Received: 13 January 2022 | Accepted: 11 April 2022

DOI: 10.1002/agg2.20274

Agrosystems, Geosciences & Environment OPEN ACCESS

ORIGINAL RESEARCH ARTICLE

Agrosystems

Forage yield and profitability of grain-type intermediate wheatgrass under different harvest schedules

Jesse Puka-Beals | **Craig C. Sheaffer** | **Jacob M. Jungers**

Dep. of Agronomy and Plant Genetics, Univ. of Minnesota, 1991 Upper Buford Circle, Saint Paul, MN 55108, USA

Correspondence
Jacob M. Jungers, Dep. of Agronomy and Plant Genetics, Univ. of Minnesota, 1991 Upper Buford Circle, Saint Paul, MN 55108, USA.
Email: junge037@umn.edu

Assigned to Associate Editor Emi Kimura.

Abstract

Intermediate wheatgrass [*Thinopyrum intermedium* (Host) Barkworth & Dewey] (IWG) is a perennial forage grass being domesticated to function as a perennial grain crop. Grain yield of improved, grain-type IWG cultivars decline by the third year of production and managing aging stands for forage production presents economic opportunities. Limited research is available on the response of second- and third-year grain-type IWG to different forage harvest schedules. We measured forage yield and nutritive value of grain-type IWG in the second and third year of production under nine forage harvest schedules varying in the timing of the first harvest (at boot, anthesis, or soft dough stage) and the number of fall harvests (none, one [Sept.], or two [Sept. and Nov.]). As timing of the first harvest was delayed and IWG maturity increased from boot to soft dough, yield increased from 2.4 to 3.7 Mg ha^{-1} and relative feed value decreased from 113 to 82. Yield at subsequent September and November harvests averaged 30% and 12% of the initial harvest yield, respectively. Total annual forage yield was not affected by the timing of the first harvest but was predictably greater for two or three harvests compared with one harvest; however, additional harvests in September and November decreased net returns. Grain-type IWG stands harvested in the third year after peak grain production have potential to provide forage similar to common perennial cool season forage grasses. Tradeoffs between forage yield and nutritive value should be considered when selecting the timing of the initial spring forage harvest.

1 | INTRODUCTION

Intermediate wheatgrass [*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey] (IWG) is an introduced, cool-season perennial grass used as a forage crop in the U.S. Great Plains (Asay & Jensen, 1996). It is also being domesticated for use as a perennial grain crop, and food-grade grain harvested from improved populations of IWG is identified as Kernza (DeHaan et al., 2018). Progress in breeding has culminated in the release of the first commercial IWG cultivar 'MN-Clearwater' which has improved grain yield, reduced shattering, reduced lodging, and uniform maturity compared with forage-type IWG (Bajgain et al., 2020). However, grain yield of IWG declines with stand age (Hunter et al., 2020a). For example, Bajgain et al. (2020) reported that yields of MN-Clearwater averaged nearly 700 kg ha^{-1} in the first year

Abbreviations: ADF, acid detergent fiber; CP, crude protein; GDD, growing degree days; IWG, intermediate wheatgrass; NDF, neutral detergent fiber; NDFD, NDF digestibility; RFV, relative feed value.

following seeding, but that yields declined 77% by the third year of production. Hunter et al. (2020a) also in Minnesota reported that grain yields of an improved IWG line (Cycle 4 selection by the Land Institute, Salinas, KS) declined 70% from the first to fourth year of production.

Intermediate wheatgrass has appeal as a perennial grain crop because it can provide multiple ecosystem services with minimum annual inputs such as tillage, which results in perennial ground cover with a deep and extensive fibrous root system (Ryan et al., 2018). Therefore, it has potential to provide ecosystem services, such as reduced nutrient leaching and improved nutrient cycling (Culman et al., 2013; Jungers et al., 2019; Pugliese et al., 2019).

Relatively low grain yields compared with annual grain crops such as wheat (*Triticum aestivum* L.) combined with declining yield over time reduce the economic viability of Kernza. Moreover, the price of Kernza grain is volatile as the crop enters the early stages of commercialization, thus increasing financial risk to growers. To overcome these economic challenges, IWG has been proposed as a dual-use crop where income is provided through both forage and grain production (Favre et al., 2019; Hunter et al., 2020b; Pugliese et al., 2019). In this scenario, forage is harvested in the spring and/or the fall with grain and straw harvested in the summer. Studies in Minnesota (Hunter et al., 2020b) and Wisconsin (Favre et al., 2019) showed that when harvested at a late vegetative stage in the spring, IWG had a forage yield averaging 1.5 Mg ha^{-1} with a relative feed value (RFV) of 163, and forage yields of 1.8 Mg ha^{-1} with an average RFV of 108 when harvested at a vegetative stage in late fall.

Another management strategy for achieving economic gain from aging Kernza production fields with low grain yield is to manage the stands primarily for forage production, which may include harvesting after stem elongation to increase forage yields. Like many cool-season grasses, IWG biomass yield follows a logistic response to growing degree days (GDD), with yields increasing through vegetative and stem elongation stages until plateauing at flowering (Jungers et al., 2018). With development, leaf fraction decreases while stem fraction increases. Therefore, forage nutritive value of many cool-season grasses decreases because stems have higher neutral detergent fiber (NDF) and lower digestibility and nitrogen (N) content compared with leaves (Buxton et al., 1996; Karn et al., 2006). However, there is no information available on the forage yield and forage nutritive value of older stands of new grain type IWG populations when initially harvested over a range of maturities typically used for forage harvest followed by harvests in the fall. Our objective was to determine the effect of three harvest systems on forage yield and nutritive value of mature IWG stands initially established and managed for grain production. This research will allow producers to determine the appropriate harvest timing to provide forage for livestock with different nutrient needs.

Core Ideas

- Intermediate wheatgrass (IWG) is perennial grass being bred as a grain crop.
- Grain yield of IWG decline with stand age, thus converting stands to forage production can extend profitability.
- Increasing forage harvests from 1 to 2 or 3 increased annual forage yield, but not net returns.
- For single-harvest systems, yields were greater when harvested at the anthesis or dough stage compared with boot.
- Forage nutritive value was negatively associated with yield as maturity increased with later harvest timing.

2 | MATERIALS AND METHODS

An experiment was conducted using two existing IWG fields from 2017 to 2019 under nonirrigated conditions at the University of Minnesota Agricultural Experiment Station in Rosemount, MN (44.988291, −93.175625) on a Tallula silt loam (coarse-silty, mixed, superactive, mesic Typic Hapludolls). The first field was seeded in 2015 and forage harvest treatments were first imposed in spring 2017 and were applied again in 2018. Baseline soil pH was 6.7, organic matter 3.5%, and P and K were 3, and 61 ppm, respectively, in the top 15 cm. The second field was seeded in fall 2016 and forage harvest treatments were first imposed in spring 2018 and were applied again in 2019. Baseline soil pH was 6.4 and N, P, and K were 5.5, 3.8, and 134.4 ppm, respectively, in the top 15 cm. Seed for both fields was from improved grain-type IWG populations developed by the breeding program at The Land Institute (Salina, KS). Seed for the first field was the fourth cycle of selection and seed from the second field was from the fifth cycle of selection. Both fields were seeded with 45 cm spacing between rows; however, as a result of inter-row recruitment via tillering and volunteers from shattered seed, there was little to no bare ground remaining between rows at the initiation of the forage harvest experiment. In the years before the forage harvesting experiment, straw and grain were removed annually in August with no additional defoliation, and both fields were fertilized with 67 kg N ha^{-1} in April of each year.

The experimental design was a randomized complete block design. There were four replicates of the nine unique treatments analyzed in a split-plot arrangement. Whole plot treatments varied IWG maturity stage at the first harvest: boot (R0), anthesis (R4), and soft dough (S2) and split-plot treatments were three harvest intensities achieved by applying

TABLE 1 Dates of forage harvests for each environment at the Rosemount Research and Outreach Center in Rosemount, MN, in 2017, 2018, and 2019

Environment (field/year)	Year	Boot	Anthesis	Dough	Second harvest	Third harvest
Field 1/Year 1	2017	6 June	21 June	17 July	15 Sept.	1 Nov.
Field 1/Year 2	2018	7 June	25 June	18 July	–	–
Field 2/Year 1	2018	7 June	25 June	18 July	27 Sept.	1 Nov.
Field 2/Year 2	2019	10 June	5 July	25 July	23 Sept.	28 Oct.

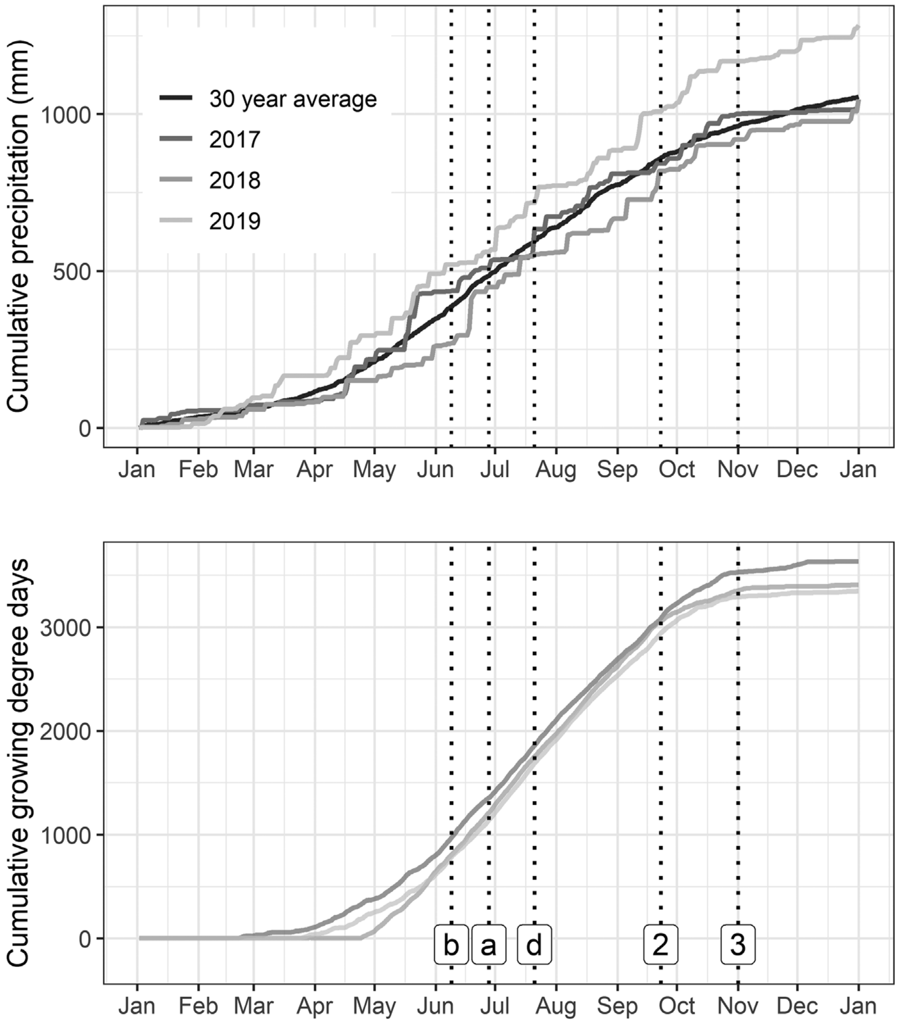

FIGURE 1 Precipitation and growing degree days (base 0 ˚C) in 2017, 2018, and 2019 at Rosemount, MN. The average date for data collection is plotted for reference where the dotted line labeled (b) represents the boot stage, (a) anthesis, (d) dough at the first harvest, (2) is when the second harvest occurred, and (3) when the third harvest occurred. Daily temperature and precipitation data were obtained primarily from the Minnesota Department of Natural Resources weather station at the Rosemount Research and Outreach Center (Station ID: 217107)

additional harvests in September and November to achieve (a) one harvest (first harvest only), (b) two harvests (first harvest plus September harvest), and (c) three harvests (first harvest, plus harvests in September and November). Plant stage at the September and November harvests were vegetative and culmless (V3). Dates of harvest are shown in Table 1. Morphological stage of development at each harvest was quantified following Moore et al. (1991).

Forage yield was determined by harvesting a 0.9 × 3 m area with a flail harvester set to leave an 8-cm stubble within each individual plot with a dimension of 1.5 × 3.7 m. Mechanically harvested forage was weighed, and dry matter

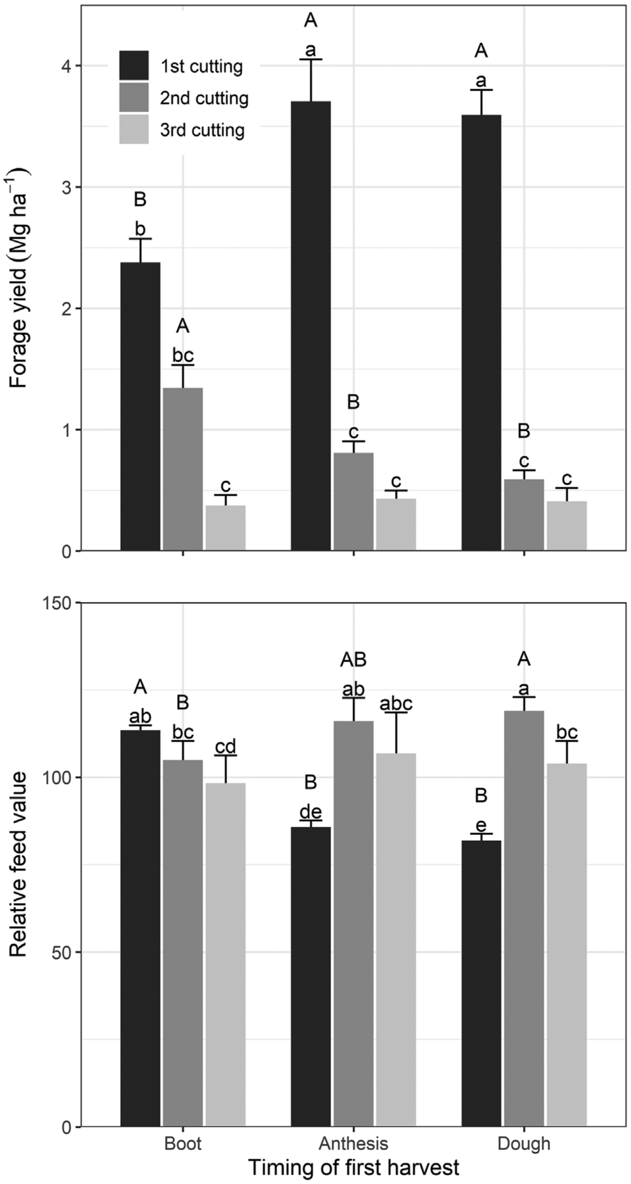

FIGURE 2 Intermediate wheatgrass forage yield and nutritive value at the first, second, and third harvests depending on the timing of the first harvest. Bars represent the mean and error bars represent the standard error of the mean. Bars that do not share the same letter differ according to Tukey honestly significant difference test (a = 0.05). Upper-case letters compare means within the same harvest timing (first, second or third harvest of the year) and across timings of first harvest (Table 2), while lower-case letters compare values across all combinations of harvest and timing of first harvest

yield was determined. To determine forage dry matter content and forage nutritive value, random duplicate samples were hand-harvested from nonborder rows within each plot to a stubble height of 8 cm, weighed fresh, dried at 60 ˚C in a forced air oven until constant mass, and weighed for dry matter determination. Subsamples were ground to pass through a 6-mm screen in a Wiley mill (Thomas Scientific, Swedesboro, NJ) followed by a 1-mm screen Cyclotec (Model CT293; Foss, Hillerød, Denmark). Crude protein (CP), NDF, NDF digestibility (NDFD), and acid detergent fiber (ADF) of ground samples were determined with near infrared reflectance spectroscopy using a Perten NIRS (Model DA 7200; Perten Instruments) with calibration equations developed in Minnesota and validated with wet chemistry. The relative feed value (RFV) of the forage was calculated based on equations from Moore and Undersander (2002). Relative feed value was used to predict forage prices using data from the nearest regional hay auction and regressions models developed by Hunter et al. (2020b). Although relative forage quality is considered a better metric for grasses when estimating animal performance, RFV was used here because it was the quality metric reported for pricing forages. Moreover, RFV is a suitable metric for comparing the relative differences in forage quality among harvest treatments. Variable input costs used in this analysis included equipment, labor, and fuel associated with mowing, raking, and baling for each harvest and were derived from enterprise budgets by Lazarus (2018).

Daily temperature and precipitation data were obtained from the Minnesota Department of Natural Resources weather station at the Rosemount Research and Outreach Center (Station ID: 217107). Missing data from the weather station was supplemented with satellite observations (Sparks, 2018). Growing degree days were calculated with a base of 0 ˚C and a maximum of 30 ˚C.

2.1 | Statistics

All statistical analyses were performed in R (R Core Team, 2021). Hypotheses were tested by developing a global model that included maturity stage at first harvest, harvest intensity (number of harvests following the initial spring harvest), and their interaction as fixed effects and a nested random effects structure of environment (field/year combination), block, and maturity stage at first harvest. For responses that were not cumulative (e.g., yields of an individual harvest in a given year), the harvest number (first vs. second vs. third harvest of the year) was included in the factorial combination of the fixed effects Table s1. Mixed effect models were generated using the *lme4* package (Bates et al., 2020) and assessed using the criterion specified by the package author (Bates et al., 2015). Differences among fixed effects were tested using the analysis of variance function of the *car* package (Fox & Weisberg, 2019). If differences were detected, pairwise comparisons among the estimated marginal means were evaluated with the *emmeans* package (Lenth, 2021) with a Tukey adjustment for multiple comparisons. Additional submodels from the global model were constructed for each response variable where random effects that did not explain variance were removed based on likelihood ratio tests confirmed by Akaike information

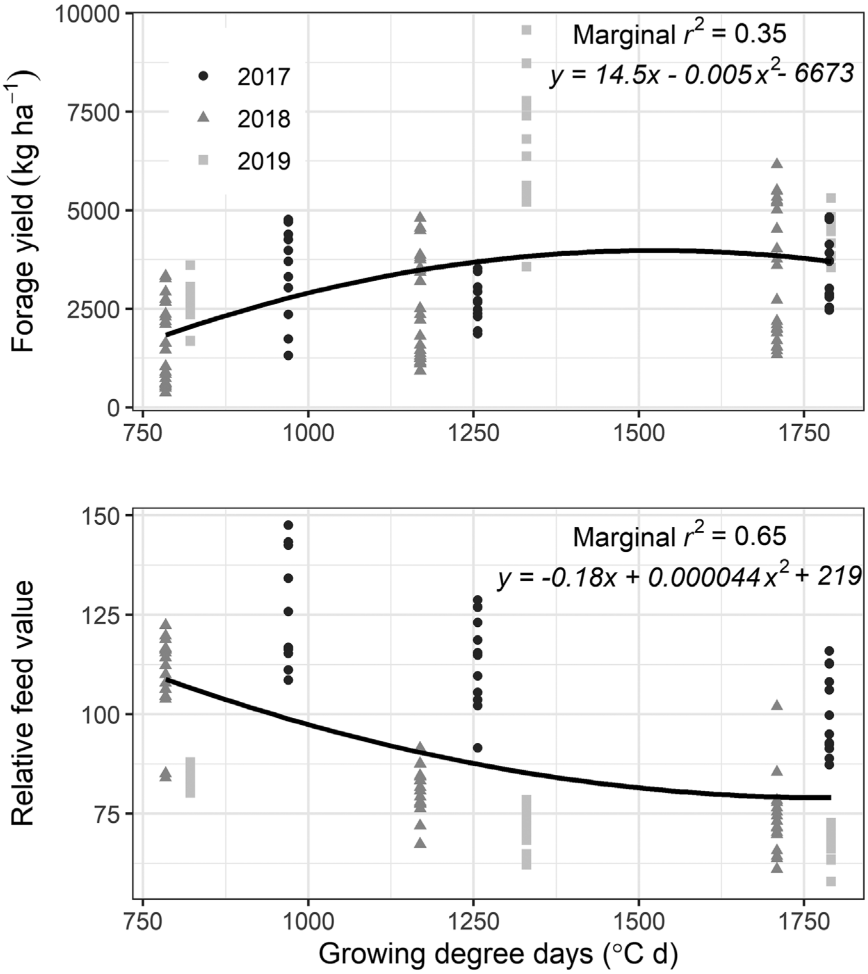

FIGURE 3 The relationship between growing degree day accumulation (base 0 ˚C) and intermediate wheatgrass forage yield and relative feed value at the first harvest. Data from all first harvest timing treatments were used from all environments

criterion adjusted for small sample size (Bolker et al., 2009; Burnham & Anderson, 2002). Box-cox procedures were used if all random effects were removed, and non-normally distributed data were either transformed or modelled using a generalized linear mixed effect model. Conclusions of the global model and the reduced model did not differ.

Yield and RFV were also tested as a function of GDD accumulation using linear and quadratic models. Models were compared using maximum likelihood ratio tests and marginal r^2 was calculated using the *performance* package (Lüdecke et al., 2021). An value of 0.05 was used to assess statistical significance for all statistical tests.

3 | RESULTS AND DISCUSSION

3.1 | Weather and field conditions

Growing conditions were favorable throughout the experiment, with monthly mean precipitation and temperature typically near long-term values during the growing season (Figure 1). Precipitation was highest in 2019 and least in 2018. Growing degree day accumulation (base temperature = 0 ˚C) was highest in 2017 and less in 2018 and 2019; GDD accumulation prior to the initial boot stage harvest was 930 GDD in 2017 and 900 in 2018 and 2019.

3.2 | Effects of timing of first harvest

Timing of the first harvest had a significant effect on IWG yield and nutritive value of forage from the first harvest (Table 2). Forage yield for the first harvest was similar for the anthesis and dough stage, and both were higher than yield harvested at boot by 55% (anthesis) and 60% (dough; Figure 2). Forage yields for the anthesis and dough stage harvests were similar at the first harvest. When regressed on GDD, the yield of the first harvest was curvilinear (Figure 3). These responses, which showed little increase in yield after anthesis, were consistent with previous reports of impact of perennial cool season grass maturity on yield (Collins & Nelson, 2018). Jungers et al. (2018) had reported a similar response to increasing GDD but found IWG forage yields plateaued after 2,000 GDD. Although no reports exist of first harvest forage yields for harvests at boot to anthesis from grain-type IWG swards, our first harvest yields were similar to those reported

TABLE 2 Analysis of variance for factorial combination of timing of the first harvest and harvest intensity (the number of harvests per year) for forage yield, relative feed value (RFV) and net returns. Results for annual yield, RFV, and net return are presented along with yield and RFV for each individual harvest

Source	Annual			First harvest		Second harvest		Third harvest	
	Yield	RFV	Return	Yield	RFV	Yield	RFV	Yield	RFV
Timing (T)	NS	***	NS	***	***	***	***	NS	NS
Intensity (I)	*	NS	***	NS	NS	NS	NS		
T × I	NS	NS	NS	NS	NS	NS	NS		

Note. NS, no differences detected at α = 0.05.
*Differences detected at α = 0.05.
***Differences detected at α = 0.001.

by Vogel et al. (1993) and Smart et al. (2006) in Nebraska with forage-type IWG cultivars.

Forage yields for second and third harvests in September and November were significantly less than for the first harvest (Figure 2). Second harvest yields were 54, 21, and 16% of the first harvest yields at boot, anthesis, and dough, respectively, while third harvest yields were 16, 10, and 10% of the first harvest yields at boot, anthesis, and dough, respectively. Because these harvests all occurred on the same date, the accumulated GDD from the first harvests at the three maturity stages until September varied. Accumulated GDD were 2,163, 1,762, and 1,252 from the boot, anthesis, and dough stages, respectively. Consequently, although the maturity for all September harvests was vegetative without stem elongation, because of the longer accumulated GDD since the first harvest, forage yields following the initial harvest at boot exceeded those for the anthesis or dough stage harvests. Yields were similar for the November harvests because the GDD from the September to November (379) were similar for all first harvest treatments. Total annual yield for each system was influenced little by the third harvest in November comprising just 8% of the total annual yield. Cumulative growing season forage yields were strongly influenced by the first harvest yields and averaged 4.1, 4.9, and 4.7 Mg ha^{-1} for the boot, anthesis, and dough first harvests. These cumulative yields were less than the 5.3 Mg ha^{-1} reported for forage type IWG harvested after heading in Nebraska (Vogel et al., 1993) and less than commonly observed cool-season forage grasses harvested three times in Minnesota (Marten & Hovin, 1980; Sheaffer et al., 1990). They are also less than the total forage yield from 3-yr-old stands of a grain-type IWG that included a straw harvest (Hunter et al., 2020b). However, the seasonal yield pattern does agree with previous reports for other cool-season forage grasses and for a forage-type IWG where most forage yields occur at the initial harvest with much less at subsequent harvests (Lawrence & Ashford, 1966). In addition, Collins and Nelson (2018) also reported that for a diversity of cool season grasses, regrowth contribution to yield decreased as maturity at harvest increased.

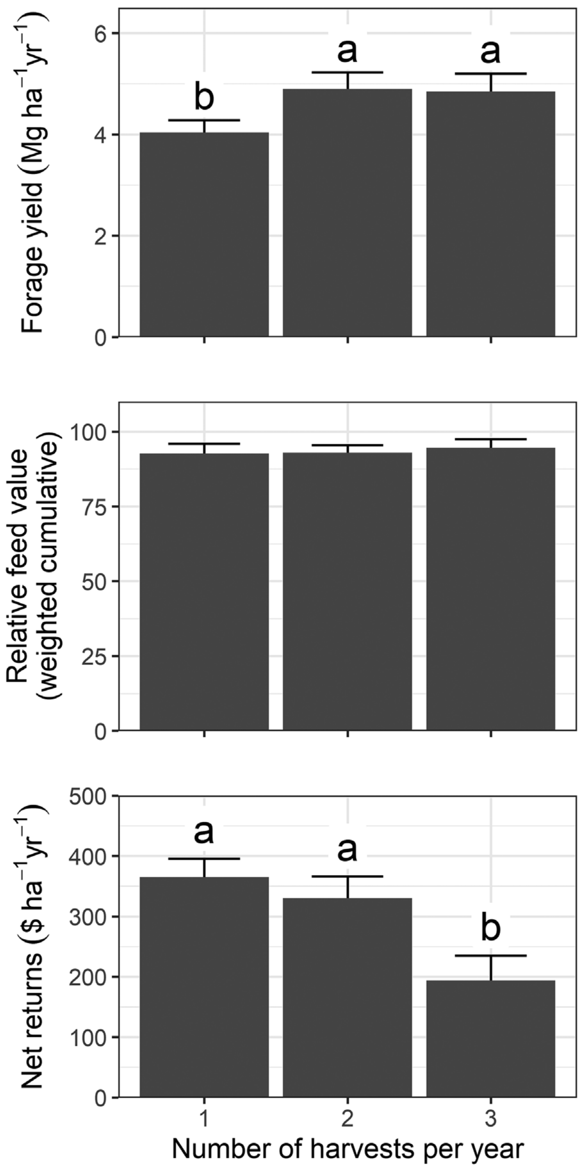

FIGURE 4 The effect of harvest intensity (number of harvests per year) on intermediate wheatgrass cumulative yield, relative forage value and net returns. Bars represent means and error bars represent standard error of the mean. Bars with the same letters do not differ according to Tukey honestly significant difference test (a = 0.05)

TABLE 3 Crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and neutral detergent digestibility at 48 h (NDFD48) of intermediate wheatgrass forage harvested at three maturities at the first harvest and at two subsequent harvests

Timing of first harvest	Harvest number	CP	ADF	NDF	NDFD48
		g kg^{-1}			
Boot	First	100.5 a	374.5 c	645.3 c	506.3
	Second (Sept.)	72.5 b	384.6 bc	712.2 ab	524.0
	Third (Nov.)	55.6 cd	382.6 bc	694.2 b	503.5
Anthesis	First	63.2 bc	432.7 a	732.8 a	499.8
	Second (Sept.)	96.3 a	376.9 c	699.9 b	514.4
	Third (Nov.)	67.8 bc	364.6 c	673.4 bc	485.6
Dough	First	46.2 d	401.1 b	696.8 b	474.4
	Second (Sept.)	108.6 a	369.1 c	688.0 b	500.0
	Third (Nov.)	65.4 bc	366.0 c	677.7 bc	493.1

Note. Values that do not share the same letter within a column differ according to the Tukey HSD among all harvest schedules ($n = 9$, $\alpha = 0.05$).

3.3 | Forage nutritive value

In contrast to forage yield, RFV is an integrative measure of forage digestibility and intake potential, declined with later initial harvest timing and IWG maturity increased from boot to anthesis. RFV was similar for forage harvested at the anthesis and dough stages (Figure 2). The overall negative association of RFV with GDD supports this relationship (Figure 4). Changes in RFV with maturity were associated with increases in ADF and NDF (Table 3). The development of readily digestible, low fiber, starchy grain at the dough stage may be associated with the lack of differences in the fiber fractions from anthesis to dough stage (see Supplemental Table S1). Forage CP content declined with each maturity stage from boot to dough while NDF digestibility was similar for forage from the boot and anthesis harvests but declined at the dough stage. The advanced maturity of stems and declining leaf fraction likely contributed to the lower RFV of forage harvested at anthesis or dough than at boot stage or at vegetative stage in September or November (Karn et al., 2006; Smart et al., 2006). There is a paucity of comparative information on changes in maturity from boot to dough stages on forage nutritive value of either grain-types or forages cultivars of IWG. However, general references with a diversity of cool-season perennial grasses (e.g., Ball et al., 2001; Brink, 2020; Collins & Nelson, 2018) all show a decrease in forage digestibility and protein concentration and an increase in fiber concentration. The rates of change in these nutritive value components can vary with cultivars, species, and environments (Buxton & Marten, 1989; Vogel et al., 1993).

Our CP values were below the range typically reported, whereas NDF and NDFD values fell within the ranges provided for other cool-season perennial grasses in the Midwest. A potential reason for relatively low CP values could have been related to nutrient deficiency. Hunter et al. (2020b) found that IWG forage CP and tissue N concentration declined in spring and fall harvested biomass as stands aged from 1 to 4 years old. We fertilized this study with 67 kg N ha^{-1}, similar to rates recommended for optimizing grain yields in newly established IWG stands (Jungers et al., 2017). However, some evidence exists that N fertilizer rates may need to increase for ageing stands as available N is depleted under certain conditions (Fernandez et al., 2020). Despite annual N fertilization in this study, N requirements for high-yielding CP production may have exceeded available N through fertilization and organic input mineralization.

Forage RFV and CP content for forage harvested in September was lower for forage regrowth from the initial boot harvest and greatest for forage regrowth from the dough harvest. As with previously discussed yield relationships, differences in these nutritive value variables is likely related to differences in time/GDD of regrowth between harvests. There was little effect of first harvest timing on forage ADF, NDF, or NDFD at 48 h content at the September harvest (Table 3). Forage nutritive value declined for most parameters from forage harvested in September to November. Relative feed value and other nutritive value indicators were similar for all first harvest timings for November harvests because the GDD from the September to November (379) were similar for all first harvest treatments. Our results for forage RFV in September and November agree with those of Hunter et al. (2020b) reported for an October harvest but our CP values are lower. Also, our NDF values were somewhat higher while ADF was similar. Our results for NDF and ADF differ somewhat from with those of Favre et al (2019) who, for an October harvested forage, found NDF and ADF of 590 and 337 g kg^{-1}, respectively.

Brink (2020), in a survey of cool-season grass research, found that harvest timing had the greatest impact on forage nutritive value at the first harvest, but the effect of harvest timing was significantly less for subsequent harvests. This supports our results that show that first harvest yield and RFV had a major effect on cumulative growing season RFV weighted for yield, which averaged 110, 85, and 82 for systems with the first harvest at boot, anthesis, and dough stage, respectively.

3.4 | Net returns

The effects of initial harvest timing and harvest intensity (one, two, or three harvests per growing season) on net returns were calculated based on total season yield and RFV weighted by yield (Table 2) as well as variable input costs associated with additional harvests (e.g., mowing, raking, and baling). Initial harvest timing did not affect net returns. There was no harvest intensity by initial harvest timing interaction on net return, but the effect of harvest intensity on net returns was significant (Figure 4). Returns were similar for one or two harvests per year, that included a June–July first harvest and a September second harvest but taking a third harvest in November reduced net returns. Diminishing returns with November harvests are associated mainly with low forage yields that did not offset the harvesting costs. However, the availability of late-season forage in the Upper Midwest can be limited during some years, thus the market price could increase. When utilized on farm, the value of late season forage can be high for producers relaying on hay or pasture for livestock feeding.

4 | CONCLUSIONS

Grain-type IWG stands harvested in the third year following years of peak grain production have potential to provide forage similar to that of widely used perennial cool-season grasses. At the initial forage harvest, as IWG maturity increased from boot to dough stage in response to increasing GDD, forage yield increased and nutritive value and RFV decreased. Net returns based on forage yield, RFV, and costs of harvesting were similar for the three timings of first harvest; therefore, optimal time of harvest will depend on the producer's need for forage yield and nutritive value. Forage yield of vegetative regrowth harvested in September and November is less than forage yield from initial harvests in June and July; therefore, net returns do not increase following the first harvest. Grazing in September and November may be a more cost-effective approach to harvest the forage than haying. Research is warranted on the effect of harvesting grain-type IWG cultivars on stand persistence.

ACKNOWLEDGMENTS

The authors thank Joshua Larson, Katherine Bohn, and Dayana Carvalho for assistance with sampling and field management.

AUTHOR CONTRIBUTIONS

Jesse Puka-Beals: Formal analysis; Visualization; Writing – original draft; Writing – review & editing. Craig C. Sheaffer: Conceptualization; Funding acquisition; Investigation; Methodology; Project administration; Writing – original draft; Writing – review & editing. Jacob M. Jungers: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Supervision; Writing – original draft; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Jesse Puka-Beals https://orcid.org/0000-0003-1829-5954
Jacob M. Jungers https://orcid.org/0000-0001-8954-7325

REFERENCES

Asay, K. H., & Jensen, K. B. (1996). Wheatgrasses. In D. R. Moser, D. R. Buxton, & M. D. Casler (Eds.), *Cool-season forage grasses* (pp. 691–724). ASA, CSSA, and SSSA.

Bajgain, P., Zhang, X., Jungers, J. M., DeHaan, L. R., Heim, B., Sheaffer, C. C., Wyse, D. L., & Anderson, J. A. (2020). 'MN-Clearwater', the first food-grade intermediate wheatgrass (Kernza perennial grain) cultivar. *Journal of Plant Registrations*, *14*(3), 288–297. https://doi.org/10.1002/plr2.20042

Ball, D., Collins, M., Lacefield, G., Martin, N., Mertens, D., Olson, K., Putnam, D., Undersander, D., & Wolf, M. (2001). *Understanding forage quality*. American Farm Bureau Federation Publication 1-01. https://pss.uvm.edu/pdpforage/Materials/ForageQuality/Understanding_Forage_Quality_Ball.pdf

Bates, A. D., Maechler, M., Bolker, B., Walker, S., Haubo, R., Christensen, B., Singmann, H., Dai, B., & Scheipl, F. (2020). *Package "lme4."* https://github.com/lme4/lme4/

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using {lme4}. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Bolker, B. M., Brooks, M. E., Clark, C. J., Geange, S. W., Poulsen, J. R., Stevens, M. H. H., & White, J.-S. S. (2009). Generalized linear mixed models: A practical guide for ecology and evolution. *Trends in Ecology & Evolution*, *24*(3), 127–135.

Brink, G. (2020). *Growing high-quality grasses for dairy rations requires attention to detail*. USDA Forage Research Center. https://fyi.extension.wisc.edu/forage/files/2016/07/20growinggrassesfordairy-1.pdf

Burnham, K. P., & Anderson, D. R. (2002). A practical information-theoretic approach. *Model Selection and Multimodel Inference*, *2*, https://doi.org/10.1111/j.1420-9101.2010.02210.x

Buxton, D. R., & Marten, G. C. (1989). Forage Quality of plant parts of perennial grasses and relationship to phenology. *Crop Science*, *29*, 429–435.

Buxton, D. R., Mertens, D. R., & Fisher, D. S. (1996). Forage quality and ruminant utilization. *Cool-Season Forage Grasses*, *34*, 229–266.

Collins, M., & Nelson, C. J. (2018). Grasses for northern areas. In M. Collins, C. J. Nelson, K. J. Moore, & R. F. Barnes (Eds.), *Forages: An introduction to grassland agriculture* (Vol. 1, pp. 87–101). Wiley Blackwell.

Culman, S. W., Snapp, S. S., Ollenburger, M., Basso, B., & DeHaan, L. R. (2013). Soil and water quality rapidly responds to the perennial grain Kernza wheatgrass. *Agronomy Journal*, *105*(3), 735–744. https://doi.org/10.2134/agronj2012.0273

DeHaan, L., Christians, M., Crain, J., & Poland, J. (2018). Development and evolution of an intermediate wheatgrass domestication program. *Sustainability (Switzerland)*, *10*(5), 1–20. https://doi.org/10.3390/su10051499

Favre, J. R., Castiblanco, T. M., Combs, D. K., Wattiaux, M. A., & Picasso, V. D. (2019). Forage nutritive value and predicted fiber digestibility of Kernza intermediate wheatgrass in monoculture and in mixture with red clover during the first production year. *Animal Feed Science and Technology*, *258*, 114298. https://doi.org/10.1016/j.anifeedsci.2019.114298

Fernandez, C. W., Ehlke, N., Sheaffer, C. C., & Jungers, J. M. (2020). Effects of nitrogen fertilization and planting density on intermediate wheatgrass yield. *Agronomy Journal*, *112*, 4159–4170. https://doi.org/10.1002/agj2.20351

Fox, J., & Weisberg, S. (2019). An {R} companion to applied regression *(3rd ed.)*. Sage. https://socialsciences.mcmaster.ca/jfox/Books/Companion/

Hunter, M. C., Sheaffer, C. C., Culman, S. W., & Jungers, J. M. (2020a). Effects of defoliation and row spacing on intermediate wheatgrass: I. Grain production. *Agronomy Journal*, *112*(3), 1748–1763. https://doi.org/10.1002/agj2.20128

Hunter, M. C., Sheaffer, C. C., Culman, S. W., Lazarus, W. F., & Jungers, J. M. (2020b). Effects of defoliation and row spacing on intermediate wheatgrass II: Forage yield and economics. *Agronomy Journal*, *112*(3), 1862–1880. https://doi.org/10.1002/agj2.20124

Jungers, J. M., Frahm, C. S., Tautges, N. E., Ehlke, N. J., Wells, M. S., Wyse, D. L., & Sheaffer, C. C. (2018). Growth, development, and biomass partitioning of the perennial grain crop Thinopyrum intermedium. *Annals of Applied Biology*, *172*(3), 346–354. https://doi.org/10.1111/aab.12425

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 and Environment*, *272*, 63–73. https://doi.org/10.1016/j.agee.2018.11.007

Jungers, J. M., DeHaan, L. H., 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

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*(6), 1400–1409. https://doi.org/10.2134/agronj2005.0293

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*(1), 9–15.

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

Lenth, R. V. (2021). *emmeans: Estimated marginal means, aka least-squares means*. https://cran.r-project.org/package=emmeans

Lüdecke, D., Ben-Shachar, M. S., Patil, I., Waggoner, P., & Makowski, D. (2021). Assessment, testing and comparison of statistical models using R. *Journal of Open Source Software*, *6*(59), 3112. https://doi.org/10.31234/osf.io/vtq8f

Marten, G. C., & Hovin, A. W. (1980). Harvest schedule, persistence, yield, and quality interactions among four perennial grasses. *Agronomy Journal*, *72*(2), 378–387. https://doi.org/10.2134/agronj1980.00021962007200020030x

Moore, J. E., & Undersander, D. J. (2002). Relative forage quality: An alternative to relative feed value and quality index. *Proceedings 13th Annual Florida Ruminant Nutrition Symposium*, *32*, 16–29.

Moore, K. J., Moser, L. E., Vogel, K. P., Waller, S. S., Johnson, B. E., & Pedersen, J. F. (1991). Describing and quantifying growth stages of perennial forage grasses. *Agronomy Journal*, *83*(6), 1073–1077.

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*, 241–254. https://doi.org/10.1007/s11104-019-03974-6

R Core Team. (2021). *R: A language and environment for statistical computing*. https://www.r-project.org/

Ryan, M. R., Crews, T. E., Culman, S. W., Dehaan, L. R., Hayes, R. C., Jungers, J. M., & Bakker, M. G. (2018). Managing for multifunctionality in perennial grain crops. *BioScience*, *68*(4), 294–304. Oxford University Press. https://doi.org/10.1093/biosci/biy014

Sheaffer, C. C., Wyse, D. L., Marten, G. C., & Westra, P. H. (1990). The potential of quackgrass for forage production. *Journal of Production Agriculture*, *3*(2), 256–259.

Smart, A. J., Schacht, W. H., Volesky, J. D., & Moser, L. E. (2006). Seasonal changes in dry matter partitioning, yield, and crude protein of intermediate wheatgrass and smooth bromegrass. *Agronomy Journal*, *98*, 986–991.

Sparks, A. H. (2018). nasapower: A NASA POWER global meteorology, surface solar energy and climatology data client for R. *The Journal of Open Source Software*, *3*(30), 1035. https://doi.org/10.21105/joss.01035

Vogel, K. P., Reece, P. E., & Nichols, J. T. (1993). Genotype and genotype × environment interaction effects on forage yield and quality of intermediate wheatgrass in swards. *Crop Science*, *33*, 37–41.

SUPPORTING INFORMATION

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

How to cite this article: Puka-Beals, J., Sheaffer, C. C., & Jungers, J. M. (2022). Forage yield and profitability of grain-type intermediate wheatgrass under different harvest schedules. *Agrosystems, Geosciences & Environment*, *5*, e20274. https://doi.org/10.1002/agg2.20274