Received: 7 August 2019 | Accepted: 27 October 2019

DOI: 10.1002/agj2.20124

Agronomy Journal

ARTICLE

Crop Economics, Production, & Management

Effects of defoliation and row spacing on intermediate wheatgrass II: Forage yield and economics

Mitchell C. Hunter[1,2] | **Craig C. Sheaffer**[2] | **Steven W. Culman**[3] | **William F. Lazarus**[4] | **Jacob M. Jungers**[2]

[1]American Farmland Trust, St. Paul, MN 55108, USA

[2]Dep. of Agronomy and Plant Genetics, Univ. of Minnesota, St. Paul, MN 55108, USA

[3]School of Environment and Natural Resources, Wooster, OH 44691, USA

[4]Department of Applied Economics, Univ. of Minnesota, St. Paul, MN 55108, USA

Correspondence
Mitchell Hunter, American Farmland Trust, St. Paul, MN 55108 and Dep. of Agronomy and Plant Genetics, Univ. of Minnesota, St. Paul, MN 55108, USA.
Email: mitchellchunter@gmail.com

Abstract

Management systems that produce both grain and biomass coproducts could enhance the profitability of the novel perennial grain crop Kernza intermediate wheatgrass [*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey] (IWG). Harvesting IWG for grain typically results in a straw harvest; in addition, vegetative biomass can be cut in spring, fall, or both for hay production. We evaluated the interacting effects of defoliation and row spacing on yield, forage quality, and economic return across the 3-yr life of a conventionally managed IWG stand in St. Paul, MN. We measured straw and hay yield and forage quality and then used recent hay auction results to model forage price and total potential value. We then used estimated production costs to calculate potential net return from straw production alone and with additional hay harvests. Overall, straw was more valuable than hay, despite being of much lower quality, since yields were 3–4 times greater. Straw potential value was similar to the cost of producing both straw and grain, greatly reducing the financial risk in Kernza grain production. Hay production was almost always profitable. Straw and hay yield and value were greater in 15- and 30-cm rows than in 61-cm rows. Defoliating in both spring and fall led to lower hay and straw yields in the third year. Our results indicate that the best strategy for achieving consistent high net return to biomass production is to plant in 15- or 30-cm rows and only cut hay in the fall.

1 | INTRODUCTION

Management systems that produce both grain and biomass coproducts could enhance the profitability of the novel perennial grain crop intermediate wheatgrass [*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey] (IWG; Bell, Byrne, Ewing, & Wade, 2008; Watt, 1989). Originally introduced to North America as a forage crop, IWG has been bred in recent years to produce higher yields of larger seeds, which have been marketed under the trade name Kernza (The Land Institute, Salina, KS; DeHaan, Christians, Crain, & Poland, 2018). Harvesting IWG for grain typically results in a straw harvest; in addition, vegetative biomass can be cut in spring, fall, or both for hay production. By improving the economic viability of this crop, dual-use management has the potential to help realize the environmental benefits of perennial agriculture, including reduced soil erosion, lower nitrate losses, increased carbon sequestration, and improved soil health (Asbjornsen et al., 2013; de Oliveira, Brunsell, Sutherlin, Crews, & DeHaan, 2018; Glover et al., 2010; Jungers,

---

Abbreviations: ADF, acid detergent fiber; CP, crude protein; Ctrl, no defoliation; Fa, defoliation only in fall; GDD, growing degree days; IWG, intermediate wheatgrass; NIRS, near-infrared reflectance spectroscopy; NDF, neutral detergent fiber; RFV, relative feed value; Sp, defoliation only in spring; SpFa, defoliation in spring and fall.

DeHaan, Mulla, Sheaffer, & Wyse, 2019). To help develop best practices for dual-use management, we evaluated the interacting effects of defoliation and increasing row spacing, two practices that have increased productivity in perennial grass seed dual-use systems.

Core ideas

- Forage production can improve the profitability of Kernza perennial grain.
- Straw value often exceeded production costs in narrow rows.
- Adding hay harvests to grain and straw production was almost always profitable.
- Planting in 15- or 30-cm rows produced more straw and hay than wider rows.
- Harvesting hay in the fall only resulted in consistent high net return.

1.1 | Use of intermediate wheatgrass for forage

Intermediate wheatgrass was introduced into North America from Eurasia in 1932 (Ogle, 2018). It has been widely used for haying, grazing, and conservation plantings in the Great Plains region (Hendrickson, Berdahl, Liebig, & Karn, 2005). Early studies indicated that IWG is not well-suited for use in pastures because stand vigor declines and susceptibility to winterkill increases under repeated frequent defoliation (Campbell, 1961; Heinrichs & Clark, 1961; Lawrence & Ashford, 1966). However, Moore, Vogel, Klopfenstein, Masters, and Anderson (1995) reported that IWG performed well over 2 yr of spring grazing, and Lawrence and Ashford (1966) harvested up to 12 Mg ha^{-1} of biomass in a single season with repeated defoliation.

In Kernza production systems, the stems and leaves remaining after IWG grain harvest in August are typically removed from the field to allow rapid regrowth. This straw has the potential for use in total mixed rations for dairy cattle, as animal bedding, or as a biomass energy feedstock (Jungers, DeHaan, Betts, Sheaffer, & Wyse, 2017; Wang et al., 2014). Here, we will focus on the forage potential of the straw. Straw yields at grain harvest can reach over 12 Mg ha^{-1} and are typically in the range of 3 to 10 Mg ha^{-1} (Jungers et al., 2017; Pugliese, 2017; Tautges, Jungers, Dehaan, Wyse, & Sheaffer, 2018; Wang et al., 2014).

Intermediate wheatgrass also produces vegetative biomass in the spring and the fall that can be harvested as high-quality hay (Hendrickson et al., 2005). In addition to producing hay, defoliating vegetative growth has also been shown to increase seed yield in perennial grass seed production (e.g., Green & Evans, 1957; Hebblethwaite & Clemence, 1981; Pumphrey, 1965). Removing fall biomass may also help preclude overwintering habitat for black grass bug (*Labops* spp.), which can reduce IWG forage yield and quality (Blodgett, Lenssen, & Cash, 2006). Across nine sites in North America (including a subset of the plots in this study), spring and fall hay production ranged from 0.5 to 3.9 and 0.1 to 3.8 Mg ha^{-1}, respectively (Pugliese, 2017).

Intermediate wheatgrass hay biomass can be very high quality, with 700–800 g kg^{-1} dry matter digestibility, greater than 200 g kg^{-1} crude protein (CP), and lower than 500 g kg^{-1} neutral detergent fiber (NDF) when harvested during spring vegetative growth, though quality declines as the plants mature (Moore et al., 1995). Mean daily gain for steers grazing on IWG pastures for 4–6 wk was 1–1.2 kg d^{-1} (Moore et al., 1995). Compared to annual winter wheat (*Triticum aestivum* L.), IWG biomass harvested in mid-spring had higher CP, dry matter digestibility, and metabolizable energy and lower NDF and acid detergent fiber (ADF; Newell & Hayes, 2017).

The dual-purpose use investigated in this study is analogous to the common practice of using winter cereal fields for backgrounding grazing animals. Likewise, perennial grass seed producers commonly harvest biomass coproducts (Green & Evans, 1957; Hare, 1993; Lawrence & Lodge, 1975; Hebblethwaite & Clemence, 1981). Incorporating dual-purpose crops can improve farm economics by providing additional forage, lengthening pasture rest periods, improving weed management, and enabling increased stocking rates (Dove & Kirkegaard, 2014). Dual-purpose use of IWG could provide similar benefits, including in regions that are too cold to support dual-purpose, winter-annual cereals. However, few studies have investigated the agronomic or economic consequences of this management approach (Pugliese, 2017; Pugliese, Culman, & Sprunger, 2019).

1.2 | Effects of defoliation

As discussed in the companion paper (Hunter, Sheaffer, Culman, & Jungers, 2020), mechanical defoliation for forage harvest stimulates tiller production in grasses by increasing both the intensity and the red/far red ratio of the light at the plant base (Aamlid, Heide, Christie, & McGraw, 1997; Deregibus, Sanchez, & Casal, 1983; Ugarte, Trupkin, Ghiglione, Slafer, & Casal, 2010; Youngner, 1972). Defoliation can improve sward density and help maintain an optimal leaf arrangement for photosynthesis (Youngner, 1972). As a result, appropriately timed defoliation can increase total forage yield within a growing season, while also enhancing forage quality by keeping tillers vegetative. However, defoliation can also reduce radiation interception and limit photosynthate production (Youngner, 1972). Repeated severe defoliation can reduce stand vigor and productivity by depleting carbohydrate reserves and causing root dieback (Alberda, 1957; Hampton & Fairey, 1997; Youngner, 1972). In perennial grass seed production, the effects of hay harvest on subsequent biomass production (hay or straw yield) have been mixed (Green & Evans, 1957; Hare, 1993).

In IWG, spring hay yield in a dual-use system in Australia tended to increase as the harvest date was delayed, allowing for additional growth, but this also tended to decrease postharvest regrowth and overall hay production (Newell & Hayes, 2017). Across 2 yr and nine sites in North America, spring hay harvest resulted in numerically lower straw yield at grain harvest in almost every case, but both spring and fall hay harvest tended to increase annual total forage yield (Pugliese, 2017). Dick, Cattani, and Entz (2018) found minimal effects of postharvest grazing on IWG straw yield the following year.

Early and repeated defoliation consistently increases IWG forage quality (Karn, Berdahl, & Frank, 2006) by maintaining stands in a vegetative state. For instance, CP concentration was highest with early defoliation (Newell & Hayes, 2017), though later and less frequent cutting optimized yields of CP and biomass (Heinrichs & Clark, 1961; Lawrence, Warder, & Ashford, 1971).

1.3 | Effects of row spacing

The effects of different row spacings on forage yield in perennial grass seed dual-purpose systems have been little studied. In many cases, planting in wider row spacings increases tillers m^{-1} of row, but decreases tillers ha^{-1} due to increased interrow space (Deleuran, Gislum, & Boelt, 2009, 2010; Deleuran, Kristensen, Gislum, & Boelt, 2013; Lawrence, 1980). Han et al. (2013) found that straw production from Altai wildrye [*Leymus angustus* (Trin.) Pilg.)] was lower in wide-row spacings until the rows filled in after 5 yr. However, Koeritz, Watkins, and Ehlke (2015) found that row spacings ranging from 10 to 30 cm had no effect on vegetative biomass at seed harvest in first-year perennial ryegrass (*Lolium perenne* L.) fields. In a 5-yr study, row spacing ranging from 76 to 152 cm did not affect forage yield of IWG or Russian wildrye [*Psathyrostachys junceus* (Fisch.) Nevski], though there was a trend toward higher yield in narrower rows when fertilizer was applied (Black & Reitz, 1969). Generally, the effects of row spacing on stand density and biomass production decrease over time, unless the initial row spacing is maintained through tillage or herbicide applications (Donald et al., 1954; Kays & Harper, 2009; Deleuran, Kristensen, Gislum, & Boelt, 2013).

1.4 | Objectives

Understanding both the agronomic and economic implications of defoliation and row spacing may help develop commercially viable dual-purpose IWG production systems. Our objectives were to evaluate the interacting effects of defoliation and row spacing on (a) the yield and forage quality of IWG straw and hay; (b) the economic value of IWG straw and hay; and (c) the net economic return to straw and hay production based on calculated potential forage value and estimated costs of production in Minnesota. We conducted this study across the 3-yr life of an IWG stand. A companion paper (Hunter et al., 2020) discusses the effects of defoliation and row spacing on IWG grain yield and yield components.

2 | MATERIALS AND METHODS

The experiment was conducted under nonirrigated conditions at the University of Minnesota Agricultural Experiment Station in Saint Paul, MN (44.988291, −93.175625) on a Waukegan silt loam (fine-silty over sandy, mixed, superactive, mesic Typic Hapludoll). The previous alfalfa (*Medicago sativa* L.) crop was terminated prior to preparing a seedbed for IWG planting. An improved grain-type IWG from the fourth cycle of a breeding program at The Land Institute (Salina, KS) was seeded at a rate of 12 kg ha^{-1} pure live seed (1.9 million seeds ha^{-1}). The IWG was seeded in 15-cm rows with 20 rows per plot on 5 September 2014. Total plot size was 3 by 4.5 m. The experiment encompassed three production years, from 2015 to 2017. The defoliation treatments were continued in 2018, as reported in Hunter et al. (2020), but complete forage yield data was not collected.

The experimental design was a split-plot, randomized complete block with defoliation as the main-plot treatment and row spacing as the split-plot treatment with four replications. Mechanical defoliation for hay production occurred in spring (Sp), fall (Fa), spring and fall (SpFa), or not at all (Ctrl). All vegetation was clipped to a height of 7.5 cm and removed immediately after clipping.

Row spacing treatments of 15, 30, and 61 cm between rows were imposed within split plots by terminating rows of IWG about 14 d after emergence by hand-hoeing. As a result, the initial seeding rate m^{-1} of row was the same across row spacings, but the seeding rate ha^{-1} was lower at wider row spacings (6 kg ha^{-1} in 30-cm rows and 3 kg ha^{-1} in 61-cm rows). After establishing row spacings, IWG recruitment between rows was not controlled, as this requires specialized equipment for interrow cultivation or herbicide banding that is not widely available on commercial cash-grain farms.

The herbicides Dual Magnum (*S*-metolachlor 82.4%, Syngenta, Basel, Switzerland) and 2,4-D (2,4-dichlorphenoxyacetic acid) were applied to IWG at the vegetative stage in early April annually at labeled rates for grass seed production. Nitrogen fertilizer was applied in early April as ammonium nitrate (NH_4^+–NO_3^-; 34-0-0) at a rate of 40 kg N ha^{-1} 2015, and then as urea (46-0-0) at a rate of

TABLE 1 Monthly mean precipitation and temperature in St. Paul, MN for August 2014–October 2017, with long-term means (normals) for 1981–2018

	Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Precipitation, mm	2014								120	45	38	29	23
	2015	11	10	20	62	113	120	157	116	100	59	97	69
	2016	12	21	79	58	78	116	154	190	185	79	42	51
	2017	33	30	29	119	145	116	94	139	52	139		
	Normal	22	22	48	77	105	129	104	110	81	63	40	31
Mean temperature, °C	2014								21.6	15.7	8.3	−4.4	−5.3
	2015	−9.0	−12.1	0.9	8.4	14.2	20.1	22.0	20.4	18.9	10.0	3.8	−3.2
	2016	−10.6	−5.8	3.6	7.6	14.8	20.3	22.5	21.7	17.0	9.8	4.6	−8.1
	2017	−9.3	−2.7	−0.2	8.2	13.0	19.6	22.0	18.7	17.8	8.9		
	Normal	−10.6	−7.9	−0.3	7.0	14.1	19.7	22.3	21.1	16.4	8.5	0.0	−7.6

56 kg N ha^{-1} in 2016, 2017, and 2018. Baseline soil pH, P, and K levels were 6.8, 105 ppm, and 514 ppm, respectively, and no lime or P or K fertilizer was applied.

Daily temperature and precipitation data from satellite observations were obtained from the NASA POWER Project (https://power.larc.nasa.gov/; Table 1). Growing degree days (GDD) were calculated with a base of 0 °C and a maximum of 30 °C, with accumulation beginning on the fifth consecutive day with nonzero GDD in spring.

2.1 | Yield data collection

Straw yield was sampled annually at grain harvest on about 4 August. Straw sampling methods are described in the companion paper (Hunter et al., 2020). Spring and fall hay samples were collected by harvesting all vegetation 7.5 cm above the soil surface in two separate 2-m lengths of row per split plot. Biomass was dried at 60 °C for 72 h and weighed. Remaining biomass was mechanically cut with a forage harvester (Carter Mfg., Brookston, IN) and removed from the plot. Spring defoliation occurred prior to stem elongation on 8, 2, and 5 May and fall defoliation occurred prior to senescence on 20, 5, and 26 October in 2015, 2016, and 2017, respectively. In the 30- and 61-cm row spacings, both straw and hay yields were adjusted to account for the colonization of interrow space that occurred in 2017 (see Hunter et al., 2020).

2.2 | Forage quality analysis

Straw and hay biomass samples were ground and analyzed for forage quality using near-infrared reflectance spectroscopy (NIRS; Model DA 7200, Perten Instruments, Springfield, IL) with calibration equations developed in Minnesota and validated with wet chemistry. Parameters analyzed included NDF, ADF, CP, and concentration of phosphorus (P) and potassium (K). The concentration of N was estimated by dividing CP by 6.25. Equations for NIRS were developed using the software program Calibrate (NIRS 3 version 4.0, Infrasoft International, Port Matilda, PA) with the modified partial least squares regression option (Shenk & Westerhaus, 1991). The validation process for this equation yielded the following coefficients of determination and standard errors of cross validation, respectively: NDF, .98 and 2.4; ADF, .95 and 1.9; CP, .98 and 1.0; P, .55 and 0.04; K, .61 and 0.4.

The relative feed value (RFV; Rohweder, Barnes, & Jorgensen, 1978) of the forage was calculated with the following equations (Moore & Undersander, 2002):

$$\text{Dry matter intake (DMI)} = 120/\text{NDF} \tag{1}$$

$$\text{Digestible dry matter (DDM)} = 88.9 - (0.779\ \text{ADF}) \tag{2}$$

$$\text{RFV} = (\text{DMI})(\text{DDM})/1.29 \tag{3}$$

2.3 | Economic analysis

The potential net return to straw and hay production was calculated from recent auction results and estimated cost of production in Minnesota. Grass hay prices from 2018 auctions at Mid-American Auction in Sauk Centre, MN (Nathaniel Drewitz, personal communication, 2018) were used to develop a simple linear regression between RFV and price Mg^{-1} dry matter. Only sales with RFV numbers and for which prices were reported by weight were used. Including CP in the model did not improve fit, and the CP term was not significant ($p = .44$). The final equation was:

$$\text{Forage price } (\$\ \text{Mg}^{-1}) = 34.0 + 1.02\text{RFV} \tag{4}$$

This equation explained 18% of the variation in forage price ($r^2 = .18$) and RFV was a significant predictor ($p < .0001$).

Price variability was high, likely due to fluctuations in supply and demand, as well as quality parameters not captured by RFV, such as weediness. The same equation was used for both straw and hay prices, even though straw is typically not sold based on RFV, because the RFVs for both types of forage were within the range of data used to develop the model. Moreover, IWG straw can be higher quality than small grain straw, so it may receive a higher price. Calculated straw prices were compared against 2018 straw auction prices to ensure that the calculated prices were reasonable. Potential forage value ha^{-1} was calculated by multiplying the calculated price by the measured yield.

The cost of production was estimated with an enterprise budgeting tool (William F. Lazarus, personal communication, 2019; based on Lazarus & Keller, 2018; AAEA Task Force, 2000). This tool accounts for the costs of seed; fertilizer; chemicals; machinery and machinery operation; crop transport and storage; nonmachinery labor and management; land rent; and interest on operating expenses calculated at a 5% annual rate. The IWG seed cost was assumed to be \$0.68 kg^{-1} and land rent was set at \$410 ha^{-1} (\$166 ac^{-1}), the mean land rent in Minnesota in 2018 (NASS, 2019). Machinery costs reflected 2018 values in Minnesota (Lazarus, 2018). Labor and management costs were derived from data from the FINBIN farm financial management database (https://finbin.umn.edu/).

The cost of production was first estimated for a baseline scenario in which only grain and straw were produced, including field preparation, seeding, fertilization, herbicide application, combining, and baling of straw. Since IWG is a perennial, the costs of field preparation and seeding were omitted after the establishment year. The cost of hay harvest—including costs for mowing, raking, and baling—was estimated separately.

Potential net return was calculated for each subplot in each year by subtracting the cost of production from the value ha^{-1}. Straw net return included the cost of production for both grain and straw production, since all of the same field operations are involved. Hay net return included the additional cost of production for one or two hay harvests, depending on the defoliation treatment. The value of the grain was not factored into the economic analysis because the Kernza market is too young to enable robust price discovery, and because most of the market demand is for organic or transitional organic grain. Moreover, currently there are no herbicides labeled for use on IWG for grain production.

2.4 | Statistics

All statistical analyses were performed in R (R Core Team, 2018). Split-plot mixed-effect linear models fit to a Gaussian distribution were specified with the lme function of the nlme package v. 3.1-137 (Pinheiro, Bates, DebRoy, & Sarkar D, 2018). Random intercepts were fitted to block, main plot, and year, when year was not included as a fixed effect. Initially, the interacting effects of year, row spacing, and defoliation were fit across all years. Then, to enable interpretation of overall effects across all four years, these three predictors were modeled one-by-one, without covariates. Finally, the interacting effects of row spacing and defoliation were modeled within each year. Pairwise comparisons among treatment means were evaluated with the emmeans function of the emmeans package v. 1.3.0 (Lenth, 2018) with a Tukey adjustment for multiple comparisons. Models were evaluated to ensure they met the assumptions of independence and normality of residuals and, if necessary, response variables were transformed following the Box–Cox procedure. The linear regression between RFV and forage price was fit with the lm function. Pearson's correlation coefficient was calculated with the cor function to assess the relationship between spring and fall GDD and hay yield. An alpha value of .05 was used to assess statistical significance.

3 | RESULTS

3.1 | Weather and field conditions

Growing conditions were generally favorable throughout the experiment, with monthly mean precipitation and temperature typically near long-term values during the growing season (Table 1). However, precipitation was highly limited during the fall regrowth period in late August and September of 2017. Growing degree day accumulation (base temperature = 0°C) prior to spring hay harvest was greater in 2015 (510 °C d) than in in 2016 and 2017 (450 °C d). Accumulation of GDD prior to grain and straw harvest was greater in 2016 (2,240 °C d) than in 2015 and 2017 (2,180 °C d). Between grain harvest and fall hay harvest, GDD accumulation was greatest in 2015 (1,340 °C d), intermediate in 2017 (1,290 °C d), and lowest in 2016 (1,210 °C d).

3.2 | Straw yield and quality

Mean yield of straw (stems and leaves remaining after grain harvest) was 10.2 Mg ha^{-1} in the first year, but then declined by 24% in 2016 and was similar in 2017 (Figure 1; Tables 2, 3). Across all years, the Fa harvest treatment produced more straw biomass than SpFa and Ctrl, and the two narrower row spacings (15 and 30 cm) produced more straw than the widest (61 cm) row spacing.

Defoliating for hay production affected straw yield differently in different years. In 2015, Sp defoliation depressed straw yield compared to Ctrl. In contrast, in 2016 all of the

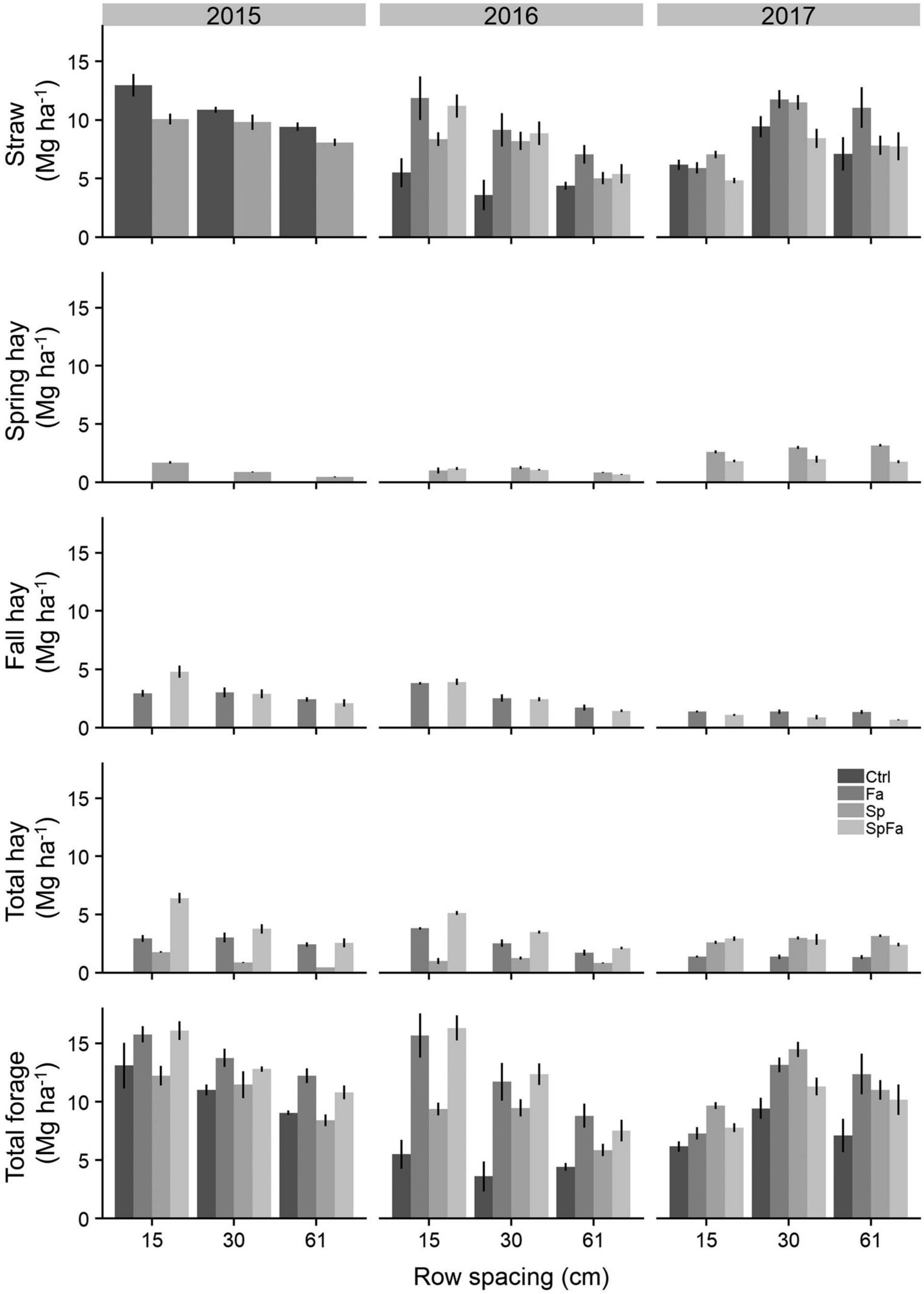

FIGURE 1 Yields (Mg ha^{-1}) of intermediate wheatgrass (A) straw, (B) spring hay, (C) fall hay, (D) total hay, and (E) total forage (straw + hay) by year, row spacing, and defoliation. Bars represent means and whiskers represent standard error. Because the fall defoliation had not occurred yet in 2015, the Ctrl and Fa defoliation treatments were pooled (dark gray bar) and the Sp and SpFa defoliation treatments were pooled (light gray bar) in panels (A) and (B). Missing bars indicate treatments in which hay was not harvested. Ctrl, no defoliation; Fa, defoliation in fall only; Sp, defoliation in spring only; SpFa, defoliation in spring and fall

defoliated treatments yielded more biomass than Ctrl, and straw yield was almost twice as high following Fa defoliation (9.4 Mg ha^{-1}) as following Ctrl (4.5 Mg ha^{-1}). The Fa treatment out-yielded SpFa defoliation in 2017.

The effects of row spacing on straw yield also shifted over time. In 2015 and 2016, straw yield was higher in narrower row spacings. However, in 2017, straw yield in the 30-cm row spacing exceeded that in the 61-cm spacing, which exceeded the 15-cm spacing.

Mean straw RFV was highest in 2017 (70), intermediate in 2016 (65), and lowest in 2015 (57; Tables 3, 4; Supplemental Figure S1). Row spacing did not affect straw RFV overall,

TABLE 2 Mean straw, hay, and total forage (straw + hay) yields by year, row spacing, and defoliation treatment. Within each category, values within a column that share a letter are not significantly different at the α = .05 level with a Tukey correction for multiple comparisons. Letters in bold indicate years in which there was a significant interaction between defoliation and row spacing. Interactions are displayed in Figure 1

		Straw	Spring hay	Fall hay	Total hay[a]	Total forage[a]
				Mg ha^{-1}		
Year	2015	10.2a	1.0b	3.0a	2.7a	12.2a
	2016	7.4b	1.0b	2.7a	2.4a	9.2b
	2017	8.2b	2.4a	1.1b	2.3a	10.0b
Row spacing	15 cm	8.9a	1.7a	3.0a	3.1a	11.2a
	30 cm	9.4a	1.5ab	2.2b	2.5b	11.2a
	61 cm	7.6b	1.2b	1.6c	1.9c	9.0b
Defoliation	Ctrl	7.7b	–	–	–	7.7c
	Fa	10.0a	–	2.3a	2.3b	12.3a
	Sp	8.6ab	1.7a	–	1.7b	10.2b
	SpFa	8.2b	1.3b	2.3a	3.5a	11.7ab
2015[b]	15 cm	11.5a	1.7a	3.9**a**	3.7**a**	14.4a
	30 cm	10.3a	0.9b	3.0**b**	2.6**b**	12.3b
	61 cm	8.8b	0.5c	2.3**b**	1.8**c**	10.1c
	Ctrl	11.1a	–	–	–	11.3bc
	Fa		–	2.8**a**	2.8**b**	13.9a
	Sp	9.3b	1.0	–	1.0**c**	10.7c
	SpFa			3.3**a**	4.3**a**	13.2ab
2016	15 cm	9.2a	1.1a	3.9a	3.3**a**	11.7**a**
	30 cm	7.5b	1.2a	2.5b	2.4**b**	9.3**b**
	61 cm	5.5c	0.8b	1.6c	1.6**c**	6.6**c**
	Ctrl	4.5b	–	–	–	4.5**c**
	Fa	9.4a	–	2.7a	2.7**b**	12.1**a**
	Sp	7.2a	1.0a	–	1.0**c**	8.2**b**
	SpFa	8.5a	1.0a	2.6a	3.6**a**	12.1**a**
2017	15 cm	6.0c	2.2a	1.3a	2.3a	7.7c
	30 cm	10.3a	2.5a	1.1a	2.4a	12.1a
	61 cm	8.4b	2.5a	1.0a	2.3a	10.2b
	Ctrl	7.6ab	–	–	–	7.6b
	Fa	9.6a	–	1.4a	1.4b	10.9a
	Sp	8.8ab	2.9a	–	2.9a	11.7a
	SpFa	7.0b	1.9b	0.9b	2.7a	9.7ab

[a] Overall means by year and row spacing reflect only those defoliation treatments for which there is data in each column. Therefore, total hay values are different than the sums of spring and fall hay, and total forage values are different than the sums of straw and total hay, because different defoliation treatments are averaged in each case.

[b] Because the fall defoliation had not occurred yet in 2015, the Ctrl and Fa defoliation treatments were pooled and the Sp and SpFa defoliation treatments were pooled for straw and spring hay.

but all defoliation treatments reduced RFV relative to Ctrl. Within individual years, row spacing only affected straw RFV in 2016, when it was lower in 30-cm than in 61-cm rows. Defoliation did not affect straw RFV in 2015, but all defoliation treatments had lower straw RFV than Ctrl in 2016 and 2017.

Mean straw CP concentration was highest in the first year, at 48 g kg^{-1}, and then dropped to 27 g kg^{-1} (Tables 3, 4; Supplemental Figure S2). Row spacing did not affect CP, either across all years or within individual years. However, CP was higher in Ctrl than in all of the defoliated treatments across all years. The effect of defoliation was not evident in 2015, but all defoliation treatments reduced CP in the following two years.

Straw P concentration was highest in 2015 (1.9 g kg^{-1}), intermediate in 2016 (1.2 g kg^{-1}), and lowest in 2017 (0.70 g kg^{-1}; Tables S1, S2). Across all years, defoliation reduced straw P concentration by roughly 0.30 g kg^{-1}; this effect was strongest in 2016 and 2017. Straw K concentration dropped sharply after the first year, from 24 g kg^{-1} to a mean of 7.8 g

TABLE 3 Tests of fixed effects on straw, hay, and total forage (straw + hay) yields, relative feed value (RFV), and crude protein, with various specifications of split-plot mixed-effect linear models

		Yield					RFV			Crude protein		
	Fixed effect	Straw	Spring hay	Fall hay	Total hay	Total forage	Straw	Spring hay	Fall hay	Straw	Spring hay	Fall hay
Full model	Year (Y)	***	***	***	NS[a]	***	***	***	***	***	***	***
	Row spacing (R)	***	***	NS	***	***	NS	NS	NS	NS	NS	NS
	Defoliation (D)	**	*	***	***	***	***	*	NS	***	NS	NS
	Y × R	***	***	**	***	***	NS	***	NS	NS	**	NS
	Y × D	***	***	**	***	***	**	***	*	***	NS	**
	R × D	NS	NS	***	***	NS	NS	NS	NS	NS	NS	NS
	Y × R × D	NS	NS	NS	***	*	NS	**	NS	NS	NS	NS
Year only		***	***	***	NS	***	***	***	***	***	***	***
Row spacing only		**	**	***	***	***	NS	NS	NS	NS	NS	NS
Defoliation only		**	**	NS	***	***	***	*	NS	***	NS	NS
2015	Row spacing	***	***	***	***	***	NS	*	NS	NS	*	NS
	Defoliation[b]	**	NS	NS	***	**	NS	NS	NS	NS	NS	NS
	R × D	NS	NS	**	***	NS	NS	NS	NS	NS	NS	NS
2016	Row spacing	***	**	***	***	***	*	***	NS	NS	NS	NS
	Defoliation	***	NS	NS	***	***	***	NS	NS	***	NS	NS
	R × D	NS	NS	NS	***	**	NS	**	NS	NS	NS	NS
2017	Row spacing	***	NS	NS	NS	***	NS	***	NS	NS	NS	NS
	Defoliation	*	**	*	***	**	**	**	NS	***	NS	*
	R × D	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS

* Significant at the .05 probability level;
** Significant at the .01 probability level;
*** Significant at the .001 probability level.

[a] NS, not significant.

[b] Because the fall defoliation had not occurred yet in 2015, the Ctrl and Fa defoliation treatments were pooled and the Sp and SpFa defoliation treatments were pooled for straw and spring hay.

TABLE 4 Mean straw and hay relative feed value (RFV) and crude protein as determined by near-infrared reflectance spectroscopy, by year, row spacing, and defoliation treatment. Within each category, numbers within a column that share a letter are not significantly different at the α = .05 level with a Tukey correction for multiple comparisons. Letters in bold indicate years in which there was a significant interaction between defoliation and row spacing. Interactions are displayed in Supplemental Figures S1, S2

		RFV			Crude protein		
		Straw	Spring hay	Fall hay	Straw	Spring hay	Fall hay
					g kg^{-1}		
Year	2015	57c	161a	107a	48a	288a	132a
	2016	65b	148b	89b	27b	220b	128a
	2017	70a	147b	107a	26b	195c	105b
Row spacing	15 cm	64a	145a	101a	34a	231a	122a
	30 cm	63a	153a	101a	33a	230a	122a
	61 cm	64a	150a	102a	35a	236a	121a
Defoliation	Ctrl	70a	–	–	48a	–	–
	Fa	61b	–	101a	26b	–	121a
	Sp	63b	144b	–	32b	239a	–
	SpFa	62b	155a	101a	28b	225a	122a
2015[a]	15 cm	56a	153b	105a	46a	269b	128a
	30 cm	57a	161ab	107a	47a	289ab	134a
	61 cm	57a	171a	110a	51a	305a	135a
	Ctrl	57a	–	–	47a	–	–
	Fa		–	105a		–	125a
	Sp	56a	162	–	50a	288	–
	SpFa			109a			139a
2016	15 cm	65ab	158**a**	89a	29a	227a	128a
	30 cm	62b	148**b**	91a	24a	216a	129a
	61 cm	68a	139**b**	89a	27a	216a	125a
	Ctrl	76a	–	–	57a	–	–
	Fa	60b	–	88a	14b	–	126a
	Sp	64b	146**a**	–	23b	230a	–
	SpFa	59b	151**a**	90a	10b	209a	129a
2017	15 cm	72a	126b	108**a**	27a	200a	109a
	30 cm	70a	150a	106**a**	27a	193a	103a
	61 cm	69a	143a	108**a**	25a	196a	103a
	Ctrl	76a	–	–	40a	–	–
	Fa	67b	–	110**a**	19b	–	113a
	Sp	69b	133b	–	21b	199a	–
	SpFa	70b	161a	105**a**	25b	191a	97b

[a] Because the fall defoliation had not occurred yet in 2015, the Ctrl and Fa defoliation treatments were pooled and the Sp and SpFa defoliation treatments were pooled for straw and spring hay.

kg^{-1} in the following years. There were few effects of row spacing or defoliation, but K concentration was lower than Ctrl in all defoliation treatments in 2016.

3.3 | Spring hay yield and quality

Mean spring hay yield increased as the stand aged, with yield in 2017 (~2.4 Mg ha^{-1}) exceeding the yield in 2015 and 2016 (~1 Mg ha^{-1}; Figure 1; Tables 2, 3). Across all years, spring hay yield was higher in 15-cm than in 61-cm rows and was higher with only spring defoliation than with SpFa defoliation. The effect of row spacing was greatest in 2015, when spring hay yield declined at each successively wider row spacing. In 2016, spring hay yield was equivalent between 15- and 30-cm rows, and there was no effect of row spacing in 2017. In contrast, the distinction between Sp and SpFa defoliation did not emerge until 2017. The number of GDD accumulated before harvest was negatively related to spring hay yield ($r = -.43$, $p < .0001$).

Mean spring hay RFV declined over time, from a high in 2015 (161) to a moderate level in 2016 and 2017 (mean of 148; Tables 3, 4; Supplemental Figure S1). Overall, row spacing did not affect RFV, but it was higher with SpFa defoliation that with Sp. Within individual years, RFV alternated between increasing and decreasing with row spacing, and only increased with SpFa defoliation in 2017.

Mean spring hay CP followed the trend of RFV and declined every year, from 290 g kg^{-1} in 2015 to 200 g kg^{-1} in 2017 (Tables 3, 4; Supplemental Figure S2). Neither row spacing nor defoliation affected CP overall, but it was higher in 61-cm than 15-cm rows in 2015.

Mean spring hay P concentration also declined every year, from 4.4 g kg^{-1} in 2015 to 2.8 g kg^{-1} in 2017 (Supplemental Tables S1, S2). Neither row spacing nor defoliation affected P concentration overall, though it was higher with SpFa than with Sp defoliation in 2017. Mean spring hay K concentration declined steadily from 2015 to 2017. K concentration was higher in 61- and 30- than in 15-cm row spacings overall (38 g kg^{-1} and 36 g kg^{-1}, respectively), mostly due to a large difference in 2017. The SpFa defoliation reduced K concentration in 2016.

3.4 | Fall hay yield and quality

Fall hay yield, in contrast to spring hay, tended to decline over time. Mean yield was lower in 2017 (1.1 Mg ha^{-1}) than in 2015 and 2016 (~2.8 Mg ha^{-1}; Figure 1; Tables 2, 3). Across all years, there was no effect of defoliation treatment on fall hay yield, but row spacing had a strong effect: yield declined in each successively wider row spacing. Within individual years, the SpFa harvest increased fall hay yield in the 15-cm row spacing in 2015, but decreased yield overall in 2017. Fall hay yield was highest in 15-cm rows in both 2015 and 2016, and higher in the 30-cm than the 61-cm rows in 2016. There was no relationship between fall hay production and the number of GDD accumulated between grain harvest and fall hay harvest ($r = .04$, $p = .91$).

Mean fall hay RFV was higher in 2015 and 2017 (~107) than in 2016 (89), but did not differ by row spacing or defoliation in any year (Tables 3, 4; Supplemental Figure S1). Mean CP was lower in 2017 than in the previous two years (110 g kg^{-1} vs. ~130 g kg^{-1}) and was lower with SpFa defoliation than Fa in 2017 (Tables 3, 4; Supplemental Figure S2). Fall hay P concentration was highest in 2016 (3.0 g kg^{-1}), intermediate in 2015 (2.7 g kg^{-1}), and lowest in 2017 (2.1 g kg^{-1}); K concentration was lower in 2017 (25 g kg^{-1}) than in the previous two years (35 g kg^{-1}; Supplemental Tables S1, S2). Row spacing and defoliation did not affect P or K concentration.

3.5 | Total hay and forage yield

Mean total hay production, the sum of spring and fall hay, did not differ among years (~2.5 Mg ha^{-1}; Tables 2, 3; Figure 1). This reflects the contrasting trends in spring and fall hay yield, with the former increasing and the latter declining. Across 2015–2017, harvesting hay twice (in both spring and fall) resulted in higher total hay yield than either Sp or Fa harvest. The SpFa defoliation was more productive than Fa in every year. The Sp defoliation was the least productive in 2015 and 2016 but was equally as productive as SpFa in 2017. Averaging across years, row spacing had a strong effect on total hay yield, with the highest yield in 15-cm rows, followed by 30-cm and then 61-cm rows. The row spacing effect was not evident in 2017. Within individual years, there are many complex and contradictory interactions between the effects of defoliation and row spacing on total hay yield, due to different effects of management on spring and fall hay yield.

Mean total forage yield—the sum of spring hay, fall hay, and straw—declined after 2015 (12.3 Mg ha^{-1}) and did not vary between 2016 and 2017 (~9.6 Mg ha^{-1}; Tables 2, 3; Figure 1). Across all years, total forage yield was higher with Fa defoliation than with Sp or Ctrl and was equivalent to that with SpFa defoliation. Total forage yield was higher in the 15- and 30-cm row spacings (mean of 11 Mg ha^{-1}) and was lower in 61-cm rows (9 Mg ha^{-1}).

3.6 | Forage price and potential value

All variations in calculated forage prices were due to variations in RFV reported above. Mean calculated straw price ranged from \$92 Mg^{-1} in 2015 to \$106 Mg^{-1} in 2017 (Tables 5, 6; Supplemental Figure S3). Defoliation reduced the mean straw price by \$8-10 Mg^{-1} across all years. Mean potential straw value ha^{-1} (yield multiplied by price) was greater in 2015 and 2017 (~\$905 ha^{-1}) than in 2016 (\$733 ha^{-1}; Tables 5, 6; Supplemental Figure S4). Across all years, straw value was lower in the 61 cm row spacing than in the 30 cm spacing, and was greater in the Fa defoliation than in the SpFa and Ctrl.

Mean spring hay prices dropped from \$200 Mg^{-1} in 2015 prices to ~\$180 Mg^{-1} in 2016 and 2017 (Tables 5, 6; Supplemental Figure S3). Mean spring hay potential value rose from a mean of ~\$190 ha^{-1} in 2015 and 2016 to \$415 ha^{-1} in 2017 (Tables 5, 6; Supplemental Figure S4). Across all years, spring hay value was greater in narrow row spacings but was not affected by defoliation. Value declined with each wider row spacing in 2015 and was lower in 61-cm rows than in the narrower row spacings in 2016. However, in 2017, spring hay value was lower in 15-cm rows than in the wider row spacings. The SpFa defoliation reduced spring hay value relative to Sp in 2017.

TABLE 5 Mean straw and hay price Mg^{-1} and potential value ha^{-1}. Within each category, numbers within a column that share a letter are not significantly different at the $\alpha = .05$ level with a Tukey correction for multiple comparisons. Letters in bold indicate years in which there was a significant interaction between defoliation and row spacing. Interactions are displayed in Supplemental Figures S3, S4

		Price			**Potential value**				
		Straw	**Spring hay**	**Fall hay**	**Straw**	**Spring hay**	**Fall hay**	**Total hay**[a]	**Total forage**[a]
		$ Mg^{-1}			$ ha^{-1}				
Year	2015	92c	199a	144a	940a	195b	436a	404a	1240a
	2016	101b	186b	126b	733b	186b	331b	345a	994b
	2017	106a	177b	144a	871a	415a	163c	386a	1160a
Row spacing	15 cm	100a	183a	137a	870ab	291a	405a	456a	1210a
	30 cm	99a	190a	138a	918a	289a	300b	385a	1210a
	61 cm	100a	188a	139a	761b	226b	225c	294b	981b
Defoliation	Ctrl	106a	–	–	799b	–	–	–	799b
	Fa	96b	–	138a	967a	–	311a	311b	1280a
	Sp	98b	182b	–	840ab	288a	–	288b	1130a
	SpFa	97b	193a	138a	795b	248a	309a	536a	1340a
2015[b]	15 cm	92a	190b	141a	1060a	311a	550**a**	548**a**	268a
	30 cm	92a	199ab	143a	952ab	179b	423**ab**	386**b**	147b
	61 cm	93a	209a	147a	813b	95c	334**b**	278**c**	65c
	Ctrl	93a	–	–	1030a	–	–	–	1050b
	Fa		–	142a		–	397**a**	397**a**	1400a
	Sp	91a	200	–	852b	194	–	201**b**	1090b
	SpFa			146a			474**a**	614**a**	1430a
2016	15 cm	101ab	196**a**	125a	909a	211a	484a	463**a**	205**a**
	30 cm	98b	186**b**	127a	704b	215a	313b	352**b**	121**b**
	61 cm	103a	176**b**	125a	562b	132b	196c	219**c**	21**c**
	Ctrl	112a	–	–	502b	–	–	–	–
	Fa	96b	–	125a	916a	–	336a	336**b**	1270**a**
	Sp	100b	184**a**	–	705ab	188a	–	188**c**	–
	SpFa	94b	188**a**	127a	829a	184a	327a	511**a**	1360**a**
2017	15 cm	107a	163b	145**a**	645c	354b	181a	356a	124c
	30 cm	105a	188a	143**a**	1080a	459a	164a	415a	168a
	61 cm	105a	181a	144**a**	883b	434a	144a	385a	146b
	Ctrl	111a	–	–	845a	–	–	–	–
	Fa	102b	–	146**a**	976a	–	200a	200b	1180a
	Sp	104b	162b	–	920a	474a	–	474a	–
	SpFa	106ab	193a	141**a**	741a	357b	126b	482a	1220a

[a] Overall means by year and row spacing reflect only those defoliation treatments for which there is data in each column. Therefore, total hay numbers are different than the sums of spring and fall hay, and total forage numbers are different than the sums of straw and total hay, because different defoliation treatments are averaged in each case.

[b] Because the fall defoliation had not occurred yet in 2015, the Ctrl and Fa defoliation treatments were pooled and the Sp and SpFa defoliation treatments were pooled for straw and spring hay.

Across all years, mean fall hay price was higher in 2015 and 2017 (~$144 Mg^{-1}) than in 2016 ($126 Mg^{-1}), but did not differ by row spacing or defoliation (Tables 5, 6; Supplemental Figure S3). Fall hay potential value ha^{-1} declined each year, from $436 in 2015 to $163 in 2017 (Tables 5, 6; Supplemental Figure S4). Across all years, mean fall hay value was greater at narrow row spacings, but there was no effect in 2017. Defoliation had no effect overall, but in 2017 fall hay value was greater with Fa defoliation than with SpFa defoliation.

Mean total hay potential value did not differ among years (mean of $378 ha^{-1}; Tables 5, 6; Supplemental Figure S4). Across all years, hay value was greater in 15- and 30-cm rows than in 61-cm rows, though there was no difference in 2017.

TABLE 6 Tests of fixed effects on straw, hay, and total forage (straw + hay) price, potential value, and net return with various specifications of split-plot mixed-effect linear models

		Price			Potential value					Potential net return		
	Fixed effect	Straw	Spring hay	Fall hay	Straw	Spring hay	Fall hay	Total hay	Total forage	Straw	Total hay	Total forage
Full model	Year (Y)	***	***	***	***	***	***	**	***	**	*	***
	Row spacing (R)	NS[a]	NS	NS	***	*	***	***	***	***	***	***
	Defoliation (D)	***	*	NS	*	*	NS	***	***	*	*	**
	Y × R	NS	***	NS	***	***	***	***	***	***	***	***
	Y × D	**	***	*	***	***	**	***	***	***	***	***
	R × D	NS	NS	NS	NS	NS	**	***	*	NS	***	*
	Y × R × D	NS	**	NS	NS	*	*	**	NS	NS	***	NS
Year only		***	***	***	***	***	***	NS	***	*	NS	*
Row spacing only		NS	NS	NS	**	***	***	***	***	**	***	***
Defoliation only		***	*	NS	*	NS	NS	***	***	*	NS	**
2015[b]	Row spacing	NS	*	NS	**	***	**	***	***	**	***	***
	Defoliation	NS	NS	NS	*	NS	NS	***	**	*	**	*
	R × D	NS	NS	NS	NS	NS	*	***	NS	NS	***	NS
2016	Row spacing	*	***	NS	***	**	***	***	***	***	***	***
	Defoliation	***	NS	NS	**	NS	NS	***	***	**	***	***
	R × D	NS	**	NS	NS	NS	NS	***	**	NS	***	**
2017	Row spacing	NS	***	NS	***	**	NS	NS	***	***	NS	***
	Defoliation	**	**	NS	NS	*	*	***	***	NS	***	**
	R × D	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS

* Significant at the .05 probability level;

** Significant at the .01 probability level;

*** Significant at the .001 probability level.

[a] NS, not significant.

[b] Because the fall defoliation had not occurred yet in 2015, the Ctrl and Fa defoliation treatments were pooled and the Sp and SpFa defoliation treatments were pooled for straw and spring hay.

The SpFa defoliation resulted in among the greatest total hay value in every year, and it exceeded Sp in 2015 and 2016 and Fa in 2016 and 2017.

Mean total forage potential value ha^{-1} was greater in 2015 and 2017 (~\$1,200 ha^{-1}) than in 2016 (\$994 ha^{-1}; Tables 5, 6; Supplemental Figure S4). Across all years, total forage value ha^{-1} was greater in the 15- and 30-cm row spacings than in the 61-cm row spacing; forage value was equivalent among all defoliated treatments but lower in Ctrl.

3.7 | Net economic return

The costs of planting, controlling weeds, fertilizing, harvesting grain, and harvesting and removing straw were estimated at \$994 ha^{-1} in the establishment year (Supplemental Table S3). Costs in subsequent years were lower, at \$877 ha^{-1}, due to lower weed control costs and avoided planting costs in this perennial system. Each hay harvest was estimated to cost \$143 ha^{-1}.

Straw production alone produced negative mean potential net return (potential value minus the cost of production) in every year, but the value of the resulting grain was not included in this analysis. The loss was greater in 2016 than in 2017 (−\$144 ha^{-1} and −\$6.3, respectively) and was not different from the other two years in 2015 (−\$54 ha^{-1}; Figure 2; Tables 6, 7; Supplemental Figure S5). Across all years, the loss was greater in 61-cm rows than in 15- and 30-cm rows. Only the Fa defoliation treatment resulted in positive straw-only net return (\$46 ha^{-1}), while all other defoliation treatments resulted in negative net return. Within individual years, differences among row spacings and defoliation treatments mirror the results for straw biomass.

Mean potential net return to total hay production was \$141 ha^{-1} and did not differ among years (Tables 6, 7; Supplemental Figure S5). Across all years, net return to hay production was greater in 15- and 30-cm rows than in 61-cm rows and did not differ among defoliation treatments (Ctrl was excluded from this analysis). In 2015, net return declined at each wider row spacing under Sp and SpFa defoliation, but there were no differences under Fa defoliation. Also in 2015, SpFa defoliation produced greater net return to hay production than Sp defoliation at all row spacings, and Fa defoliation produced greater net return than Sp at 30- and 61-cm row spacings. In 2016, net return declined at each wider row spacing under Fa and SpFa defoliation, while under Sp defoliation net return was only greater in 30- than in 61-cm rows. Correspondingly, both SpFa and Fa defoliation produced greater net return than Sp in 15-cm rows, SpFa exceeded Sp in 30-cm rows, and there were no differences by defoliation in 61-cm rows. In 2017, row spacing did not affect net return to hay production, but Sp defoliation produced greater net return than SpFa, which produced greater net return than Fa.

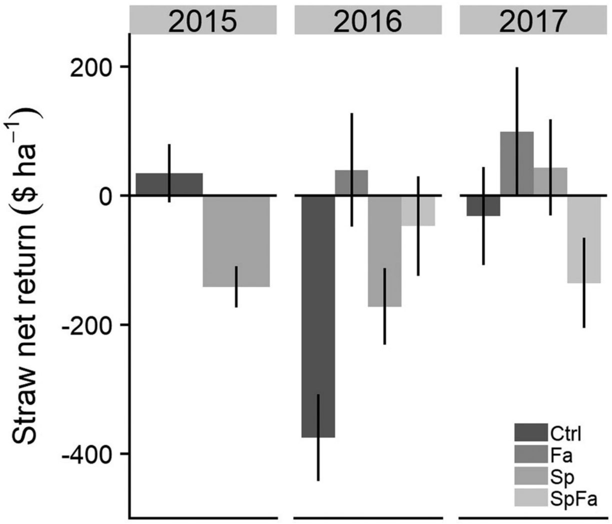

FIGURE 2 Intermediate wheatgrass straw potential net return (\$ ha^{-1}), not accounting for the value of grain or hay, by defoliation treatments (all row spacings pooled). Because the fall defoliation had not occurred yet in 2015, the Ctrl and Fa defoliation treatments were pooled (dark gray bar) and the Sp and SpFa defoliation treatments were pooled (light gray bar). Ctrl, no defoliation; Fa, defoliation in fall only; Sp, defoliation in spring only; SpFa, defoliation in spring and fall

Overall, treatment effects on potential net return to total forage mirrored those for net return to straw production, but the mean net return was greater for total forage (Tables 6, 7; Supplemental Figure S5). Net return was greater in 2017 than in 2016 (\$140 and −\$23, respectively), while it was intermediate and not different from the other years in 2015 (\$106 ha^{-1}). Net return to total forage was also greater in 15- and 30-cm row spacings than in 61-cm rows. Net return did not vary among the defoliated treatments, though only the Fa and SpFa treatments exceeded Ctrl.

4 | DISCUSSION

Successful dual-purpose management of IWG stands will require tactics that optimize both grain and forage production while maximizing net economic return. Our results show that both row spacing and defoliation for hay production affected not only forage yield and quality, but also overall profitability. Straw and hay production were typically maximized in fall-defoliated stands (Fa or SpFa) planted in narrower rows, which produced consistent positive potential net return.

Overall, straw yields were 3–4 times higher than hay yields, so straw was much more valuable than hay, despite lower quality. While straw production alone resulted in negative potential net return in many cases, the potential value of the straw typically covered a large percentage of the production costs of both grain and straw. In fall-defoliated stands (Fa or SpFa), straw production covered the full costs of grain

TABLE 7 Mean potential net return ha^{-1} to straw, hay, and total forage (straw + hay) production, not including the value of grain. Within each category, numbers within a column that share a letter are not significantly different at the $\alpha = .05$ level with a Tukey correction for multiple comparisons. Letters in bold indicate years in which there was a significant interaction between defoliation and row spacing. Interactions are displayed in Supplemental Figure S5

		Potential net return		
		Straw	**Total hay**[a]	**Total forage**[a]
		\$ ha^{-1}		
Year	2015	−54ab	160a	106ab
	2016	−144b	116a	−23b
	2017	−6a	146a	140a
Row spacing	15 cm	−46ab	199a	153a
	30 cm	1a	145a	148a
	61 cm	−157b	77b	−76b
Defoliation	Ctrl	−117b	–	−117b
	Fa	51a	168a	223a
	Sp	−76ab	145a	70ab
	SpFa	−121b	250a	136a
2015[b]	15 cm	62a	268**a**	329a
	30 cm	−42ab	147**a**	105b
	61 cm	−181b	65**b**	−116c
	Ctrl	35a	–	57ab
	Fa		254**a**	267a
	Sp	−142b	58**b**	−51b
	SpFa		328**a**	153ab
2016	15 cm	32a	205**a**	237**a**
	30 cm	−173b	121**b**	−50**b**
	61 cm	−315b	21**c**	−291**c**
	Ctrl	−375b	–	−375**b**
	Fa	39a	192**a**	248**a**
	Sp	−172ab	45**b**	−132**b**
	SpFa	−47a	225**a**	199**a**
2017	15 cm	-232c	124a	−107c
	30 cm	207a	168a	375a
	61 cm	6b	146a	152b
	Ctrl	−32a	–	−32b
	Fa	99a	57c	156ab
	Sp	43a	331a	374a
	SpFa	−136a	196b	61b

[a] Overall means by year and row spacing reflect only those defoliation treatments for which there is data in each column. Therefore, total hay numbers are different than the sums of spring and fall hay, and total forage numbers are different than the sums of straw and total hay, because different defoliation treatments are averaged in each case.

[b] Because the fall defoliation had not occurred yet in 2015, the Ctrl and Fa defoliation treatments were pooled and the Sp and SpFa defoliation treatments were pooled for straw.

and straw production. The grain yield would provide another source of revenue that would improve net return to grain and straw production. When hay production was added to the system by defoliating in spring and/or fall, the additional hay revenue always covered the hay harvesting cost, which would further improve the economics of dual-purpose IWG production.

Overall, our economic analysis represents values and net returns that may be difficult to achieve in real-world production environments. The forage samples taken in this study were removed from the field by hand and promptly placed in the drier, so they were not subject to degradation by weather or biological processes, or to mass losses in the raking and baling processes. Therefore, the two factors that determine forage value in our calculation—quality and quantity—represent maximum values. The results reported here should be taken as the upper bounds of the potential net returns to IWG forage production. Additional research is needed to quantify the economic value of IWG forage produced with field-scale equipment.

4.1 | Straw

Straw production was high and relatively consistent, with yields in the upper half of the previously reported range (Jungers et al., 2017; Pugliese, 2017; Tautges et al., 2018; Wang et al., 2014). Straw yield declined as the row spacing increased in 2015 and 2016. This could potentially be mitigated if the seeding rate ha^{-1} were kept constant in the wider rows, as it was in Koeritz et al. (2015), where row spacing did not affect the yield of perennial ryegrass vegetative biomass at seed harvest. The diminished effect of initial row spacing in the final two years—both for straw and hay yields—is in line with the literature on the population dynamics of grass swards (Donald et al., 1954; Kays & Harper, 2009; Deleuran et al., 2013).

Defoliation for hay production generally increased or did not affect straw production. The exception was the spring defoliation in 2015, the first year of the stand, when spring defoliation reduced straw yield by 16%. This may have occurred because the young plants had few initiated tillers and therefore were not able to respond to the increase in light intensity and red/far red ratio at the crown caused by defoliation. Indeed, this defoliation did not increase tiller numbers, unlike in 2016 (Hunter et al., 2020).

The decrease in straw yield after the first year occurred despite an increase in the number of elongated tillers ha^{-1} (13.8 to 15.4 million tillers ha^{-1}) between 2015 and 2017 (Hunter et al., 2020). Likewise, Fa defoliation tended to increase straw yield in 2016–2017, even though it did not maximize tiller number, and the Sp and SpFa defoliation treatments often decreased straw yield, despite resulting in greater tiller numbers. The only year in which Sp or SpFa defoliation did not negatively affect straw yield was 2016, when tiller numbers were very low. These findings indicate that overproduction of tillers does not maximize straw yield, likely due to inter-tiller competition that results in lower mass per tiller. Therefore, tiller numbers could be reduced, as we recommend for increased grain yield (Hunter et al., 2020) without jeopardizing straw yield.

Straw quality was strongly affected by defoliation for hay production, but almost never by row spacing. Defoliation consistently reduced both RFV and CP in 2016 and 2017, when it also greatly increased tiller numbers. Competition among tillers may have caused nitrogen stress, resulting in lower CP and potentially reducing leaf expansion, thereby increasing the stem/leaf ratio and reducing digestibility (Karn et al., 2006). This suggests that fertilizer rates may need to be increased in dual-purpose IWG stands, to make up for increased nutrient removal and greater tiller numbers. The CP values reported here are somewhat lower than those typically reported for IWG biomass harvested in mid-summer (Vogel, Reece, & Lamb, 1986; Heinrichs & Clark, 1961), but past studies have focused solely on forage production and so have harvested closer to flowering than to grain maturity. Our values are in line with values reported from harvest in early August (Sedivec, Tober, Duckwitz, Dewald, & Printz, 2007).

The mean calculated straw price of $92–106 was somewhat higher than the mean 2018 auction price for small grain straw in Sauk Centre, MN, which was $91, but within the observed range of $12–218 (Nathaniel Drewitz, personal communication, 2019). Slightly elevated prices may be warranted, since the mean ADF and NDF for IWG straw in this study were both slightly below the mean for wheat straw (460 g kg^{-1} vs. 510 g kg^{-1} and 760 g kg^{-1} vs. 790 g kg^{-1} dry matter, respectively; Nielsen, Stubbs, Garland-Campbell, & Carter, 2019). While straw yield declined after the first year, increasing quality mitigated the resulting drop in economic value (Tables 5, 6; Supplemental Figure S4).

The potential net return to straw production covered a wide range, from −$230 to over $200 ha^{-1}, but the value of the resulting grain was not included in this analysis. Net return was always lowest in the 61-cm rows, while the 15-cm rows were best in the first two years and the 30-cm rows were best in 2017. The Fa defoliation treatment was clearly superior for straw production, as it produced positive net return in every year and was the only treatment to produce positive return overall.

Overall, with narrower row spacings and Fa defoliation, the potential value of the straw was similar to the cost of producing both grain and straw, and often exceeded it. This indicates that, in regions with a strong market for straw, IWG straw sales have the potential to cover the total costs of production, with grain sales adding profitability. However, under current regulatory and market conditions, economic outlets for IWG grain that has been sprayed with an herbicide are very limited. Both the yields and costs of production of IWG straw may be different under organic or no-herbicide management.

4.2 | Spring hay

Spring hay production climbed from the low end of the range reported previously (Pugliese, 2017) in the first two years toward the middle of the range in 2017. The increase may be due to improved stand establishment, since annual GDD accumulation was negatively related to yield. Pugliese (2017) found that spring hay yield increased numerically between the first and second years in five out of six states. In the present study, the increase in spring hay yield was most pronounced in the wider row spacings, due to the potential for increasing colonization of interrow space over time. In contrast, the more intensive defoliation in the SpFa treatment depressed spring hay production over time, likely due to a depletion of nutrients and/or carbohydrate reserves (Alberda, 1957; Hampton & Fairey, 1997; Youngner, 1972). This is in line with the grain yield results, which showed a decline under defoliation in 2017 (Hunter et al., 2020), and with past literature on managing IWG for forage (Campbell, 1961; Heinrichs & Clark, 1961; Lawrence & Ashford, 1966).

Spring hay quality decreased over time even as yield increased, reflecting the common tradeoff between yield and quality (Heinrichs & Clark, 1961; Youngner, 1972). The CP value in 2015 (290 g kg^{-1}) was similar to that reported in Newell and Hayes (2017), and the value in 2017 (200 g kg^{-1}) was similar to that reported for leaves in Karn et al. (2006). The concentrations of N, P, and K were above the common critical values for vegetative growth in grass (25 g kg^{-1}, 2.0 g kg^{-1}, and 22 g kg^{-1}, respectively; NCDACS 2013).

Despite the higher price that resulted from SpFa defoliation, total potential value of spring hay was lower in this treatment due to reduced yield (Tables 5, 6; Supplemental Figure S4). Overall, yield was more important than price for value, so the value increased over time even as the hay quality declined.

4.3 | Fall hay

Fall hay production declined from the upper half of the reported range (Pugliese, 2017) in 2015 and 2016 to the lower end of the range in 2017. Pugliese did not find a consistent pattern in the fall hay yields between the first and second production years, which may indicate that maximum IWG fall hay yield potential is reached in the first year after planting and that interannual variation is therefore mostly due to weather conditions.

Growing degree day accumulation did not explain the yield decline, so it was likely due to the rainfall deficit in the 6 wk following grain harvest in 2017. Future studies should include multiple planting dates to avoid confounding interannual weather variability with stand age. Nutrient deficiency may have also played a role, since biomass N concentration (15–20 g kg^{-1}) was below the common critical value for vegetative grasses (25 g kg^{-1}), and the P and K concentration values (2.1 g kg^{-1} and 25 g kg^{-1}, respectively) were similar to the critical values (2.0 g kg^{-1} and 22 g kg^{-1}, respectively) in 2017. Applications of P and K fertilizer to replace the nutrients removed in the biomass, as well as a postgrain-harvest N application, could help address these declines in nutrient content.

The declining yield drove a decline in fall hay potential value over time, despite the increase in RFV in 2017. As with spring hay, the SpFa defoliation decreased fall hay yield in 2017, indicating again that intensive defoliation can deplete stand vigor.

4.4 | Total hay

The stability in total hay yield over time was due to the different patterns in spring and fall hay production across the years of the study, with spring yield increasing and fall yield declining. This is likely an idiosyncrasy of the particular years included in this study, rather than a robust feature of multi-year IWG stands. The SpFa defoliation treatment produced the most total hay in 2015 and 2016, but by 2017 it had reduced both spring and fall hay yield. As a result, it no longer out-yielded the Sp treatment in 2017. This finding is in line with past studies that found IWG had relatively low tolerance to repeated defoliation (Campbell, 1961; Heinrichs & Clark, 1961; Lawrence & Ashford, 1966).

Total hay production almost always had a positive potential net return, though in 61-cm rows with Sp defoliation it was negative in 2015 and neutral in 2016. The SpFa defoliation provided among the highest net return in the first two years, despite incurring twice the production costs of a single hay cutting, but the combination of this additional cost and falling yields led to a net return below that of Sp defoliation in 2017.

It may be prudent to limit IWG hay harvests to a single cut per year in situations in which there is at least 1 Mg ha^{-1} of biomass available and little to no risk of damaging the stand through soil compaction or removal of growing points. In general, these rules favor fall hay harvests. However, spring harvests may be viable in the right conditions, when ample biomass is present and the soil is trafficable. Spring defoliation may also help reduce lodging in rich soils. As reported in the companion paper (Hunter et al., 2020), spring defoliation caused a large decrease in lodging and increase in grain yield in 30-cm rows in 2015. These benefits may outweigh the lower profitability and higher risk of spring hay harvest.

4.5 | Total forage

Defoliation for hay production almost always increased total forage production. In some cases, hay harvest actually stimulated additional straw production, and in others the hay yield more than compensated for small reductions in straw yield. Pugliese (2017) found similar results across nine North American sites, though hay harvest never increased straw yield in any of the site-years. In contrast, Pugliese et al. (2019) found that a fall hay harvest reduced total forage production in one year. The SpFa defoliation treatment presented a tradeoff, in which more total hay was produced, but straw yield was reduced relative to a Fa cut.

Overall, there was greater potential net return from the 15- and 30-cm row spacings than the 61-cm spacing for both straw and hay, though the pattern differed by year. The 15-cm row spacing provided greater return in the first two years, and thereafter the 30-cm row spacing provided greater return. This suggests that the choice of row spacing may depend on how long a farmer intends to maintain a stand. However, grain yields were also greater in 30-cm than in 15-cm row spacings over four years (Hunter et al., 2020), so the intermediate row spacing appears to offer the best overall economic return.

The fall harvest treatment stood out for consistently producing among the greatest straw and hay potential net return, except for hay in 2017, and for producing the numerically greatest annual net return to total forage (\$223 ha^{-1}; not statistically different than the other two defoliation treatments). This suggests that harvesting only fall hay in addition to straw may be a wise, low-risk strategy for IWG forage production. The spring harvest is also more logistically challenging, given the need to cut hay before stem elongation while avoiding wet soil conditions. If hay harvest is delayed due to spring rains, wheel traffic from raking and baling operations may harm the developing culms and damage the stand.

5 | CONCLUSIONS

Straw and hay production have the potential to contribute substantially to the profitability of IWG dual-use production systems. Since the straw is highly valuable—potentially covering the total cost of grain and straw production under optimal conditions—managing for high straw yield can greatly reduce financial risk in Kernza grain production. Our results indicate that the best strategy for achieving consistently high net return to biomass production is to plant in 15- or 30-cm rows and only cut hay in the fall. However, 30-cm rows and Sp or SpFa defoliation produced the highest grain yield (Hunter et al., 2020), so the best strategy to maximize overall net return will depend on the price of Kernza grain. Further research on the economics of IWG production systems will be needed as the Kernza market develops.

Surprisingly, our findings suggest that high tiller numbers are not important for straw yield in IWG and may even be detrimental to yield when they cause excessive inter-tiller competition. This supports the breeding targets outlined in the companion paper (Hunter et al., 2020), particularly the need to reduce culmed tiller numbers and to limit rhizomatous growth. If these targets are met, it is likely that 15-cm rows will become more advantageous than 30-cm rows for both grain and biomass production.

The goal of Kernza development is to provide an environmentally sustainable source of grain for human consumption. However, the economic viability of this new crop enterprise may depend heavily on its biomass coproducts. This study shows that harvesting IWG straw and hay may be critical to the profitability of Kernza production systems.

ACKNOWLEDGMENTS

The authors would like to acknowledge the help of the many people who helped make this work possible, especially Joshua Larson, Brett Heim, Lindsay Wilson, and Katherine Bohn. Weather data were obtained from the NASA Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science/Applied Science Program.

ORCID

Mitchell C. Hunter https://orcid.org/0000-0002-4562-7806
Jacob M. Jungers https://orcid.org/0000-0001-8954-7325

REFERENCES

AAEA Task Force. (2000). *Commodity costs and returns estimation handbook: A Report of the AAEA Task Force on Commodity Costs and Returns*. Ames, IA: Natural Resources Conservation Service.

[NCDACS] North Carolina Department of Agriculture and Consumer Services Agronomic Division. (2013). Reference sufficiency ranges for plant analysis in the southern region. In C. R. Campbell, (Ed.), *Southern Cooperative Series Bulletin No. 394*. Raleigh, NC: NCDACS.

Aamlid, T. S., Heide, O. M., Christie, B. R., & McGraw, R. L. (1997). Reproductive development and the establishment of potential seed yield in grasses and legumes. In D. T. Fairey & J. G. Hampton (Eds.), *Forage seed production* (Vol. *1*, pp. 9–44). Wallingford, UK: CAB International.

Alberda, T. (1957). The effects of cutting, light intensity and night temperature on growth and soluble carbohydrate content of *Lolium perenne* L. *Plant and Soil*, *3*, 199–230. https://doi.org/10.1007/BF01666158

Asbjornsen, H., Hernandez-Santana, V., Liebman, M., Bayala, J., Chen, J., Helmers, M., … Schulte, L. A. (2013). Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. *Renewable Agriculture and Food Systems*, *29*, 101–125. https://doi.org/10.1017/S1742170512000385

Bell, L. W., Byrne, F., (nee Flugge), Ewing, M. A., & Wade, L. J. (2008). A preliminary whole-farm economic analysis of perennial wheat in an Australian dryland farming system. *Agricultural Systems*, *96*, 166–174. https://doi.org/10.1016/j.agsy.2007.07.007

Black, A. L., & Reitz, L. L. (1969). Row spacing and fertilization influences on forage and seed yields of intermediate wheatgrass, Russian wildrye, and green needlegrass on dryland. *Agronomy Journal*, *61*, 801–805. https://doi.org/10.2134/agronj1969.00021962006100050045x

Blodgett, S. L., Lenssen, A. W., & Cash, S. D. (2006). Black grass bug (*Hemiptera:Miridae*) damage to intermediate wheatgrass forage quality. *Journal of Entomological Science*, *41*, 92–94. https://doi.org/10.18474/0749-8004-41.1.92

Campbell, J. B. (1961). Continuous versus repeated-seasonal grazing of grass–alfalfa mixtures at Swift Current, Saskatchewan. *Journal of Range Management*, *14*, 72–77.

de Oliveira, G., Brunsell, N. A., Sutherlin, C. E., Crews, T. E., & DeHaan, L. R. (2018). Energy, water and carbon exchange over a perennial Kernza wheatgrass crop. *Agricultural and Forest Meteorology*, *249*, 120–137. https://doi.org/10.1016/j.agrformet.2017.11.022

DeHaan, L., Christians, M., Crain, J., & Poland, J. (2018). Development and evolution of an intermediate wheatgrass domestication program. *Sustain*, *10*, 1–19. https://doi.org/10.3390/su10051499

Deleuran, L. C., Gislum, R., & Boelt, B. (2009). Cultivar and row distance interactions in perennial ryegrass. *Acta Agriculturae Scandinavica, Section B - Plant Soil Science*, *59*, 335–341. https://doi.org/10.1080/09064710802176642

Deleuran, L. C., Gislum, R., & Boelt, B. (2010). Effect of seed rate and row spacing in seed production of *Festulolium*. *Acta Agriculturae Scandinavica, Section B - Plant Soil Science*, *60*, 152–156. https://doi.org/10.1080/09064710902744463

Deleuran, L. C., Kristensen, K., Gislum, R., & Boelt, B. (2013). Optimizing the number of consecutive seed harvests in red fescue (*Festuca rubra* L.) and perennial ryegrass (*Lolium perenne* L.) for yield, yield components and economic return. *Acta Agriculturae Scandinavica, Section B - Plant Soil Science*, *63*, 1–10. https://doi.org/10.1080/09064710.2012.703229

Deregibus, V. A., Sanchez, R. A., & Casal, J. J. (1983). Effects of light quality on tiller production in *Lolium* spp. *Plant Physiology*, *72*, 900–902. https://doi.org/10.1104/pp.72.3.900

Dick, C., Cattani, D., & Entz, M. (2018). Kernza intermediate wheatgrass (*Thinopyrum intermedium*) grain production as influenced by legume intercropping and residue management. *Canadian Journal of Plant Science*, *98*, 1376–1379. https://doi.org/10.1139/cjps-2018-0146

Donald, C. M. (1954). Competition among pasture plants II. The influence of density of flowering and seed production in annual pasture plants. *Australian Journal of Agricultural Research*, *5*, 585–597. https://doi.org/10.1080/00288233.1973.10421159

Dove, H., & Kirkegaard, J. (2014). Using dual-purpose crops in sheep-grazing systems. *Journal of the Science of Food and Agriculture*, *94*, 1276–1283. https://doi.org/10.1002/jsfa.6527

Glover, J. D., Reganold, J. P., Bell, L. W., Borevitz, J., Brummer, E. C., Buckler, E. S., … Xu, Y. (2010). Increased food and ecosystem security via perennial grains. *Science*, *328*, 1638–1639. https://doi.org/10.1126/science.1188761

Green, J. O., & Evans, T. A. (1957). Grazing management for seed production in leafy strains of grasses. *Grass and Forage Science*, *12*, 4–9. https://doi.org/10.1111/j.1365-2494.1957.tb00085.x

Hampton, J. G., & Fairey, D. T. (1997). Components of seed yield in grasses and legumes. In D. T. Fairey & J. G. Hampton (Eds.), *Reproductive development and the establishment of potential seed yield in grasses and legumes* (pp. 45–69). Wallingford, UK: CAB International.

Han, Y., Wang, X., Hu, T., Hannaway, D. B., Mao, P., Zhu, Z., … Li, Y. (2013). Effect of row spacing on seed yield and yield components of five cool-season grasses. *Crop Science*, *53*, 2623–2630. https://doi.org/10.2135/cropsci2013.04.0222

Hare, M. D. (1993). Post-harvest and autumn management of tall fescue seed fields. *New Zealand Journal of Agricultural Research*, *36*, 407–418. https://doi.org/10.1080/00288233.1993.10417741

Hebblethwaite, P. D., & Clemence, T. G. A. 1981. Effect of autumn and spring defoliation and defoliation method on seed yield of *Lolium perenne*. 257–260. In J. A. Smith & V. W. Hays (eds.), *Proceedings of the 14th International Grasslands Conference*. Lexington, KY: International Grassland Congress.

Heinrichs, D. H., & Clark, K. W. (1961). Clipping frequency and fertilizer effects on productivity and longevity of five grasses. *Canadian Journal of Plant Science*, *41*, 98–108. https://doi.org/10.4141/cjps61-013

Hendrickson, J. R., Berdahl, J. D., Liebig, M. A., & Karn, J. F. (2005). Tiller persistence of eight intermediate wheatgrass entries grazed at three morphological stages. *Agronomy Journal*, *97*, 1390–1395. https://doi.org/10.2134/agronj2004.0179

Hunter, M. C., Sheaffer, C. C., Culman, S. W., & Jungers, J. M. (2020). Effects of defoliation and row spacing on intermediate wheatgrass I: Grain production. *Agronomy Journal*, https://doi.org/10.1002/agj2.20128

Jungers, J. M., DeHaan, L. R., Betts, K. J., Sheaffer, C. C., & Wyse, D. L. (2017). Intermediate wheatgrass grain and forage yield responses to nitrogen fertilization. *Agronomy Journal*, *109*, 462–472. https://doi.org/10.2134/agronj2016.07.0438

Jungers, J. M., DeHaan, L. H., Mulla, D. J., Sheaffer, C. C., & Wyse, D. L. (2019). Reduced nitrate leaching in a perennial grain crop compared to maize in the Upper Midwest, USA. *Agriculture, Ecosystems & Environment*, *272*, 63–73. https://doi.org/10.1016/j.agee.2018.11.007

Karn, J. F., Berdahl, J. D., & Frank, A. B. (2006). Nutritive quality of four perennial grasses as affected by species, cultivar, maturity, and plant tissue. *Agronomy Journal*, *98*, 1400–1409. https://doi.org/10.2134/agronj2005.0293

Kays, A. S., & Harper, J. L. (2009). The Regulation of Plant and Tiller Density in a Grass Sward. *Journal of Ecology*, *62*(1): 97–105. https://www.jstor.org/stable/2258882

Koeritz, E. J., Watkins, E., & Ehlke, N. J. (2015). Seeding rate, row spacing, and nitrogen rate effects on perennial ryegrass seed production. *Crop Science*, *55*, 2319–2333. https://doi.org/10.2135/cropsci2014.02.0130

Lawrence, T. (1980). Seed yield of Altai wild ryegrass as influenced by row spacing and fertilizer. *Canadian Journal of Plant Science*, *60*, 249–253. https://doi.org/10.4141/cjps80-034

Lawrence, T., & Ashford, R. (1966). The productivity of intermediate wheatgrass as affected by initial harvest dates and recovery periods. *Canadian Journal of Plant Science*, *46*, 9–15. https://doi.org/10.4141/cjps66-002

Lawrence, T., Warder, F. G., & Ashford, R. (1971). Effect of stage and height of cutting on the crude protein content and crude protein yield of intermediate wheatgrass, bromegrass, and reed canarygrass. *Canadian Journal of Plant Science*, *51*, 41–48. https://doi.org/10.4141/cjps71-008

Lawrence, T., & Lodge, R. W. (1975). Grazing seed field aftermath of Russian wild ryegrass, Altai wild ryegrass and green needlegrass. *Canadian Journal of Plant Science*, *55*, 397–406. https://doi.org/10.4141/cjps75-063

Lazarus, W. F., & Keller, A. (2018). *Crop enterprise budgets for use in the working lands watershed restoration project: Key results, spreadsheet design, and data sources*. St. Paul, MN: Minnesota Board of Water and Soil Resources (BWSR).

Lazarus, W. F. (2018). *Farm machinery economic cost estimation spreadsheet (MACHDATA.XLSM)*. St. Paul, MN: University of Minnesota Extension.

Lenth, R. (2018). emmeans: Estimated marginal means, aka least-squares means. https://cran.r-project.org/web/packages/emmeans/index.html

Moore, K. J., Vogel, K. P., Klopfenstein, T. J., Masters, R. A., & Anderson, B. E. (1995). Evaluation of four intermediate wheatgrass populations under grazing. *Agronomy Journal*, *87*, 744–747. https://doi.org/10.2134/agronj1995.00021962008700040022x

Moore, J. E., & Undersander, D. J. (2002). Relative forage quality: An alternative to relative feed value and quality index. In *13th Annual Florida Ruminant Nutrition Symposium* (pp. 16–32).

[NASS] National Agricultural Statistics Service. (2019). *Quick stats*. Washington, DC: USDA NASS.

Newell, M. T., & Hayes, R. C. (2017). An initial investigation of forage production and feed quality of perennial wheat derivatives. *Crop Pasture Science*, *68*, 1141–1148. https://doi.org/10.1071/cp16405

Nielsen, N. S., Stubbs, T. L., Garland-Campbell, K. A., & Carter, A. H. (2019). Rapid estimation of wheat straw decomposition constituents using near-infrared spectroscopy. *Agronomy*, *9*, 462. https://doi.org/10.3390/agronomy9080462

Ogle, D. (2018). Intermediate Wheatgrass: *Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey. Boise, ID. http://phytozome.jgi.doe.gov/

Pinheiro, J., Bates, D., DebRoy, S., & Sarkar D, R. C. T. (2018). nlme: Linear and nonlinear mixed effects models. Retrieved from https://cran.r-project.org/package=nlme

Pugliese, J. Y. (2017). *Above-and belowground response to managing kernza (Thinopyrum intermedium) as a dual-use crop for forage and grain*. [Master's thesis, The Ohio State University].

Pugliese, J. Y., Culman, S. W., & Sprunger, C. D. (2019). Harvesting forage of the perennial grain crop Kernza (*Thinopyrum intermedium*) increases root biomass and soil nitrogen. *Plant and Soil*, *437*, 241–254. https://doi.org/10.1007/s11104-019-03974-6

Pumphrey, F. V. (1965). Residue management in Kentucky bluegrass (*Poa pratensis* L.) and red fescue (*Festuca rubra* L.) seed fields. *Agronomy Journal*, *57*, 559–561.

R Core Team. (2018). R: A language for statistical computing. Retrieved from https://www.r-project.org/

Rohweder, D. A., Barnes, R. F., & Jorgensen, N. (1978). Proposed hay grading standards based on laboratory analyses for evaluating quality. *Journal of Animal Science*, *47*, 747–759.

Sedivec, K. K., Tober, D. A., Duckwitz, W. L., Dewald, D. D., & Printz, J. L. (2007). *Grasses for the Northern Plains: Growth patterns, forage characteristics and wildlife values* (Vol. 1: Cool-season). North Dakota State University Extension Service

Shenk, J. S., & Westerhaus, M. O. (1991). Population structuring of near infrared spectra and modified partial least squares regression. *Crop Science*, *31*, 1548–1555. https://doi.org/10.2135/cropsci1991.0011183x003100060034x

Tautges, N. E., Jungers, J. M., Dehaan, L. R., Wyse, D. L., & Sheaffer, C. C. (2018). Maintaining grain yields of the perennial cereal intermediate wheatgrass in monoculture v. bi-culture with alfalfa in the Upper Midwestern USA. *Journal of Agricultural Science*, *156*, 758–773. https://doi.org/10.1017/S0021859618000680

Ugarte, C. C., Trupkin, S. A., Ghiglione, H., Slafer, G., & Casal, J. J. (2010). Low red/far-red ratios delay spike and stem growth in wheat. *Journal of Experimental Botany*, *61*, 3151–3162. https://doi.org/10.1093/jxb/erq140

Vogel, K. P., Reece, P. E., & Lamb, J. F. S. (1986). Genotype and genotype × environment interaction effects for forage yield and quality of intermediate wheatgrass. *Crop Science*, *26*, 653–658. https://doi.org/10.2135/cropsci1986.0011183X002600040001x

Wang, G. J., Nyren, P., Xue, Q. W., Aberle, E., Eriksmoen, E., Tjelde, T., … Nyren, A. (2014). Establishment and yield of perennial grass monocultures and binary mixtures for bioenergy in North Dakota. *Agronomy Journal*, *106*, 1605–1613. https://doi.org/10.2134/agronj14.0068

Watt, D. (1989). Economic feasibility of a perennial grain: Intermediate wheatgrass. In *Grass or grain? Intermediate wheatgrass in a perennial cropping system for the Northern Plains* (pp. 11–13). Fargo: ND: North Dakota State University Rodale Research Center.

Youngner, V. B. (1972). Physiology of defoliation and regrowth In V. B. Youngner & C. M. McKell (Eds.), *The biology and utilization of grasses* (pp. 292–303). New York, NY: Academic Press.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Hunter MC, Sheaffer CC, Culman SW, Lazarus WF, Jungers JM. Effects of defoliation and row spacing on intermediate wheatgrass II: Forage yield and economics. *Agronomy Journal*. 2020;112:1862–1880. https://doi.org/10.1002/agj2.20124