmers, and consumers around the world due to its environmental and economic benefits [6]. However, much remains to be understood about the viability of Kernza as a crop and its potential fit into farming systems.

Although Kernza intermediate wheatgrass has the potential to simultaneously provide diverse ecosystem services, the decline in yield in subsequent years discourages its adoption. Kernza is the first commercially developed perennial grain crop in North America [6,7]. Its cultivation benefits farmers with high-value human-edible grain yield and forage produced in spring and fall, which provides an extra source of income [8]. Several

studies have been conducted to assess the forage nutritive value and functional properties of Kernza flour including dough elasticity [6,9]. The increase in demand for this grain crop is promising but the economic viability of this crop is limited by low initial grain yields that further decline over the life of the stand [10,11]. This trend demands research in agronomic management practices that increase and maintain grain yield over time, alongside breeding for increased grain yield [12,13].

One possible reason for Kernza grain yield decline over time is that light penetration is limited during fall. The presence of straw, biomass residues, or stubble in older stands reduces light quality at the crown, reducing reproductive tiller initiation or triggering the light avoidance syndrome [14,15]. Total biomass production generally remains constant or increases over years, while harvest index usually declines, suggesting a change in whole-plant resource allocation [11]. The penetration of light to the crown before the onset of vernalization is an important factor because more than 90% of the seed yield potential of perennial grasses is dependent on flowering initiation [16]. During the establishment year of Kernza intermediate wheatgrass light penetration is not a problem as there is little fall biomass shading growth points, but it becomes a major problem when plants regrow after the first harvest. Because increasing light penetration in the fall could increase the number of spikes the following year [17], management practices that increase light penetration to the canopy could maintain Kernza grain yields in the long term.

Several post-harvest management practices have proven to successfully maintain long-term yield in perennial grasses. Historically, field burning has been a residue management practice largely adopted in cool-season grass seed crops due to be an effective and economical method [18]. Removing stubble and straw with post-harvest burning changes the plant and soil environment, and promotes early vigorous new growth which results in higher seed yields in the subsequent crop year [19–22]. Nevertheless, public concern over air quality has necessitated the identification of alternative nonthermal residue management practices, such as residue removal, chopping on the straw, and thinning. In some perennial grasses, these practices are as effective as the fire in reducing the shade generated by the accumulation of straw to favor fertile tiller production [17,19,22–25]. However, these management practices not only modify the light penetration but also reduce aboveground biomass, disturb the root zone, or destroy rhizomes by mechanical tillage, reducing the accumulation of reserves and limiting the subsequent tiller development [10,11,26].

While post-harvest management practices could increase tiller fertility through increasing light penetration, could reduce other yield components, and compromise the actual grain yield. The components of potential Kernza grain yield, as in most cool-season grass species, include (i) number of plants/area, (ii) number of tillers/plant, (iii) number of spikes/tiller, and (iv) spike weight [16]. Both chemical and mechanical thinning reduce the number of plants/area because rows are removed to open the row spacing [10,24,27]. Furthermore, the number of tillers/plant could decrease with burning or mechanical tillage [11,19,26], or when aboveground biomass is reduced by burning, chopping, or mechanical/chemical thinning [10,19,20]. Finally, the actual Kernza grain yield is limited by the occurrence of lodging, which reduces tiller fertilization and the proportion of harvestable spikes [14,22,27–30]. This means that those post-harvest management practices that reduce lodging achieve actual grain yield similar to potential grain yield [14,29,30]. Therefore, our objectives were to (1) test whether increasing light penetration in the fall increase Kernza spike number and seed yield in the second year of production, (2) identify the management practices that improve light penetration and Kernza grain yield, and (3) propose a conceptual model to explain the mechanisms contributing to Kernza grain yield.

## 2. Materials and Methods

### 2.1. Location of the Experiment and Soil and Climatic Conditions

The experiments were established at two locations: the Lancaster Agricultural Research Station (ARS) of University of Wisconsin-Madison, Lancaster, WI (42°49'52.56" N, 90°48'1.78" W) and a collaborating farmer field in Montfort, WI (42°57'11.0" N, 90°28'19.1" W). The mean annual temperature is 7.9 °C, with a mean minimum and maximum temperature of 2.4 °C and 13.4 °C, respectively [31]. The mean annual precipitation is 836 mm. In both locations, Kernza intermediate wheatgrass was established in September 2017, the first grain harvest was in August 2018 and the second grain harvest in August 2019. Between April and August, the accumulated precipitation was 521 mm in 2018 and 564 mm in 2019, and the accumulated growing degree days (base temperature = 0 °C) was 4637 and 4429 °C d, respectively. The dominant soil is a Fayette silt loam (Typic Hapludalfs) with 6 to 12 percent slopes in Lancaster and, 2 to 6 percent slopes in Montfort [32]. Soil analyses at 15 cm at the beginning of the experiment were: 7.0 pH, 3.2% organic C, 36 P ppm, and 121 K ppm in Lancaster, and 7.0 pH, 3.3% organic C, 34 P ppm, and 71 K ppm in Montfort.

### 2.2. Agronomic Practices

The Kernza seeds used in this study were harvested from a certified field at the Lancaster ARS, originated from The Land Institute (Salina, KS) breeding cycle 4 [13]. In both locations, Kernza was no-till drilled at the rate of 10.6 kg ha<sup>-1</sup> and a row spacing of 0.19 m, on 15 September 2017. The previous crop in Lancaster was a failed grass-Alfalfa field and in Montfort was a mixed grass-clover pasture. Two weeks before sowing, both fields were sprayed with glyphosate to control weeds. The Lancaster field was sprayed with 2–4 D amine at the rate of 1.4 L ha<sup>-1</sup> on 15 November 2017 and 2.8 L ha<sup>-1</sup> on 31 August 2018 to control weeds; the field was fertilized with 56 kg ha<sup>-1</sup> N, 45 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub>, and 84 K<sub>2</sub>O on 26 April 2018, with 50 kg ha<sup>-1</sup> N on 13 August 2018, and with 100 kg ha<sup>-1</sup> N and 300 kg ha<sup>-1</sup> K<sub>2</sub>O on 5 May 2019. The Montfort field was sprayed with 2–4 D amine to control weeds at the rate of 4.2 L ha<sup>-1</sup> on 23 August 2018 only (herbicide was not applied the first year so that the farmer could market the Kernza grain); the field was fertilized with 56 kg ha<sup>-1</sup> N and 224 kg ha<sup>-1</sup> K<sub>2</sub>O on 13 June 2018, with 50 kg ha<sup>-1</sup> N on 23 August 2018, and with 50 kg ha<sup>-1</sup> N and 150 kg ha<sup>-1</sup> K<sub>2</sub>O on 4 May 2019.

### 2.3. Experimental Design

The experimental design was a randomized complete block with 3 replications, repeated in two locations, and the treatment structure was a partial factorial. The plot size was 6 × 16 m in Lancaster and 6 × 20 m in Montfort, separated by 4 m alleys. Within two weeks after the first harvest (18 August 2018 in Lancaster and 6 August 2018 in Montfort), ten different management practices were applied, as a result of the combination of two factors: residue management and additional management. Residue management had two levels: (i) residue-left—stubble standing in the field after grain harvest and (ii) residue-exported—stubble cut at 10 cm, baled, and removed from plots. Additional management included the following levels: (i) control—no additional management, (ii) fall burning of the residue, (iii) chopping (cut and leave residues at 4 cm) in fall (August), (iv) chopping twice in fall (August and September), (v) chopping in spring (May), (vi) fall mechanical thinning, and (vii) fall chemical thinning. Mechanical thinning was done using TroyBilt walk-behind rototiller 0.57 m wide. In Lancaster fall mechanical thinning couldn't be completed due to machine failure, so mechanical thinning was re-done in April 2019 using a reverse rotary tiller. Chemical thinning was performed by spraying 90 mL Glyphosate 41% in 21.7 L water at Lancaster and 6 L water at Montfort. In both thinning treatments, the new row spacing was 0.76 m, therefore, 3 out of 4 rows were removed. All additional management treatments were applied for the residue-exported plots, but only control, fall burning, and fall chopping were applied for the residue-left plots. This allowed for a large

gradient of crop residue in the fall, and therefore a full range of light penetration in the canopy from minimal (residue-left control) to full light exposure (residue-exported with fall burning).

#### 2.4. Data Collection

Light penetration was measured using LICOR LI-191 (Lincoln, NE) bar sensor and point sensor LI-190 connected to the datalogger LI-1400. The measurements were taken in August 2018 (a day after treatment application), in September 2018, in October 2018, and in May 2019 (after spring chopping was performed). Three random measurements were taken per plot.

The grain yield was measured by harvesting two rows of a 0.25 m<sup>2</sup> (i.e., 0.5 m × 0.5 m quadrat) in the years 2018 and 2019. Each plot was sampled from two random locations, and the grain yield was expressed in g m<sup>-2</sup>. Total biomass was cut at 0.1 m stubble height. The plots where mechanical and chemical thinning were applied included only one row in a quadrat of 0.25 m<sup>2</sup>. The number of spikes was counted as the total number of spikes in a 0.25 m<sup>2</sup> quadrat, total spike dry weight was the weight of spikes cut at 0.1 m under the last seeds after drying, expressed in g. The weight per spike was estimated dividing total spike dry weight by the number of spikes in a quadrat of 0.25 m<sup>2</sup>. In addition, 5 spikes were collected in each plot to estimate the spikes ratio (i.e., weight per spike considering all the spikes divided by weight per spike considering only 5 spikes), which is an estimate of the proportion of spikes with high yields. Lodging score was rated on a scale of 1 to 10, 1 being no lodging and 10 being highly lodged plants.

#### 2.5. Data Analysis

A two-way analysis of variance (ANOVA) was performed using InfoStat software [33] to test the effects of treatments and locations using the following fixed effects model:

$$y_{ijkl} = \mu + \text{location}_i + \text{block}(\text{location})_{ij} + \text{treatment}_k + \text{treatment} \times \text{location}_{ik} + e_{ijkl}$$

where  $y_{ijkl}$  represented measured variable,  $\mu$  is overall mean;  $\text{location}_i$  is the effect of  $i$ th location,  $\text{block}(\text{location})_{ij}$  represented the effect of  $j$ th block on the  $i$ th location,  $\text{treatment}_k$  represented the effect of the  $k$ th treatment,  $\text{treatment} \times \text{location}_{ik}$  is the interaction effect of  $k$ th treatment and  $i$ th location, and  $e_{ijkl}$  is the residual. Mean separations were performed using Fisher's least significant difference procedure. The regression analysis of yield components against light interception was performed on the least-squares means. The Pearson's correlation matrix using the means of each treatment in each location was estimated and graphed using GraphPad Prism 8.

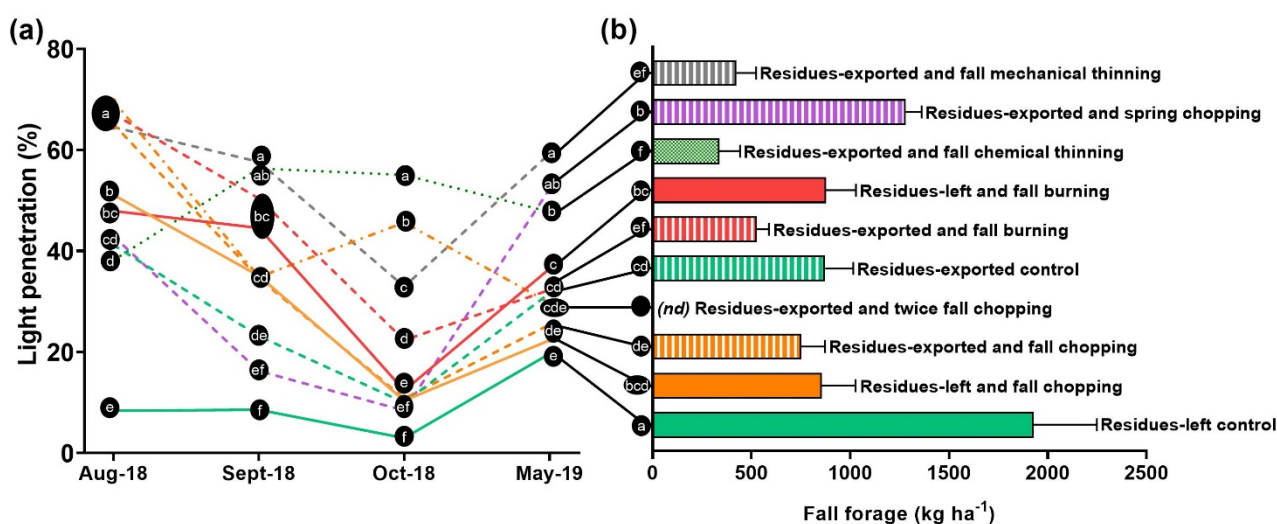
### 3. Results

#### 3.1. Establishment and First Year

In both locations, the establishment of Kernza was similar among plots. The stand count ranged from 12 to 18 plants m<sup>-1</sup> and no differences were found among the plots ( $p = 0.30$ ) or between locations ( $p = 0.58$ ). The height of Kernza measured in August 2018 was 150 cm in Lancaster and 115 cm in Montfort. The number of tillers plant<sup>-1</sup> (only evaluated in the subset of plots assigned to the treatments: Residues-left and fall chopping; Residues-exported control; Residues-exported and fall burning and Residues-exported and twice fall chopping) ranged from 4 to 15 tillers in June, and from 14 to 22 tillers in October 2018. In June, no differences were found among the plots ( $p = 0.75$ ) but Lancaster had more tillers than Montfort (13 vs. 5 on average,  $p < 0.01$ ). In October, the number of tillers was rather constant among the plots ( $p = 0.23$ ) and between locations ( $p = 0.78$ ). In Lancaster, the presence of weed in August 2018 was negligible but in Montfort, where no herbicide had been applied, the mean of weed biomass was 77.4 g m<sup>-2</sup>. The grain yield in the first year was also similar among the plots assigned to the different treatments ( $p = 0.46$ ) but higher in Lancaster than in Montfort (20.3 vs. 14.3 g m<sup>-2</sup>,  $p = 0.03$ ).

### 3.2. Light Penetration and Fall Forage Biomass

The management practices affected light penetration and fall forage biomass (Figure 1). The residue-left control treatment accumulated 1929 kg ha<sup>-1</sup> of forage biomass in the fall and had the lowest light penetration both in the fall of 2018 and in the spring of 2019 (ranging from 3 to 20%, Figure 1a). The light penetration was strongly associated with the percentage of bare soil ( $y = 0.7x + 16$ ,  $R^2 = 0.68$ ,  $p < 0.01$ ). The highest light penetration was observed in August 2018 for treatments with residues-exported combined with fall chopping, burning, or mechanical thinning (67% on average, Figure 1a). In September, the light penetration was lower than in August in all the treatments of residues-exported or chopping (29% and 54% on average, respectively), whereas was similar or higher in mechanical thinning, chemical thinning, and burning treatments (52% and 54 on average, respectively). Overall, light penetration decreased in October except for fall chemical thinning and twice fall chopping treatments, which also showed the highest light penetration (50% on average). In contrast, light penetration in May was higher than in October and the treatment with the highest light penetration were residues-exported in combination with fall mechanical thinning, spring chopping, or fall chemical thinning (53% on average). As expected, all the treatments had lower fall forage biomass than the control (Figure 1b). Residues-exported in combination with fall mechanical thinning or chemical thinning had the lowest fall forage biomass (381 kg ha<sup>-1</sup>, Figure 1b).



**Figure 1.** Percentage of light penetration to a height of 2 cm above the soil surface at four times after management treatments (a). Forage biomass in October 2018 (b). In both panels, different letters show significant differences among the treatments at each time. Black lines connect fall forage references with light penetration data.

Light penetration, fall forage biomass accumulation and lodging score were different between locations. In 2018, the light penetration in Lancaster was higher than in Montfort in the three fall times (41% vs. 31% on average,  $p < 0.01$ ) but in May 2019 it was similar between locations (36% on average,  $p = 0.148$ ). The treatment  $\times$  location interaction was only significant in August 2018 ( $p < 0.01$ ). The treatments that showed the greatest differences between locations were fall burning with residue-left (35% vs. 61% in Lancaster and Montfort, respectively) and residues-exported & fall chemical thinning (52% vs. 25% in Lancaster and Montfort, respectively). Fall forage in Lancaster was higher than in Montfort (1029 and 682 kg ha<sup>-1</sup>, respectively,  $p < 0.01$ ) and the treatment  $\times$  location interaction was not significant ( $p = 0.22$ ). The treatment  $\times$  location interaction and the main effects of location and treatment were significant for lodging score (Table 1). The interaction effect on lodging score showed a non-crossover effect for all treatments with Montfort having higher lodging scores than Lancaster, except for chemical thinning where Lancaster

showed a higher lodging score than Montfort. The lodging score ranged from 2.3 to 7.3 and 3.8 to 8.6 in Lancaster and Montfort, respectively. In both locations, mechanical thinning showed the lowest lodging score (Table 1).

### 3.3. Grain Yield and Yield Components in the Second Year

In the second year of Kernza grain harvest the yield components per row and per area were differentially affected by the management practices applied after the first year harvest. The mean vegetative biomass ranged from 195 to 449 g row<sup>-1</sup> and from 418 to 1432 g m<sup>-2</sup> (Table 1). The highest values of vegetative biomass per row were observed when residue exported was combined with fall mechanical or chemical thinning (averaging 384 g row<sup>-1</sup>) but these management practices had the lowest vegetative biomass per area (averaging 503 g m<sup>-2</sup>). The number of spikes, which ranged from 59 to 168 spikes row<sup>-1</sup> and from 155 to 454 spikes m<sup>-2</sup>, was also higher in both thinning treatments per row (averaging 144 spikes row<sup>-1</sup>) but was lower per area (averaging 188 spikes m<sup>-2</sup>) than the rest of the treatments (Table 1). Finally, both fall mechanical and chemical thinning had higher grain yield per row than other management practices (on average, 13 vs. 4 g row<sup>-1</sup>) but the grain yield per area was rather constant among all the treatments ( $p = 0.83$ ).

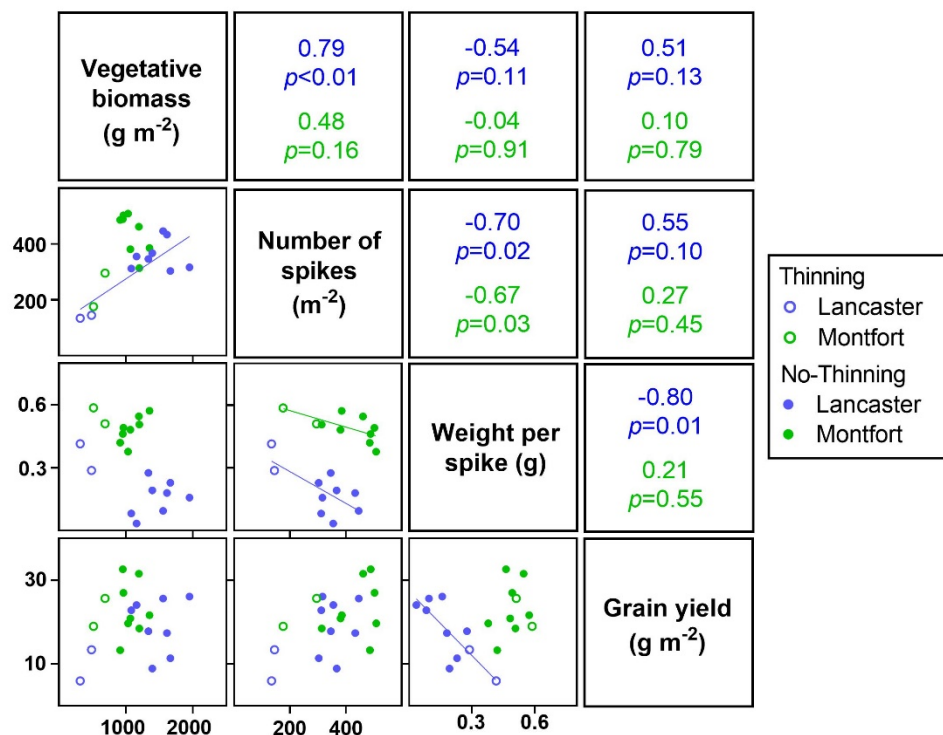
The management practice effects on yield components per area were consistent in both locations since, despite their differences, no treatment  $\times$  location interaction was detected (Table 1). In Lancaster, the vegetative biomass was higher than in Montfort (1255 vs. 988 g m<sup>-2</sup> on average) but the grain yield was lower (18 vs. 23 g m<sup>-2</sup>). Besides, Montfort had higher values than Lancaster in the number of spikes per area (400 vs. 316 spikes m<sup>-2</sup>), in the weight per spike (0.5 vs. 0.2 g), the harvest index (2.4 vs. 1.5%), and the spikes ratio (0.9 vs. 0.3). On the other hand, comparing grain yield between years showed the Kernza stand age did not affect grain yield ( $p = 0.371$ ) but there was a significant year  $\times$  location interaction ( $p = 0.01$ ). In Lancaster, the grain yield in 2018 was higher than in 2019 (27 vs. 18 g m<sup>-2</sup>) whereas in Montfort it was similar between years (23 g m<sup>-2</sup> in 2019 and 19 g m<sup>-2</sup> in 2018).

**Table 1.** *p*-values for the analysis of variance and means for Kernza Intermediate wheatgrass's vegetative biomass, number of spikes, and grain yield row<sup>-1</sup> and m<sup>-2</sup>, and spike weight, spike ratio, harvest index, and lodging score under 10 different management treatments at the second-year harvest at two locations (Lancaster and Montford<sup>1</sup>, Wisconsin, USA).

Source of Variation	Df	Vegetative Biomass		Number of Spikes		Grain Yield		Spike Weight (g)	Spike Ratio	Harvest Index (%)	Lodging Score
		(row <sup>-1</sup> )	(g m <sup>-2</sup> )	(row <sup>-1</sup> )	(m <sup>-2</sup> )	(g row <sup>-1</sup> )	(g m <sup>-2</sup> )				
Location	1	0.37	0.08	<0.01	<0.01	<0.01	0.18	<0.01	<0.01	<0.01	<0.01
Block (Location)	4	0.01	0.01	0.01	0.03	0.12	0.21	0.25	0.37	0.87	0.40
Treatment	9	0.05	0.04	<0.01	<0.01	<0.01	0.83	0.85	0.33	0.22	<0.01
Treatment * Location	9	0.25	0.68	0.02	0.58	0.10	0.74	0.68	0.61	0.38	0.01
Error	36										
<b>Means of Post-Harvest Treatments</b>											
Residues-exported with fall mechanical thinning		448.9 a	588.1 bc	168.3 a	220.5 cd	14.9 a	19.5	0.4	0.5	3.1	3.1 d
Residues-exported with spring chopping		223.5 b	1173.4 ab	81.6 c	428.3 ab	4.0 b	20.8	0.3	0.5	2.1	6.0 abc
Residues-exported with fall chemical thinning		318.8 ab	417.7 c	118.6 b	155.4 d	10.5 a	13.8	0.5	1.0	2.5	5.7 c
Residues-left with fall burning		194.6 b	1021.6 abc	81.3 c	426.8 ab	4.7 b	24.9	0.3	0.6	1.9	5.8 bc
Residues-exported with fall burning		239.3 b	1256.1 ab	70.6 c	370.6 ab	4.4 b	22.8	0.3	0.5	1.8	6.6 abc
Residues-exported control		272.8 b	1432.4 a	76.5 c	401.6 ab	3.8 b	19.7	0.3	0.5	1.3	6.9 abc
Residues-exported and twice fall chopping		272.7 b	1431.5 a	58.8 c	308.7 bc	2.8 b	14.9	0.4	0.6	1.3	7.7 a
Residues-exported with fall chopping		225.5 b	1183.9 ab	81.5 c	427.9 ab	3.6 b	18.8	0.3	0.6	1.8	7.4 ab
Residues-left with fall chopping		261.7 b	1373.8 a	86.6 c	454.4 a	5.4 b	28.6	0.3	0.5	2.3	7.1 abc
Residues-left control		255.3 b	1340.5 a	77.7 c	407.8 ab	3.6 b	19.1	0.3	0.6	1.7	6.2 abc

<sup>1</sup> Lancaster, WI (42°49'52.56" N, 90°48'1.78" W) and Montfort, WI (42°57'11.0" N, 90°28'19.1" W). \*Different letters denote significant differences.

The number of spikes was negatively associated with the weight per spike both in Lancaster ( $y = -0.0008x + 0.43$ ;  $R^2 = 0.49$ ) and in Montfort ( $y = -0.0004x + 0.65$ ;  $R^2 = 0.45$ ; Figure 2). In Lancaster, the vegetative biomass was positively associated with the number of spikes ( $y = 0.16x + 115.1$ ;  $R^2 = 0.63$ ); and the weight per spike was negatively associated with grain yield ( $y = -51.1x + 27$ ;  $R^2 = 0.63$ ). However, no significant associations were found among these variables in Montfort ( $p > 0.16$  and  $p > 0.55$  respectively, Figure 2). On the other hand, when both locations were considered together the Kernza grain yield was positively associated with the number of spikes, showing a better fit per row ( $y = 0.1x - 3.7$ ;  $R^2 = 0.81$ ; data not shown) than per area ( $y = 0.03x + 8.8$ ;  $R^2 = 0.25$ , Figure 2).



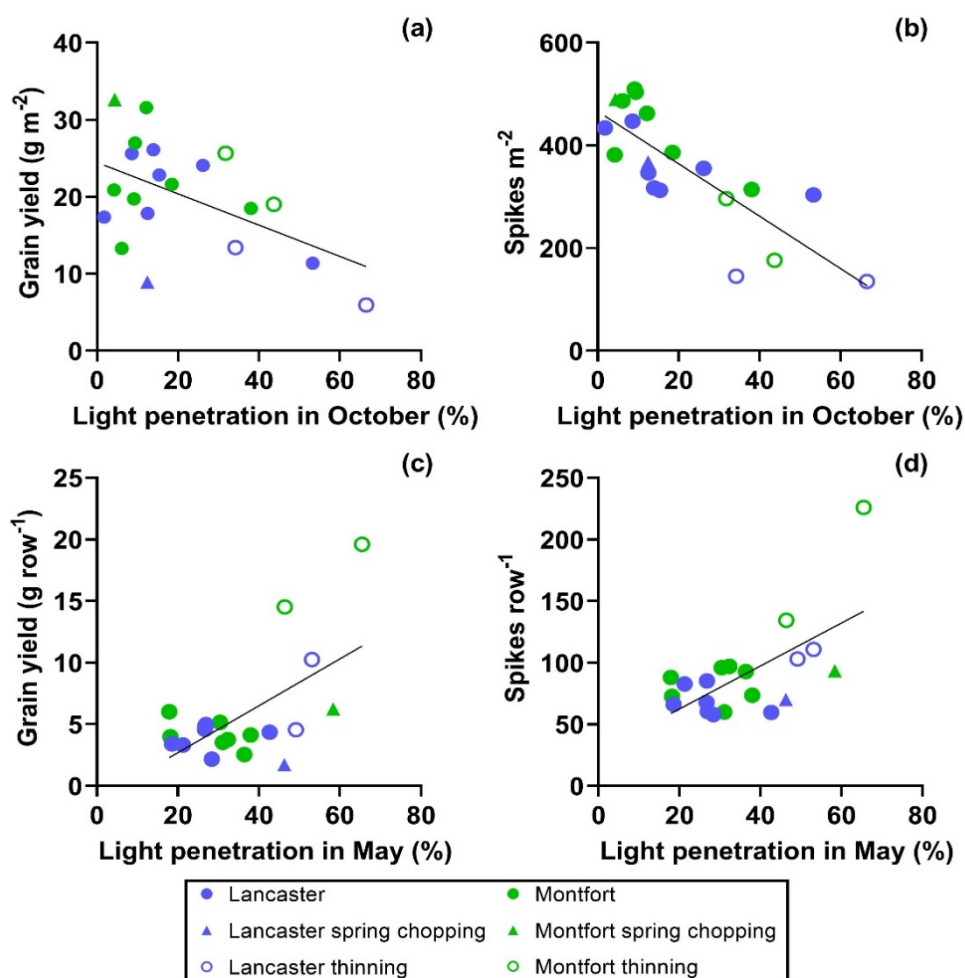
**Figure 2.** Correlation matrix plot with significance levels among the yield components per area. The lower triangular matrix is comprised of the bivariate scatter plots with a fitted line only when  $p < 0.05$ . The upper triangular matrix shows the Pearson correlation plus significance level ( $p$ -values) in Lancaster (blue) or Montfort (green). In all the panels, each dot corresponds to the mean value of each treatment in Lancaster (blue dots) or Montfort (green dots). The treatments with mechanical or chemical thinning are showed as empty circles and all the other treatments as filled circles.

### 3.4. Light Penetration and Yield Components

Light penetration in August 2018 was positively associated with light penetration in September 2018 ( $0.64$ ,  $p < 0.01$ ; Figure 1), and this last one was positively associated with light penetration in October 2018 ( $0.69$ ,  $p < 0.01$ ; Figure 1). However, light penetration in May 2019 was not associated with any of the fall 2018 measurements ( $p = 0.92$  in August,  $p = 0.18$  in September and,  $p = 0.13$  in October). Light penetration in August was not associated with any of the yield components ( $p = 0.32$  or higher, data not shown). Light penetration in September was negatively associated with vegetative biomass per area ( $r = -0.49$ ,  $p = 0.03$ ), and also with the number of spikes per area ( $r = -0.63$ ,  $p < 0.01$ ). Light penetration in October was negatively associated with the grain yield per area ( $r = -0.51$ ,  $p = 0.02$ ;  $y = -0.20x + 24$ ,  $R^2 = 0.26$  Figure 3a), and also with the number of spikes per area ( $r = -0.81$ ,  $p < 0.01$ ;  $y = -5.1x + 466$ ,  $R^2 = 0.65$  Figure 3b). In contrast, light penetration in May 2019 was positively associated with the grain yield per row ( $r = 0.61$ ,  $p < 0.01$ ;  $y = 0.19x - 1.1$ ,



$R^2 = 0.37$  Figure 3c), and also with the number of spikes per row ( $r = 0.64$ ,  $p < 0.01$ ;  $y = 1.7x + 27.5$ ,  $R^2 = 0.41$  Figure 3d).



**Figure 3.** Relationship of the grain yield (a) and the number of spikes (b) per area in August 2019 as a function of the percentage of light penetration in October 2018, and the grain yield (c) and the number of spikes (d) per row in August 2019 as a function of the percentage of light penetration in May 2019. In all the panels, each symbol corresponds to the mean for each treatment in Lancaster (blue) or Montfort (green), the empty circles correspond to the treatments which combined residue-exported with mechanical or chemical thinning, the filled triangles correspond to residue-exported and spring chopping, and the filled circles correspond to the other treatments.

#### 4. Discussion

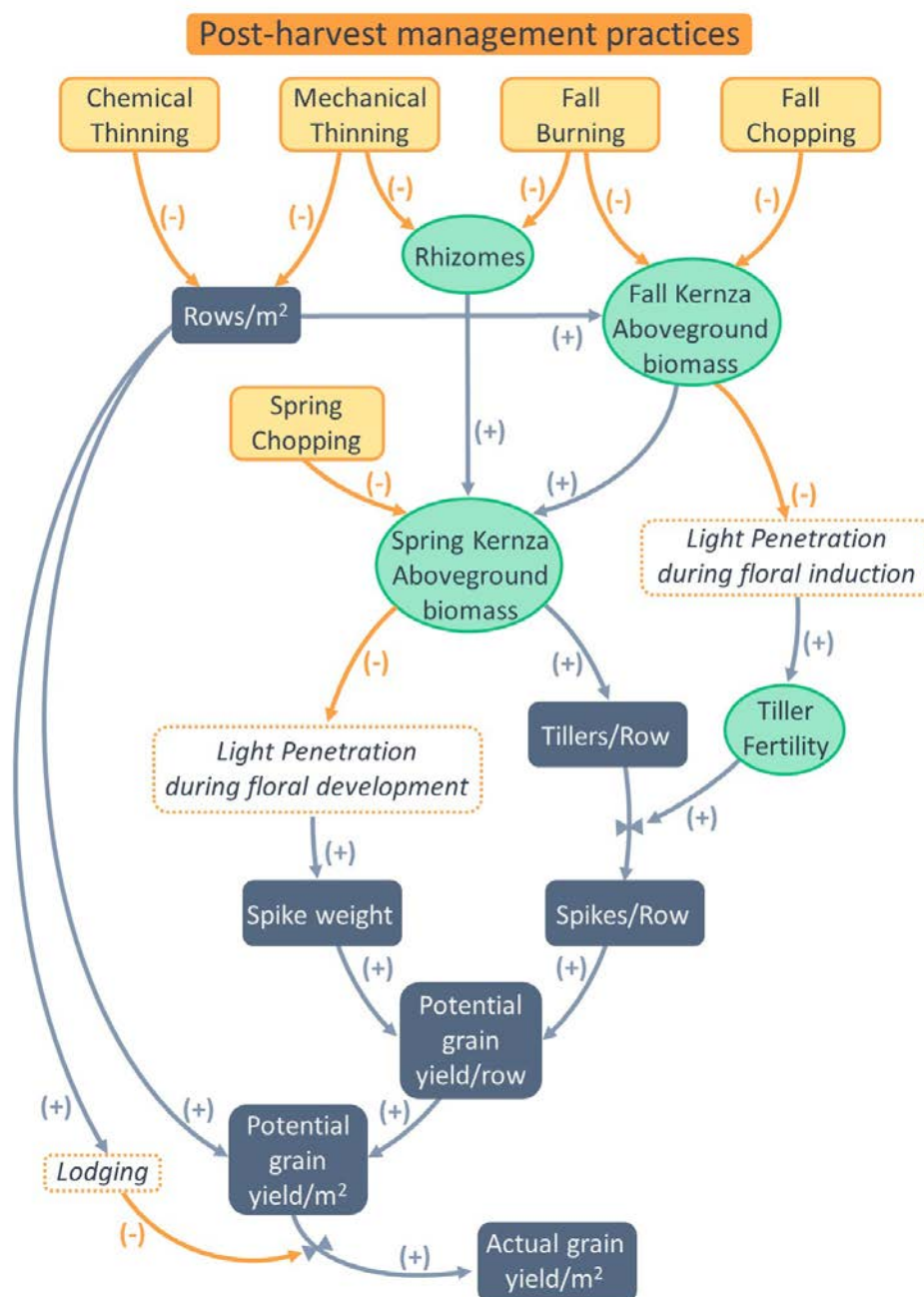
Contrary to what has been often reported [10,14,26,30,34,35], we did not observe an overall decline in yield in the second year. Although large declines in perennial crop grains often come in the third year, 40–57% declines in Kernza grain yield have been observed since the second year [10,14,30]. Similar grain yields between years in our experiment could be because the grain harvest in the first year (22.7 g m<sup>-2</sup> on average) was much lower than what is generally reported in the bibliography (range = 76.3 to 87.6 g m<sup>-2</sup> [10,14,30]). It is likely that excessive rainfall in 2018 negatively impacted yield since 2018 was the wettest year in the last 100 years (Palmer Z-Index = 3.62 [31]). In our experiments, management practices after the first grain harvest did not change grain yield in the second year, in contrast with our original hypothesis and previous literature [10,11,17,22,25,29]. However, all treatments generated changes in light penetration. Yield components were also similar among the different treatments but both mechanical and chemical thinning increased the number of spikes per row, but reduced the number of spikes per area, negatively affecting

yield. However, post-harvest management that left residues and burned or chopped once in the fall had the highest number of spikes and the highest grain yield, although not significantly different (Table 1). Furthermore, the treatment with double chopping in the fall, had the lowest number of spikes, and lowest grain yield, although not significantly different (Table 1). This suggests that multiple forage harvests in the fall may negatively impact the grain yield in the following year, by reducing the number of spikes.

Although post-harvest management practices increased light penetration, did not increase Kernza grain yield in the second year because they reduced other yield components (Figure 4). In different perennial grasses, removing stubble and straw with post-harvest burning increases seed yields in the subsequent crop year [19–22]. This was generally explained by an increase in light penetration that favors floral induction, and consequently the allocation to reproductive biomass [19–22]. In our experiment, post-harvest burning had higher light penetration than both controls, but similar to other studies, the management practices of chopping and thinning were as effective as burning in increasing light penetration [17,19,22–25]. Besides, fall burning mainly increased light penetration in August and September, whereas double chopping and chemical or mechanical thinning maintained high light penetration also in October (Figure 1). Overall, increasing light penetration by management practices did not lead to increase grain yield (Table 1, Figure 3). This suggests that increasing light penetration *per se* is not enough to increase grain yield, and several physiological processes are interacting to explain the effect of management practices on yield.

The lack of a positive association between light and grain yield per area (Figure 3) suggests that there are trade-offs among yield components. The number of spikes and grain yield per row increased as light penetration in May increased but both variables decreased as light penetration in October increased, when they were expressed per area. Those associations were given mostly by thinning treatments, which show higher penetration of light at both points and reverse their order in the ranking when expressed by area or by row. In turn, the number of spikes and grain yield per row in the spring chopping treatment were lower than the thinning treatments. This suggests that increases light penetration only in spring is not enough to increase grain yield per row.

Increasing light penetration to the soil surface had a positive impact on Kernza yield components per row, although it was not enough to compensate for the reduction in rows per area (Figure 4). Among the management practices studied, the highest grain yield, number of spikes, and vegetative biomass per row were observed when residue removal was combined with fall chemical or mechanical thinning. This result suggests that opening the row spacing after the first Kernza harvest could have a similar effect on yield components per row as planting in wider row spacings [10,24,27]. In addition to increasing light by opening rows, mechanical thinning disturbs the root zone and destroys rhizomes (Figure 4) and this increased the number of spikes more than the chemical thinning (Table 1). The use of deep and narrow strip-tillage in the fall between the third and fourth year grain harvests had shown increases in grain yield of Kernza because of increased resource allocation to seed production, increasing number of spikes and harvest index [11]. In our experiment, mechanical thinning was applied to a lesser depth, in a younger stand (i.e., between the first and second grain harvests), and removing 3 out of 4 rows, which could explain why the grain yield was similar to the control treatment. Furthermore, the increase number of spikes and grain yield per row suggests that applying mechanical or chemical thinning but removing only 1 out of 4 rows may optimize number of spikes per area and maintain yields in subsequent years. Further research is needed to optimize this post-harvest management practice, but the evidence suggests that thinning is a promising alternative for maintain grain yields.



**Figure 4.** Conceptual model proposed to explain how different post-harvest management practices modified the components of Kernza grain yield in this experiment. The orange boxes represent the post-harvest management practices considered: chemical and mechanical thinning, fall burning, fall chopping and spring chopping. The blue boxes represent the yield components. The arrows show the effect each box has on other, blue arrows are positive effects (+) and orange arrows are negative effects (-). Therefore, if one box has a negative effect on other box which has a positive effect on a third, the first have a negative effect on the third. The bows in the arrows indicate proportions that are affected.

The observed decrease in lodging with mechanical and chemical thinning treatments suggests these treatments can maintain Kernza yield in the long term. Lodging has been an ongoing challenge in intermediate wheatgrass grain production systems because it is a yield-limiting factor [14,22,27–30]. Since lodging can reduce harvested spikes, it can decrease the proportion of potential grain yield that becomes actual grain yield (Figure 4). Our results show that lodging decreased with wider row spacings generated by both

chemical or mechanical thinning. This is in strong agreement with the pattern observed in Kernza stands with wider row spacings [10,27] and with destroyed rows by mechanical tillage [22]. In the subsequent years, it could be convenient especially when nitrogen fertilization begins to be necessary [14]. In high N environments, lodging might be exacerbated [14] and Kernza stands with less intraspecific competition could be more able to maintain yields in the long-term.

Our experiments combined for the first time ten post-harvest management practices with very different intensity and timing of disturbance. They were useful for understanding mechanisms explaining the yield components in dual-use Kernza (Figure 4). Our results show that spike weight is negatively associated with the number of spikes, and that grain yield depends more on number of spikes than spike weight (Figure 2). Opening the row spacing with mechanical or chemical thinning increases light penetration, spikes and grain yield per row. In this experiment the thinning treatments likely were too extreme, removing 3 out of 4 rows of Kernza, and therefore reducing the yield per area. Future research should explore thinning treatments with less intensity, such as removing 1 out of 2 rows. Continuing research on how different practices affect Kernza grain yield following the second year should be a priority. The demand for perennial crops is likely to increase to improve the stability and resilience of food, feed, fiber, and fuel production [36]. Developing management practices to increase productivity will provide economic benefits that will facilitate adoption of perennial dual-use systems.

## 5. Conclusions

This study explored how post-harvest management practices modify light penetration during floral induction and floral development and impact Kernza intermediate wheatgrass yield components. Overall, the application of post-harvest management practices (which combined residues-left in the field after grain harvest or residues-exported with burning, chopping, and chemical or mechanical thinning) increased light penetration, but they did not increase Kernza grain yield in the second year because they reduced other yield components. When the row spacing was widened with mechanical or chemical thinning, spikes and grain yield per row increased. However, in our experiment the thinning treatments likely were too extreme, removing 3 out of 4 rows of Kernza, and therefore reducing the yield per area. Finally, the conceptual model proposed in this study summarized the trade-off between the different yield components of Kernza intermediate wheatgrass related. We believe it could be useful for the design of future post-harvest management to maintain Kernza yield over time.

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