Received: 26 August 2019 | Accepted: 19 February 2020 | Published online: 17 April 2020

DOI: 10.1002/agj2.20194

Agronomy Journal

ARTICLE

Pest Interactions in Agronomic Systems

Effective weed suppression in dual-use intermediate wheatgrass systems

Joseph W. Zimbric | **David E. Stoltenberg** | **Valentin D. Picasso**

Department of Agronomy, University of Wisconsin – Madison, 1575 Linden Dr., Madison, WI 53706, USA

Correspondence
Valentin D. Picasso, Department of Agronomy, University of Wisconsin – Madison, 1575 Linden Dr., Madison, WI 53706, USA.
Email: picassorisso@wisc.edu

Funding information
The Land Institute, KS; University of Wisconsin Madison

Abstract

Intermediate wheatgrass [IWG; *Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey] is a cool-season perennial forage grass bred for higher seed yield. It is the first perennial grain crop in the United States, commercialized as Kernza since 2015. Managing IWG as a dual-use grain and forage crop could provide several ecosystem services including conserving soil and clean water while increasing economic income to growers. However, little is known about the weed management risks associated with IWG. Therefore, we studied weed community composition, biomass, IWG grain, and aboveground biomass in a factorial experiment with two weed management treatments, two nitrogen fertilization rates, and four forage harvest schedules (no harvest, summer only, summer + fall, and spring + summer + fall). Over three production years, weed biomass decreased by 88% regardless of treatment, and the weed community composition changed from predominantly winter annual to perennial species. In the second and third production years the weed community composition remained relatively stable. Grain yield was 16% greater with 135 kg N ha^{-1} than 90 kg N ha^{-1} but was not affected by in-season forage harvest or weed management treatments in the second and third years. Grain yield decreased from 763 to 371 kg ha^{-1} over three years, while aboveground biomass remained stable. Weed presence did not affect yields in second and third years. Dual-use IWG cropping systems effectively suppressed weeds and IWG is a promising grain crop alternative for farmers interested in diversifying their cropping systems under similar conditions.

1 | INTRODUCTION

Soil erosion and consequent water quality impairments are major problems associated with annual grain cropping systems (Asbjornsen et al., 2013; Matson, Parton, Power, & Swift, 1997). Development of perennial grain cropping systems offers a novel way to solve this problem in the long term (Culman, Snapp, Ollenburger, Basso, & DeHaan, 2013; DeHaan & Ismail, 2017; Glover et al., 2010; Jungers, DeHaan, Betts, Sheaffer, & Wyse, 2017). Intermediate wheatgrass (IWG) is a deep-rooted perennial grass species that has been the focus of extensive plant breeding efforts to increase seed size and seed yield in Kansas and Minnesota (DeHaan, Christians, Crain, & Poland, 2018). The IWG grain has been marketed under the tradename Kernza in the United States since 2015 (Charles, 2019). While the grain size is still considerably

---

Abbreviations: AIC, Akaike's Information Criterion; IWG, intermediate wheatgrass.

smaller compared to annual wheat, IWG grain yields are expected to be similar to annual wheat grain yields within the next two decades if the breeding gains continue at the current rate (DeHaan et al., 2013). There is increasing interest in using IWG as a dual-use grain and forage crop in order to reduce the economic risk associated with low grain IWG yields (Ryan et al., 2018). The majority of IWG forage that is available for use in dual-use systems comes in the form of residual biomass that is leftover after grain harvest (straw); however, the forage quality of the material is relatively low (Favre, Munoz Castiblanco, Combs, Wattiaux, & Picasso, 2019). Spring growth and fall regrowth can also be utilized as forage with a much higher nutritive value but provide relatively lower biomass yield (Favre et al., 2019). Harvesting spring and fall forage has been shown to increase seasonal forage yield, root biomass production, and have a positive effect on grain yields as the stand ages (Pugliese, Culman, & Sprunger, 2019).

To date, research on IWG has focused on forage yield (Jungers et al., 2017; Liebig, Hendrickson, Berdahl, & Karn, 2011; Wagoner, 1990; Wang et al., 2014), forage quality (Favre et al., 2019; Jungers et al., 2017; Karn, Berdahl, & Frank, 2006), grain yield (Jungers et al., 2017; Lee, Owens, Boe, & Koo, 2009; Tautges, Jungers, DeHaan, Wyse, & Sheaffer, 2018), and grain quality (Zhang, Ohm, Haring, DeHaan, & Anderson, 2015). However, there is a lack of scientific information relative to many aspects of agronomic management in IWG cropping systems. In particular, there has not been a characterization of weed community dynamics and suppression in these cropping systems. Furthermore, weed suppression and weed community dynamics over time have been identified by farmers as a major information gap in dual-use IWG cropping systems (Lanker, Bell, & Picasso, 2019). Increasing our understanding of the weed suppressive characteristics in IWG cropping systems is necessary because herbicides are not an option for weed control in IWG systems. This is due to two reasons: the demand for Kernza grain is predominantly from organic food consumers, and no herbicide is currently registered for use in IWG grain production (Lanker et al., 2019).

Core Ideas

- Weed biomass decreased 88% over three years in dual-use intermediate wheatgrass systems.
- Weed community changed from predominantly annual to perennial species over time.
- Grain yield decreased 50% over three years while biomass remained stable.

When compared to annual crops, perennial crops impose a unique set of selection pressures on the landscape that have major effects on weed community assemblage and weed suppression, primarily due to reduced soil disturbances, increased aboveground disturbance from forage and grain harvests, high levels of competition associated with an extended period of plant vegetation, and high levels of belowground competition from deep rooting systems (Booth & Swanton, 2002; Meiss, Médiène, Waldhardt, Caneili, & Munier-Jolain, 2010). Harvesting IWG forage as well as grain may have important effects on weed suppression. Individual weed species may respond differently to forage harvest depending on the cutting height (Hume, 1991), cutting frequency (Magda, Duru, & Theau, 2004), weed size at the time of harvest (Vesk, Warton, & Westoby, 2004), weed species morphology (Mager, Young, & Theau, 2006), weed species ability to remobilize nonstructural carbohydrates from root reserves (Meiss, Munier-Jolain, Henriot, & Canehill, 2008), as well as external environmental factors. Forage harvest would likely select against weed species with key characteristics such as an annual lifecycle, vertical morphologies with apical meristems above the soil surface, and few belowground starch reserves in root systems. However, forage harvest may offer a temporary competitive advantage to weeds by reducing competition for light, particularly in forage species that exhibit relatively slow regrowth (Meiss et al., 2010). Therefore, we hypothesized that (a) in dual-use IWG systems weed community composition would change from predominantly annual to perennial weed species, and (b) weed biomass will decrease over time, but will be greater in systems that include more forage harvests.

Previous research has shown a quadratic response of IWG aboveground biomass to increasing levels of nitrogen fertilization where the optimal nitrogen rate ranges were 60–96 kg N ha^{-1} (Jungers et al., 2017). When nitrogen was applied at the optimal levels for grain production, the residual IWG aboveground biomass (straw) following grain harvest was consistent with biomass yields observed in forage-type varieties of IWG. Other results have shown much lower residual forage following grain harvest (Pugliese et al., 2019). However, the optimal rates and timing of nitrogen applications when an early (spring) or late season (fall) vegetative forage harvest is included into the system have not been established. Weed competition for soil nitrogen can severely limit crop productivity (Patterson, 1995). In field conditions where weed density is high, higher levels of nitrogen fertilization confer a competitive advantage to weeds and tend to favor weed productivity more than crop productivity (Carlson & Hill, 1986; Di Tomaso, 1995). Consequently, weeds that are able to outcompete crops for soil nitrogen show an increased ability to compete for other important resources including water and light (Okafor & De Datta, 1976). However, the magnitude of weed species responses to high nitrogen fertility levels differ among species and environmental conditions (Blackshaw et al., 2003). Therefore, we hypothesized that nitrogen fertilization would increase IWG grain, forage yield, and weed biomass.

Our objectives were to characterize changes in weed community composition and quantify weed aboveground biomass, IWG grain yield, and IWG aboveground biomass production over three production years of IWG when managed as dual-purpose crop. We quantified these changes in a replicated field experiment with a range of IWG management treatments combining weed management, nitrogen fertilization, and forage harvest schedules.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental design

The field experiment was conducted at the University of Wisconsin-Madison Arlington Agricultural Research Station near Arlington, WI (43°18′6.9″N, 89°21′9.98″W) on a Plano silt loam soil (fine-silty, mixed, mesic Typic Argiudolls; USDA-NRCS, 2018). The mean annual air temperature and precipitation during the study period was 6.8 °C and 870 mm, respectively (Figure 1).

The research site was planted to corn in 2011, orchardgrass (*Dactylis glomerata* L.; spaced plants) in 2012–2014 and was fallow in spring and summer 2015. During the summer of 2015, the site was mowed regularly to suppress weeds prior to IWG planting in the fall. Seedbed preparation included tillage with a field cultivator followed by one pass with a cultipacker to improve soil-seed contact. Cycle 4 IWG seeds from The Land Institute, Kansas were seeded at a rate of 18 kg ha^{-1} pure live seed on 15 September 2015. Cycle 4 IWG is the product of a Kansas breeding population that has been through four cycles of selection for increased spike mass and increased seed mass (Zhang et al., 2015). Seed was planted at a depth that ranged from 6 to 12 mm in a row spacing of 19 cm. Establishment was assessed on 7 October 2015 by counting the number of IWG plants in two 1-m row lengths per plot; the mean plant density was 7.3 plants m^{-1} (standard deviation, SD = 2.4). Soil sampling to 15-cm depth and analysis were conducted in the spring of 2016 following the methods described by Peters and Laboski (2013). Soil analyses results for the site were: pH = 7.3, organic matter = 3.0%, P = 36 mg kg^{-1}, K = 109 mg kg^{-1}, Ca = 1824 mg kg^{-1}, Mg = 538 mg kg^{-1}, CEC = 15 meq 100 g^{-1}, B = 0.9 mg kg^{-1}, and bulk density 1.08 g cm^{-3}.

The experimental design was a randomized complete block with three replications with a full factorial arrangement of treatments. The plot size was 1.8 by 6.4 m, separated by 1.5-m alleys between plots. The treatments were a combination of three factors: weed management, nitrogen rate, and forage harvest schedule (2 × 2 × 4). During the first production year (2016), no weed management was applied in any plot, which is the standard management practice for growers given that there are no herbicides currently registered for spraying IWG grain produced for human consumption (Lanker et al., 2019). In the second (2017) and third (2018) production years, weed management treatments included weedy (no weed management) and weed-free treatment, where weeds were removed biweekly by hand, carefully avoiding not to step into plots to minimize disturbance. Nitrogen in the form of urea was broadcast applied at 90 or 135 kg N ha^{-1} based on recommendations for total N fertilization from experiments in Minnesota (Jungers et al., 2017). Each rate was split equally between early spring prior to IWG stem elongation and following grain harvest (Table 1). Plots were harvested for grain in the summer of each year (Table 1). Forage harvest schedule treatments were: no forage harvest (i.e., only grain harvest and crop residue remained in plots); summer forage harvest (after grain harvest); summer (after grain) and fall (regrowth) forage harvests; and spring (before elongation), summer (after grain), and fall (regrowth) forage

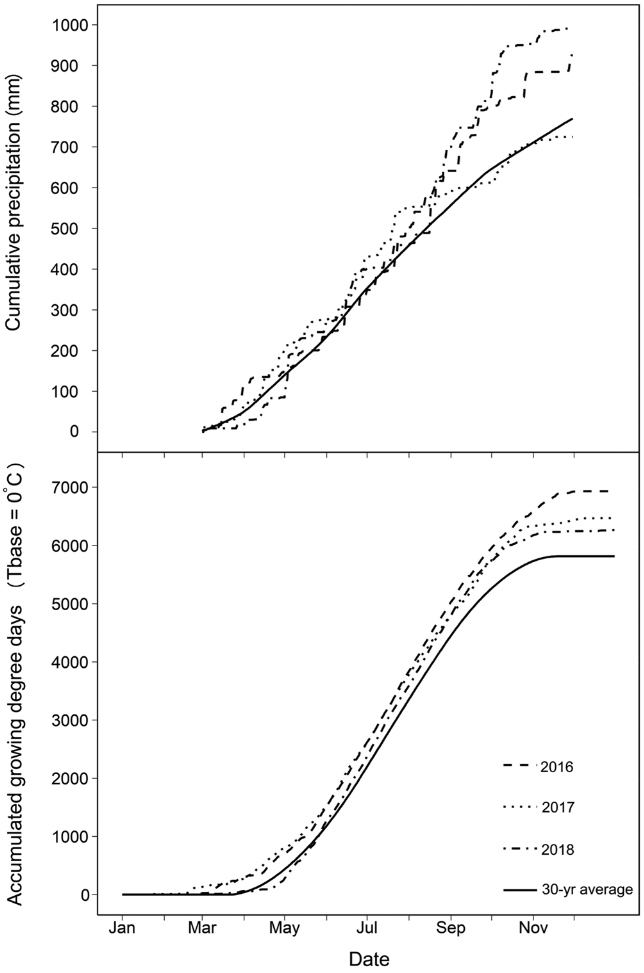

FIGURE 1 Cumulative precipitation (1 Mar.–30 Nov.) and accumulated growing degree days (base temperature 0 °C) at the University of Wisconsin–Madison Arlington Agricultural Research Station near Arlington, WI during the 2016, 2017, and 2018 growing seasons. The solid line shows the 30-yr (1981–2011) average

TABLE 1 Dates for N fertilization, grain harvest, and forage sampling and harvest for intermediate wheatgrass systems for three production years at Arlington, WI

Item	2016	2017	2018
Stand age, yr	1	2	3
Spring forage sample	-	18 Apr.	10 May
Spring N fertilization	16 May	26 Apr.	18 May
Fall N fertilization	18 Aug.	25 Aug.	24 Aug.
Summer grain and forage harvest	1 Aug.	31 July	7 Aug.
Fall forage harvest	7 Oct.	25 Oct.	24 Oct.

harvests. The summer forage harvest consisted of cutting and baling the crop residue (straw) as forage immediately after grain harvest.

2.2 | Data collection

In the first production year (2016), total weed community abundance was determined by estimating the relative ground cover of weeds in one 0.25-m^2 quadrat per plot on 2 June 2016, using a scale of 0–100% (in 10% increments). In the second (2017) and third (2018) production years, weed community composition was determined by weed species density counts from one 0.25-m^2 quadrat placed randomly in each plot using the random-number technique (Nkoa, Owen, & Swanton, 2015). Weed densities were measured on 5 June, 23 June, and 13 July 2017 in all plots. After confirming that the hand-weeding treatment effectively reduced weed abundance and biomass in 2017 (see Results section), the next year weed density was measured only in weedy plots on 19 June and 18 July 2018. On these dates only weed plants were counted, but weed biomass was not measured then. Weed biomass was determined from one quadrat at the time of grain harvest every year (2016, 2017, and 2018) as described below. In the first year of the experiment only (2016), weed biomass was also sampled frequently (nine times: 15, 20, and 25 July; 2 Aug; 14 Sept.; 6, 14, and 27 Oct.; and 17 Nov.) using one quadrat per plot for all 24 plots. No additional in-season weed biomass sampling was conducted in 2017 and 2018.

Intermediate wheatgrass grain yields were determined by hand cutting spikes from all tillers within two 0.25-m^2 quadrats placed near the center of each plot. Grain was considered to be mature when it reached the Feekes 11.3 or the equivalent Moore 4.5 stage of growth (Large, 1954; Moore et al., 1991). Immediately after the spikes were removed (see Table 1 for harvest dates), IWG and a composite sample of weed species within quadrats were cut at the soil surface, removed from plots, and dried at 60 °C for at least 5 d and weighed. Grain was dried at 60 °C for at least 2 d and then threshed using a custom research-grade seed thresher (Jungers et al., 2017). The palea and lemma fractions were intact on the seed when the grain was weighed; however, many seeds became de-hulled during the threshing process. Following quadrat harvests, grain was harvested from each plot using a combine harvester (a Gleaner F2, Allis-Chalmers, Indendence, MO, in 2016 and a small plot Wintersteiger Elite Wintersteiger, Salt Lake City, UT in 2017 and 2018) at a cutting height of 50–70 cm. Biomass from each plot was harvested using a forage harvester (FH-88, Almaco, Nevada, IA) at a cutting height of 10 cm and baled off (removed from the plots). Aboveground IWG biomass and weed biomass (composited of all weed species) were also sampled in the spring and in the fall from one 0.25-m^2 quadrat placed randomly within each plot (see Table 1 for dates). Samples were processed as described above.

2.3 | Statistical analysis

Data were tested for normality and homogeneity of variances and log or square root transformed to satisfy the assumptions of the analyses if needed. Analysis of variance was performed on aboveground weed biomass, IWG grain yield, and aboveground IWG biomass data using PROC MIXED procedure in SAS software (SAS Institute, 2013). Block, forage harvest, nitrogen, year, and all interactions were treated as fixed effects. The year was considered a repeated measure (plots as subjects) with an unstructured covariance structure. Significant differences were determined at the $P = .05$ level. Means were compared using the Tukey–Kramer honest significant difference test at $\alpha = .05$. Linear, quadratic, two-parameter Weibull, and two-parameter logistic models were fit to the weed biomass, grain yield, and IWG aboveground biomass [$f(x)$] using stand age as a predictor variable (x) in the *nls* package of base R (R Core Team, 2018). The best fit regression model was selected on the basis of the smallest Akaike's Information Criterion (AIC) value. In all cases the two-parameter logistic model (Equation 1) provided the best fit for the data. The two-parameter logistic equation is:

$$f\ (x) = \frac{\mu}{1 + \left(1 + \exp\left\{b\left[\log\left(x\right) - e\right]\right\}\right)} \qquad (1)$$

where b is the scaling factor, e is the inflection point, and μ is the upper limit in the logistic model. If forage harvest, nitrogen rate, or weed management effects were not significant in the analysis of variance, data were pooled across levels of that factor. Graphs were produced using the base R graphics package in version 3.5.1 (R Core Team, 2018).

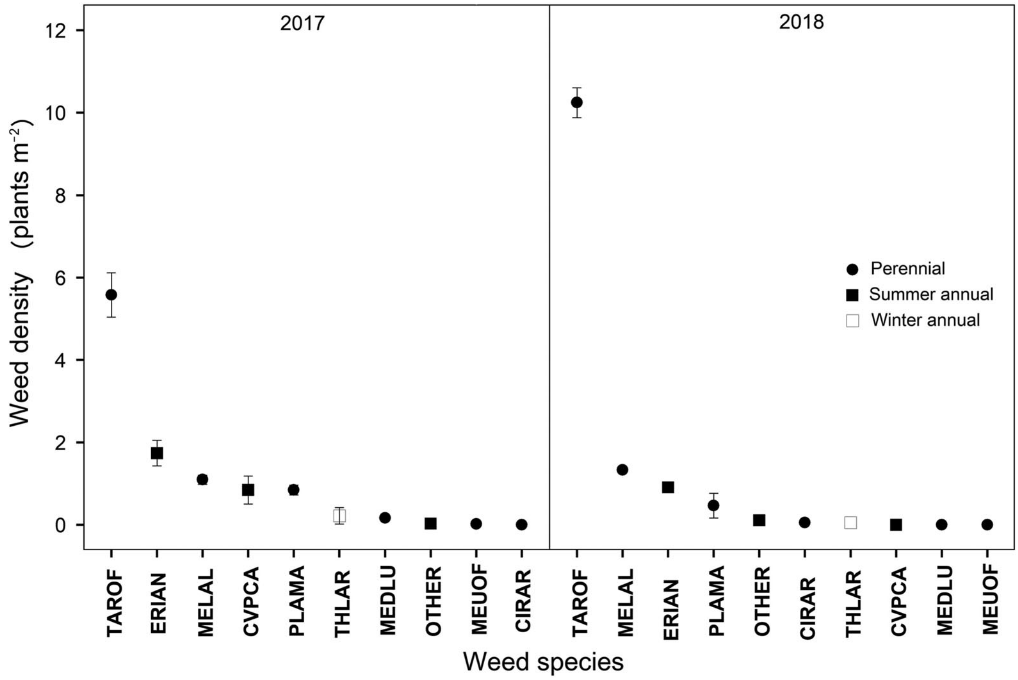

FIGURE 2 Abundance rankings (least squares means ± standard error) of weed species based on density counts in second (2017) and third (2018) production years of intermediate wheatgrass at Arlington, WI. Data were pooled across sampling times, for weedy plots (no weed control). CIRAR, Canada thistle; CVCPA, smooth hawksbeard; ERIAN, annual fleabane; MELAL, white campion; MEDLU, black medic; MEUOF, yellow sweetclover; OTHER, other weeds species (timothy, annual bluegrass, curly dock); PLAMA, broadleaf plantain; TAROF, dandelion; THLAR, field pennycress

3 | RESULTS

3.1 | Weed community composition

During the first production year (2016), when there was no weed management in all the plots, the winter annual weed species shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik.] and field pennycress (*Thlaspi arvense* L.) were the most abundant species in the weed community (data not shown) comprising 38 ± 2 and 7 ± 1% of vegetative cover, respectively, pooled across all treatments. Intermediate wheatgrass accounted for most of the other vegetative cover (32 ± 2%) pooled across treatments. During the second production year (2017), perennial species were 73% of total weed density in the weedy treatment (no weed management) pooled across other treatments. The perennial species dandelion (*Taraxacum officinale* F.H. Wigg.) was the most abundant, followed by annual fleabane [*Erigeron annuus* (L.) Pers.], white campion (*Silene latifolia* Poir.), smooth hawksbeard [*Crepis capillaris* (L.) Wallr.], and broadleaf plantain (*Plantago major* L.; Figure 2). Field pennycress, black medic (*Medicago lupulina* L.), yellow sweetclover [*Melilotus officinalis* (L.) Lam.], and Canada thistle [*Cirsium arvense* (L.) Scop.] were also present but in low densities. In the third production year (2018), perennial species were 96% of total weed density in the weedy treatment pooled across other treatments. Total weed density was not different ($P = .08$) between the second and third production years (11.7 ± 1.2 and 15.0 ± 1.4 plants m^{-2}, respectively); however, total perennial weed density increased from 8.6 ± 1.0 in the second to 14.4 ± 1.2 plants m^{-2} in the third production year ($P < .001$). Dandelion accounted for the largest increase in density, from 5.8 ± 0.9 in the second year to 11.5 ± 1.1 plants m^{-2} in the third production year ($P < .001$; Figure 2). White campion, annual fleabane, broadleaf plantain, Canada thistle, smooth hawksbeard, black medic, and yellow sweetclover were also present but at low densities.

There was no interaction for forage harvest × nitrogen rate × year for total weed density in the weedy plots ($P = .78$), but there was an interaction for forage harvest × nitrogen rate ($P < .01$). In plots where no forage was harvested in the fall (control and summer only), total weed density was 6.8 plants m^{-2} and not different between nitrogen rates. However, in the plots where forage was harvested in the fall (summer + fall and spring + summer + fall), total weed density was higher for the lower nitrogen rate (averaging 30.6 plants m^{-2}) than for the higher nitrogen rate (averaging 9.4 plants m^{-2}). The same trend was observed for density of perennial weeds, averaging 5.5 plants m^{-2} for the plots were no forage was harvested in the fall, regardless of N rate, and increasing to 26.9 plants m^{-2} for the high N rate in the fall harvested plots, and 8.0 plants m^{-2} for the low N rate.

TABLE 2 Means of intermediate wheatgrass (IWG) grain yield, IWG aboveground biomass, and weed biomass at grain harvest (summer) for the main effects of forage harvest schedule, nitrogen fertilization rate, and production year at Arlington, WI, for weedy plots (no weed control). Means for each effect within a column for each factor followed by the same letter do not differ at the $P = .05$ level of significance

Treatment	Weed biomass	IWG grain yield	IWG biomass
		kg ha $^{-1}$	
Stand age			
1 yr stand (2016)	745a	763a	5,170
2 yr stand (2017)	342b	453b	5,775
3 yr stand (2018)	87c	371b	5,940
Forage harvest			
No forage harvest	369	453	5,910a
Summer only harvest	311	622	6,350a
Summer and fall harvest	437	516	5,500ab
Spring, summer, and fall harvest	451	524	4,755b
N rate			
90 kg N ha^{-1}	400	483b	5,160b
135 kg N ha^{-1}	382	576a	6,095a

3.2 | Weed biomass

There were no interactions among main effects for weed biomass. Weed biomass was greatest in the first year and decreased 88% over the next two years ($P = < .01$; Table 2). Weed biomass decreased nonlinearly over time (Figure 3) and was best described by a two-parameter logistic model (Equation 1, AIC = 2041.8) where parameter estimates and 95% confidence intervals were: $\mu = 2000$, $b = 2.02$ ($P < .001$), [1.35, 2.69]; $e = 0.98$ ($P = < .001$) [0.89, 1.11]. Weed biomass was not affected by IWG forage harvest ($P = .54$) or nitrogen fertilization rate ($P = .70$) over three production years (Table 2).

In the first year of the experiment (2016), when weed biomass was sampled more frequently, weed biomass declined from 89 g m^{-2} in July to 14 g m^{-2} in November. The weed biomass in 2016 was best described by a linear regression model: $WB = -0.55x + 83.2, r^2 = .88$, $P < .01$, where WB is weed biomass (g m^{-2}) and x is number of days after July 1. No effect of Nitrogen or forage harvest was observed (data not shown).

3.3 | Intermediate wheatgrass grain and biomass yield

No interactions were found among main effects for intermediate wheatgrass grain yield. There was a stand age (year) effect: intermediate wheatgrass grain yield decreased 50% over three years (Table 2; Figure 4). A two-parameter logistic model (Equation 1) best described the decline between grain yield and stand age (Figure 4), where parameter estimates and 95% confidence intervals for 90 kg N ha^{-1} treatment were: $\mu = 2000$, $b = 0.89$ ($P < .001$), [0.55, 1.16]; $e = 0.49$ ($P < .001$), [0.27, 0.69], and the parameter estimates and 95% confidence intervals for the 135 kg N ha^{-1} treatment were: $\mu = 2000$, $b = 0.88$ ($P < .001$) [0.56, 1.20]; $e = 0.68$ ($P < .001$), [0.44, 0.93]. A nitrogen effect was observed ($P < .01$) across years, where grain yield was 16% greater in treatments that received 135 kg N ha^{-1} compared to 90 kg N ha^{-1} (Table 2; Figure 4). Grain yield was not affected by forage harvest ($P = .35$; Table 2).

No interactions were found among main effects for IWG aboveground biomass. Intermediate wheatgrass aboveground biomass at grain harvest did not differ over three production years, but there were differences attributed to harvest timing and N levels (Table 2). As expected, IWG aboveground biomass was 14% greater in the 135 kg N ha^{-1} treatment than in the 90 kg N ha^{-1} treatment ($P = .01$). Intermediate wheatgrass summer aboveground biomass was lower when a spring forage harvest was included ($P < .01$), which is logical given that the spring forage was removed in that treatment. No differences were observed for total cumulative IWG forage biomass (sum of spring, summer, and fall harvests each year) across forage harvest treatments (data not shown).

3.4 | Weed management effect

Weed management treatments were not applied in the first production year. The high IWG productivity in the first year despite presence of winter annual weeds suggests that weeds may not have affected yields significantly. As expected, total weed density was reduced from 11.7 ± 0.9 plants m^{-2} in the weedy plots to 3.8 ± 0.9 plants m^{-2} in the weed-free (hand-weeded) plots in the second production year. In the third year weed density was not assessed for the weed-free plots. Weed biomass was 85 and 83% lower in the weed-free than weedy treatment in second and third production years, respectively ($P < .01$; Figure 5c). However, no differences were observed for IWG grain and biomass yield between these two treatments ($P > .05$; Figure 5a, 5b).

4 | DISCUSSION

4.1 | Weed community composition and weed biomass

Our hypothesis that the weed community composition would change from annual to perennial species was not rejected.

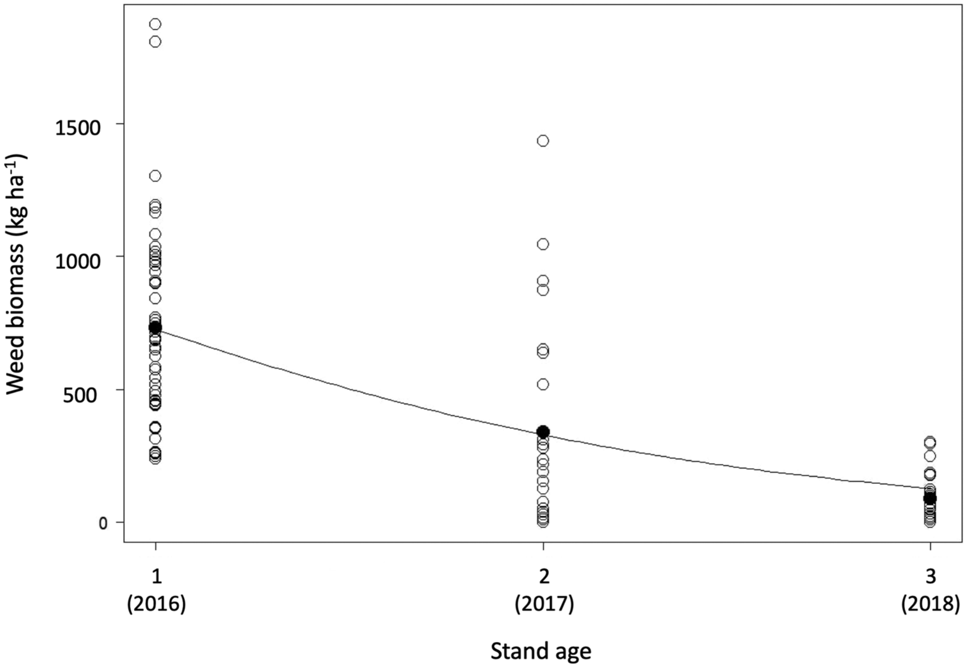

FIGURE 3 Weed biomass as a function of intermediate wheatgrass stand age for 1 (2016), 2 (2017), and 3 (2018) production years at Arlington, WI for weedy plots (no weed control). Open circles represent plot values and closed circles represent mean values. Equation and parameter estimates are given in text

During the first production year, winter annual weeds were the most abundant, whereas in second and third production years, perennial weeds were the most abundant. The lack of soil disturbance in the fall and spring of the establishment year (when intermediate wheatgrass had not covered the soil yet) allowed winter annual species to germinate and emerge in the fall, overwinter, and resume growth early in the following spring while the IWG was in the seedling stage. This is consistent to what is expected from ecological theory on weed invasion (Wolkovich & Cleland, 2011). Given that the main goal of these IWG systems is grain production, mowing after elongation is not recommended in order to avoid cutting the reproductive stems. Because the use of herbicides is not authorized yet, the only other option for weed control would be mechanical inter-row cultivation. Cultivation is not a common practice in IWG systems, and in our case, the row spacing was too narrow and we would have risked damaging the establishing stand. Shepherd's-purse, field pennycress, and IWG formed a dense canopy which likely excluded establishment of spring and summer annual weed species and may have accounted for the relatively low diversity that was observed in the weed community in the first production year. The winter annual species were at the anthesis stage in early June and senescence was completed before the time of IWG grain harvest at the end of July. One potential option for weed control to investigate in future research could be timely mowing in the spring before IWG stem elongation to reduce weed competition in the first production year in situations where winter annual weed density is high.

In the second production year, a major transition was observed in weed community composition. Dandelion was the most abundant species followed by annual fleabane, white cockle, and smooth hawksbeard. As described by Meiss et al. (2008), multiple harvests in forage crops may generate divergent selection pressures favoring species with long or very short life cycles in the weed community, which may explain our observations. The greater abundance of dandelion compared to the other weed species in the community is likely a result of its low growth habit, allowing it to escape defoliation during forage harvests and take advantage of the greater light availability during periods of IWG regrowth. Dandelion was also cited as the most abundant wild weed species in perennial polyculture plots including IWG in Iowa (Picasso, Brummer, Liebman, Dixon, & Wilsey, 2008). In the third production year, changes in the weed community composition were less pronounced than the changes observed between the first and second production years. The relative abundances of the weed species remained mostly stable between these years; however, the relative abundance of dandelion increased. This may be in part due to dandelions distinctive biology and lifecycle. It does not exhibit a regular pattern of germination over the growing season, allowing it to become established after a forage harvest (Chepil, 1946). Additionally, in the second production year, very little precipitation occurred in the fall. This likely

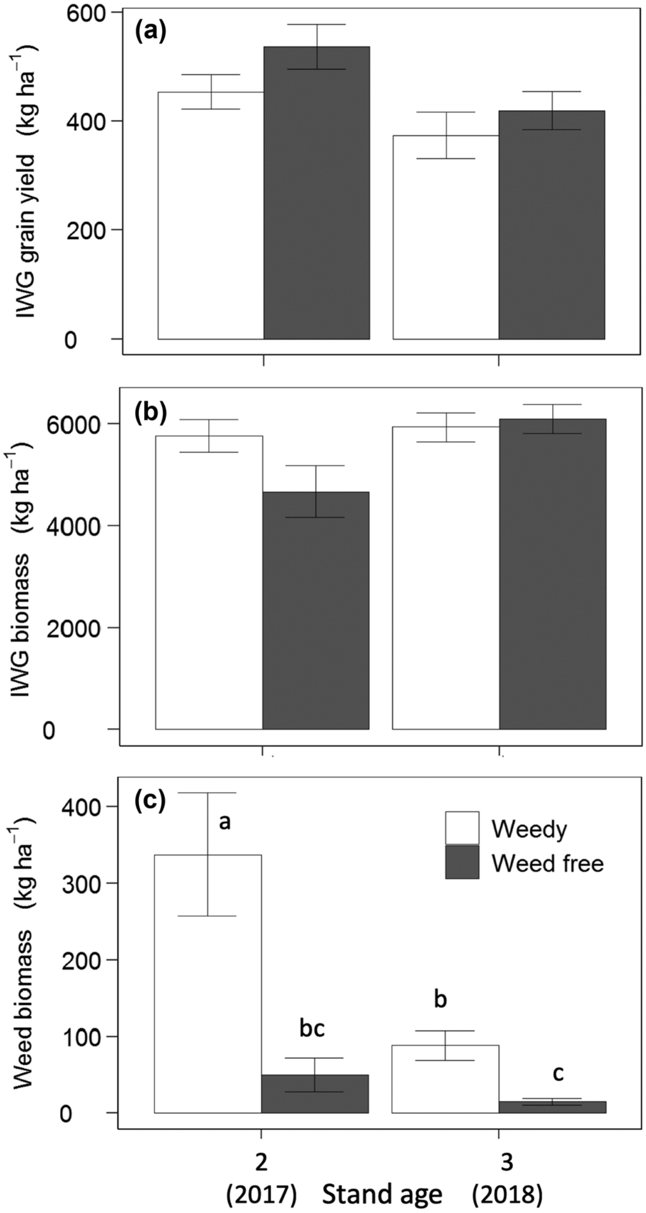

FIGURE 4 Intermediate wheatgrass grain yield (a), IWG biomass (b), and weed biomass (c) in weedy and weed-free treatments in second (2017) and third (2018) production years of IWG at Arlington, WI. Values are means across N levels and forage harvest treatments. Bars represent means ± standard error. Means with different letters are different at $P < .01$

slowed IWG regrowth and potentially left resources available for dandelion to germinate and establish. Nitrogen fertilization did not affect the density of perennial weed species when no fall forage harvest was conducted, which were situations with the highest IWG biomass standing in the fall, and therefore a perennial short growing species like dandelion could not compete well. In the cases where there was a fall forage harvest, and therefore competition from IWG was reduced, weed density was increased overall. In these cases, the plots with higher N rate applied had lower weed density compared to the ones with low N rate, possibly due to the fact that N was better used by IWG, thus weed suppression increased.

Our results are consistent with previous research which has shown that perennial forage cropping systems tend to favor perennial weeds over the duration of the crop rotation (Andersson & Milberg, 1998). In a study that characterized the weed community composition of annual cereal grain crops that were preceded by either alfalfa (*Medicago sativa* L.) or annual cereals, a marked increase in the relative abundance of perennial weeds was found at sites that included alfalfa the previous year (Ominski, Entz, & Kenkel, 1999). Perennial alfalfa forage systems have also been shown to suppress weed species that are problematic in annual crops, and they exhibit a similar change in weed community composition toward perennial weed species (Meiss et al., 2010). In short-term perennial grass crops, perennial weed species density has been shown to increase with time, and become the most abundant species in the weed communities in subsequent crops (Hiltbrunner et al., 2008). After the second year, the dense canopy of intermediate wheatgrass, as well as the extensive root system (Pugliese et al., 2019), provided soil cover and captured soil nutrients and light, excluding any other annual weeds (winter or summer annuals). Previous research has shown that cool-season perennial grasses can effectively suppress highly competitive weed species over time when no other weed management practices are implemented (Whitson & Koch, 1998; Wilson & Kachman, 1999).

Harvesting IWG forage increased dandelion (and other perennials) abundance over time and may select for weed species with similar lifecycles and morphologies. Although perennial grass weed species were not observed in this study, they would be particularly well-adapted to this cropping system. It is important to note that the inferences from our study are highly dependent on the innate weed community composition, given that our study was conducted only at one location in a field that had been fallow and mowed the year before establishment. Had the weed community been composed of species with more aggressive competitive traits, the results and inferences would likely vary substantially from what are reported here. For instance, in another research site at Lancaster, WI, with a land history of pasture and perennial forages, we observed that IWG plots managed for dual use under grazing became invaded by Canada thistle and perennial grasses (data not shown). Farmers who are currently growing IWG observed major changes in weed community composition from annual weed species to predominantly perennial weed species (Lanker et al., 2019). The most commonly observed weed species in IWG cropping systems were Canada thistle, red clover (*Trifolium pratense* L.), yellow sweetclover, Kentucky bluegrass (*Poa pratensis* L.), and other perennial species, as well as the annual species waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer]. Therefore, it is recommended that IWG be established in fields where

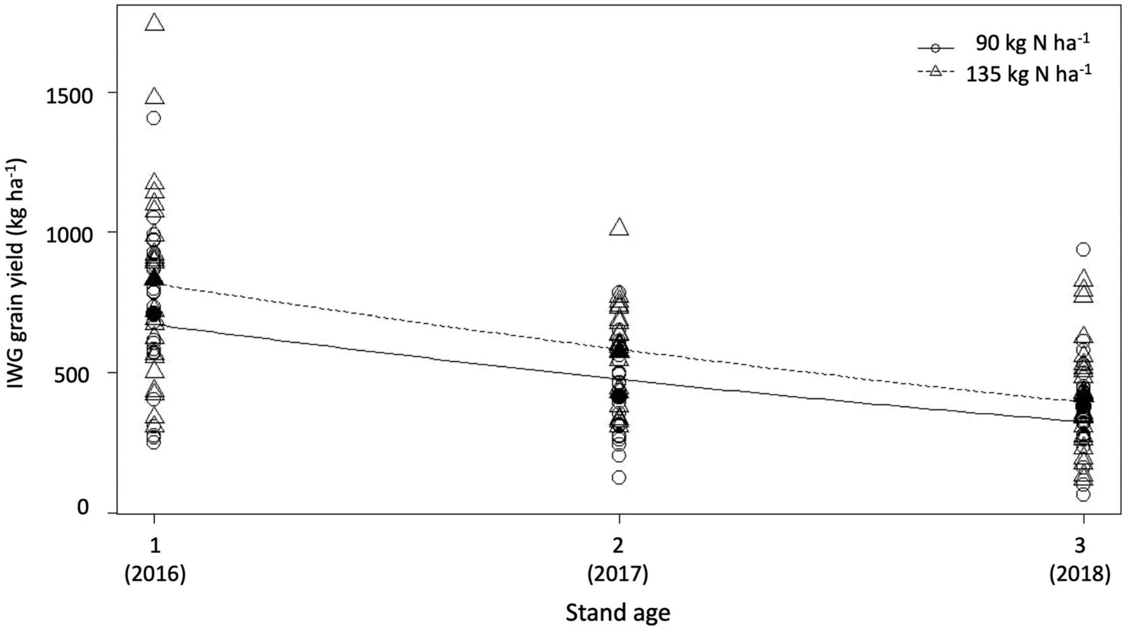

FIGURE 5 Intermediate wheatgrass (IWG) grain yield as a function of IWG stand age and N rate (circles, 90 kg ha^{-1}; triangles, 135 kg N ha^{-1}) at Arlington, WI, for weedy plots (no weed control). Open symbols represent plot values and closed symbols represent mean values. The equations and parameters are given in the text

perennial weed species, especially grasses, are not present. If perennial weed species are present in the field, weed management practices like herbicides or cultivation may be needed.

The marked decrease in weed biomass in the summer that was observed over three production years suggests that IWG can successfully suppress weed productivity and growth. Intermediate wheatgrass is generally not regarded as a species that exhibits particularly fast regrowth characteristics, especially in low rainfall environments (Ogle, St. John, Tober, & Jensen, 2011), which could leave the stand vulnerable to weed establishment and competition following forage harvest. However, including one or more forage harvests did not have an appreciable effect on weed biomass, suggesting that the regrowth characteristics of the IWG were sufficient to limit the level of weed competition in an environment with relatively high rainfall. Furthermore, previous research has shown that dandelion and white cockle have minimal negative impacts on forage quality (Dutt, Harvey, & Fawcett, 1982). Moreover, as shown by Pugliese et al. (2019), IWG root biomass production is substantial. In our study the level of nitrogen fertilization did not have an impact on weed productivity, and this may suggest that IWG has a belowground competitive advantage for nutrient resources. Our findings are consistent with the observation by several farmers who noted enhanced weed suppression over time in IWG cropping systems compared to annual cereal cropping systems (Lanker et al., 2019).

4.2 | Intermediate wheatgrass grain and biomass yield

Grain yields of IWG were relatively low compared with other cereal grains but forage biomass yields were relatively high compared to other perennial forages, which suggests that dual-use grain and forage IWG cropping systems may be economically profitable for farmers. Consistent with previous research, IWG grain yields were greatest in the first production year and decreased over time (Jungers et al., 2017; Pugliese et al., 2019; Tautges et al., 2018) under these management practices. Given that aboveground biomass did not change over time, the cause of grain yield decline is not related to biomass productivity, weed competition, or nitrogen availability. Future research should address this problem, in order to understand the physiological causes and identify management practices to avoid this grain yield decline. In the second and third production years, grain yield did not differ between weed-free and weedy treatments, suggesting that the magnitude of crop–weed competition was not big enough to have negative effects on IWG. Since the weed-free treatment was not imposed in first year of grain production, the extent to which grain yields were reduced as a result of weed competition is unclear in that first year. However, grain yields in the first production year were similar to those that were observed in other studies where weeds were controlled with herbicides and where other agronomic management factors were similar to those in our study (Jungers et al., 2017;

Tautges et al., 2018). In the first production year, the majority of the crop–weed competition likely occurred while the IWG was in its vegetative stage early in the growing season, and by the time of crop anthesis and grain fill, the majority of the winter annual weeds had senesced which likely reduced the overall level of yield loss. Contrary to what was reported by Pugliese et al. (2019), we did not detect differences in grain yield between treatments that included forage harvest compared to grain-only harvest treatments; however, we observed higher grain yields in treatments that received 135 kg N ha^{-1} compared to 90 kg N ha^{-1}. Others have reported a higher incidence of stem lodging in IWG when fertilized at high N rates, resulting in decreased grain yields (Jungers et al., 2017); however, we did not observe lodging during any of the three production years of this study (data not shown).

Intermediate wheatgrass aboveground biomass yields following grain harvest were consistent with what has been previously observed in other dual-use IWG experiments (Pugliese et al., 2019). Aboveground biomass did not change over the three production years, which is similar to that reported by Jungers et al. (2017). The reduction in summer biomass that was observed in treatments that received a spring forage harvest is not surprising. When vegetative tillers are removed during the spring forage harvest, photosynthetic capacity of the plant is reduced (Richards, 1993), and in winter wheat (*Triticum aestivum* L.), this has been documented to reduce reproductive biomass at the time of grain harvest (Pumphrey, 1970). Aboveground biomass did not differ between weed-free and weedy treatments, suggesting that crop–weed competition was not a limiting factor for IWG growth and biomass production. That IWG showed a biomass response to increasing levels of nitrogen fertilization while weed biomass showed no response may suggest that IWG has a belowground competitive advantage for soil nutrients. Since nitrogen was applied at the time of IWG stem elongation immediately prior to a period of exponential growth, it is possible that the IWG was able to use soil nitrogen more efficiently as suggested by Angonin, Caussanel, and Meynard (1996). A clear understanding of the weed species that are present in the community and key crop developmental stages can reduce the level of crop-yield loss due to crop–weed competition for soil nitrogen.

5 | CONCLUSIONS

Our results indicate that IWG cropping systems can effectively suppress weeds when managed as a dual-use grain and forage crop. Intermediate wheatgrass can maintain relatively high levels of productivity in the first production year in presence of a high density of winter annual weeds, suggesting that weed management may not be economically justified for such a weed community. Notwithstanding, this cropping system is vulnerable to invasion by winter annual weed species in the first production year after a fall planting. We documented a major transition in weed community composition from annual to perennial species over three production years. Intermediate wheatgrass grain yields decreased with stand age, but they were not affected by the inclusion of a forage harvest, and IWG aboveground biomass remained relatively stable. Our results are limited to one location in the Upper Midwest, and results may differ in other conditions, particularly when perennial grass weeds are present. The results suggest that IWG dual-use cropping systems are a promising alternative for farmers interested in diversifying their cropping systems.

AKNOWLEDGEMENTS

The authors thank the staff at University of Wisconsin Arlington Agricultural Research Station for their support, Nicholas Leete for his technical support, and students at the Picasso lab for help with field work.

ORCID

Valentin D. Picasso
https://orcid.org/0000-0002-4989-6317

REFERENCES

Andersson, T. N., & Milberg, P. (1998). Weed flora and the relative importance of site, crop, crop rotation, and nitrogen. *Weed Science*, *46*, 30–38. https://doi.org/10.1017/S0043174500090135

Angonin, C., Caussanel, J. P., & Meynard, J. M. (1996). Competition between winter wheat and *Veronica hederifolia*: Influence of weed density and the amount and timing of nitrogen application. *Weed Research*, *36*, 175–187. https://doi.org/10.1111/j.1365-3180.1996.tb01813.x

Asbjornsen, H., Hernandez-Santana, V., Liebman, M. Z., Bayala, J., Chen, J., Helmers, M. J., … Schulte, L. A. (2013). Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. *Renewable Agriculture and Food Systems*, *29*(2), 101–125. https://doi.org/10.1017/S1742170512000385

Booth, B. D., & Swanton, C.J. (2002). Theory applied to Weed Communities. *Weed Science*, *50*, 2–13. https://doi.org/10.1614/0043-1745(2002)050%5b0002:AIATAT%5d2.0.CO;2

Blackshaw, R. E., Brandt, R. N., Janzen, H. H., Entz, T., Grant, C. A., & Derksen, D. A. (2003). Differential response of weed species to added nitrogen. *Weed Science*, *51*, 532–539. https://doi.org/10.1614/0043-1745(2003)051%5b0532:DROWST%5d2.0.CO;2

Carlson, H. L., & Hill, J. T. (1986). Wild oat (*Avena fatua*) Competition with spring wheat: Effects of nitrogen fertilization. *Weed Science*, *34*, 29–33. https://doi.org/10.1017/S0043174500026394

Charles, B. (2019). Can This Breakfast Cereal Help Save The Planet? National Public Radio. https://www.npr.org/sections/thesalt/2019/04/13/711144729/can-this-breakfast-cereal-help-save-the-planet?t=1557265475320

Chepil, W. S. (1946). Germination of weed seeds: I. Longevity, periodicity of germination, and vitality of seeds in cultivated soil. *Scientific Agriculture*, *26*, 306–346. https://doi.org/10.4141/sa-1946-0038

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*, 735–744. https://doi.org/10.2134/agronj2012.0273

DeHaan, L. R., Christians, M., Crain, J., & Poland, J. (2018). Development and Evolution of an Intermediate Wheatgrass Domestication Program. *Sustainability*, *10*(5). https://doi.org/10.3390/su10051499

DeHaan, L. R., & Ismail, B. P. (2017). Perennial Cereals Provide Ecosystem Benefits. *Cereal Foods World*, *62*(6), 278–281. https://doi.org/10.1094/CFW-62-6-0278

DeHaan, L. R., Wang, S., Larson, S. R., Cattani, D. J., Zhang, X., & Katarski, T. (2013). Current efforts to develop perennial wheat and domesticate *Thinopyrum intermedium* as a perennial grain. In C. Batello, L. Wade, S. Cox, N. Pogna, A. Bozzini, & J. Choptiany (Eds.), *Perennial Crops for Food Security: Proceedings of FAO Expert Workshop* (pp. 72–89). Rome, Italy: Food and Agriculture Organization of the United Nations.

Di Tomaso, J. M. (1995). Approaches for improving crop competitiveness through the manipulation of fertilization strategies. *Weed Science*, *43*, 491–497. https://doi.org/10.1017/S0043174500081522

Dutt, T. E., Harvey, R. G., & Fawcett, R. S. (1982). Feed quality of hay containing perennial broadleaf weeds. *Agronomy Journal*, *74*, 673–676. https://doi.org/10.2134/agronj1982.00021962007400040019x

Favre, J. R., Munoz Castiblanco, T., Combs, D. K., Wattiaux, M. A., & Picasso, V. D. (2019). Forage nutritive value and 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.

Glover, J. D., Culman, S. W., DuPont, S. T., Broussard, W., Young, L., Mangan, M. E., … Wyse, D. L. (2010). Harvested perennial grasslands provide ecological benchmarks for agricultural sustainability. *Agriculture Ecosystems and Environment*, *137*, 3–12. https://doi.org/10.1016/j.agee.2009.11.001

Hiltbrunner, J., Scherrer, C., Streit, B., Jeanneret, P., Zihlmann, U., & Tschachtli, R. (2008). Long-term weed community dynamics in Swiss organic and integrated farming systems. *Weed Research*, *48*(4), 360–369. https://doi.org/10.1111/j.1365-3180.2008.00639.x

Hume, D. E. (1991). Effect of cutting on production of and tillering in prairie grass (*Bromus willdenowii* Kunth) compared to two ryegrass (*Lolium*) species. *Annals of Botany*, *67*, 553–541. https://doi.org/10.1093/oxfordjournals.aob.a088195

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

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

Lanker, M., Bell, M., & Picasso, V. (2019). Farmer perspectives and experiences introducing the novel perennial grain Kernza Intermediate wheatgrass in the US Midwest. *Renewable Agriculture and Food Systems*, 1–10. https://doi.org/10.1017/S1742170519000310

Large, E. C. (1954). Growth stages in cereals illustrations of the Feekes scale. *Plant Pathology*, *3*, 128–129. https://doi.org/10.1111/j.1365-3059.1954.tb00716.x

Lee, D., Owens, V. N., Boe, A., & Koo, B. C. (2009). Biomass and seed yields of big bluestem, switchgrass, and intermediate wheatgrass in response to manure and harvest timing at two topographic positions. *GCB Bioenergy*, *1*, 171–179. https://doi.org/10.1111/j.1757-1707.2009.01008.x

Liebig, M. A., Hendrickson, J. R., Berdahl, J. D., & Karn, J. F. (2011). Soil resistance under grazed intermediate wheatgrass. *Canadian Journal of Soil Science*, *88*, 833–836. https://doi.org/10.4141/CJSS08016

Magda, D., Duru, M., & Theau, J. (2004). Defining management rules for grasslands using weed demographic characteristics. *Weed Science*, *52*, 339–345. https://doi.org/10.1614/P2202-067

Mager, D., Young, B. G., & Theau, J. P. (2006). Characterization of compensatory weed growth. *Weed Science*, *54*, 274–281. https://doi.org/10.1614/WS-05-028R1.1

Matson, P. A., Parton, W. J., Power, A. G., & Swift, M. J. (1997). Agricultural Intensification and Ecosystem Properties. *Science*, *277*(5325), 504–509. https://doi.org/10.1126/science.277.5325.504

Meiss, H., Médiène, S., Waldhardt, R., Caneili, J., & Munier-Jolain, N. (2010). Contrasting weed species composition in perennial alfalfas and six annual crops: Implications for integrated weed management. *Agronomy for Sustainable Development*, *30*, 657–666. https://doi.org/10.1051/agro/2009043

Meiss, H., Munier-Jolain, N., Henriot, F., & Canehill, J. (2008). Effects of biomass, age, and functional traits on regrowth of arable weeds after cutting. *Journal of Plant Diseases and Protection Special Issue*, *21*, 493–500.

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*, 1073–1077. https://doi.org/10.2134/agronj1991.00021962008300060027x

Nkoa, R., Owen, M. D. K., & Swanton, C. J. (2015). Weed abundance, distribution, diversity, and community analyses. *Weed Science*, *63*, 64–90. https://doi.org/10.1614/WS-D-13-00075.1

Ogle, D. L., Jr. John, L., Tober, D., & Jensen, K. (2011). Plant guide for intermediate wheatgrass (*Thinopyrum intermedium*). USDA-Natural Resources Conservation Service, Idaho and North Dakota Plant Materials Centers. Retrieved from https://plants.usda.gov/plant-guide/pdf/pg_thin6.pdf

Okafor, L. I., & De Datta, S. K. (1976). Competition between upland rice and purple nutsedge for nitrogen, moisture, and light. *Weed Science*, *24*, 43–46. https://doi.org/10.1017/S0043174500065383

Ominski, P. D., Entz, M. H., & Kenkel, N. (1999). Weed suppression by *Medicago sativa* in subsequent cereal crops: A comparative survey. *Weed Science*, *47*, 282–290. https://doi.org/10.1017/S0043174500091785

Patterson, D. T. (1995). Effects of Environmental Stress on Weed/Crop Interactions. *Weed Science*, *43*(3), 483–490 https://doi.org/10.1017/S0043174500081510

Peters, J. B., & Laboski, C. A. M. (2013). *Sampling soils for testing*. (University of Wisconsin–Madison Extension Publication No. A2100). Madison, WI: University of Wisconsin.

Picasso, V. D., Brummer, E. C., Liebman, M., Dixon, P. M., & Wilsey, B. J. (2008). Crop Species Diversity Affects Productivity and Weed Suppression in Perennial Polycultures under Two Management Strategies. *Crop Science*, *48*, 331–342. https://doi.org/10.2135/cropsci2007.04.0225

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. (1970). Semidwarf Winter Wheat Response to Early Spring Clipping and Grazing. *Agronomy Journal*, *62*, 641–643. https://doi.org/10.2134/agronj1970.00021962006200050028x

R Core Team (2018). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. https://www.r-project.org/

Richards, J. H. (1993). Physiology of plants recovering from defoliation. In *Proceedings of the 17th International Grasslands Congress* (pp. 85–94). Palermerston North, New Zealand: International Grasslands Congress.

Ryan, M. R., Crews, T. E., Culman, S. W., DeHaan, L. R., Hayes, R. C., Jungers, J. M., … Culman, S. W. (2018). Managing for multifunctionality in perennial grain crops. *Bioscience*, *68*, 294–304. https://doi.org/10.1093/biosci/biy014

SAS Institute. (2013). *Base SAS 9.4 procedures guide: Statistical procedures* (2nd ed.). Cary, NC: SAS Institute.

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*, *158*, 758–773. https://doi.org/10.1017/S0021859618000680

USDA-NRCS. (2018). *Official Soil Series Descriptions and Series Classification*. U.S. Department of Agriculture National Resources Conservation Service. Retrieved from https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx

Vesk, P. A., Warton, D. I., & Westoby, M. (2004). Sprouting by semi-arid plants: Testing a dichotomy and predictive traits. *Oikos*, *107*, 72–89. https://doi.org/10.1111/j.0030-1299.2004.13122.x

Wang, G. J., Nyren, P., Xue, Q. W., Aberlere, E., Eriksomoen, 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

Wagoner, P. (1990). Perennial grain: New use for intermediate wheatgrass. *Journal of Soil and Water Conservation*, *45*, 81–82. Retrieved from https://www.jswconline.org/

Whitson, T. D., & Koch, D. W. (1998). Control of downy brome (*Bromus tectorum*) with herbicides and perennial grass competition. *Weed Technology*, *12*, 391–396. https://doi.org/10.1017/S0890037X00043980

Wilson, R. G., & Kachman, S. D. (1999). Effect of perennial grass on Canada thistle (*Cirsium arvense*) control. *Weed Technology*, *13*, 83–87. https://doi.org/10.1017/S0890037X0004495X

Wolkovich, E. M., & Cleland, E. E. (2011). The phenology of plant invasions: A community ecology perspective. *Frontiers in Ecology and the Environment*, *9*, 287–294. https://doi.org/10.1890/100033

Zhang, X., Ohm, J. B., Haring, S., DeHaan, L. R., & Anderson, J. A. (2015). Towards the understanding of end-use quality in intermediate wheatgrass (*Thinopyrum intermedium*): High-molecular-weight glutenin subunits, protein polymerization, and mixing characteristics. *Journal of Cereal Science*, *66*, 81–88. https://doi.org/10.1016/j.jcs.2015.10.008

How to cite this article: Zimbric JW, Stoltenberg DE, Picasso VD. Effective weed suppression in dual-use intermediate wheatgrass systems. *Agronomy Journal*. 2020;112:2164–2175. https://doi.org/10.1002/agj2.20194