

ORIGINAL ARTICLE

Turfgrass Science

Spring wheat canopy effects on light dynamics and yield of intercropped fine fescues

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Abstract

Turfgrass stakeholder surveys have indicated fine fescue (*Festuca* spp.) seed will become in higher demand, but fine fescue seed production in the United States, especially in Oregon, has not increased. Northern Minnesota is conducive for cool-season turfgrass seed production and has existing infrastructure to produce turfgrass seed. There is an exciting opportunity for Northern Minnesotan farmers to increase revenue by producing fine fescue seed; however, fine fescues require a growing season for establishment prior to seed production, and an economic crop during the first growing season is needed. Most fine fescues are considered shade tolerant and should establish under spring wheat (*Triticum aestivum* L.), which is the current cropping system used for perennial ryegrass (*Lolium perenne* L.) seed production in Minnesota. Experiments were established in Roseau (2018 and 2019) and St. Paul (2018) in which several cultivars of Chewings, hard and strong creeping red fescue were interseeded with spring wheat. Our objectives were to examine stand and seed production of these three fine fescue taxa in comparison with perennial ryegrass. All three taxa were negatively affected by wheat, possibly from excessive shade from the wheat canopy. The fine fescue culm index (number of culms relative to whole-plant biomass) grown in wheat was lower, indicating that vernalization was negatively impacted, resulting in seed yield reduction. Our results demonstrate that the currently used perennial ryegrass–spring wheat cropping system is not optimized for fine fescue seed production, especially hard fescue, and more research is needed to improve this cropping system in Northern Minnesota.

Abbreviations: B:G, blue to green ratio; CH, Chewings fescue; FF, fine fescue; HD, hard fescue; PR, perennial ryegrass; R:FR, red to far red ratio; ST, strong creeping red fescue; W, wheat.

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1 | INTRODUCTION

The fine fescue turfgrass taxa including sheep fescue (*Festuca ovina* L., syn. *Festuca ovina* L. spp. *hirtula* [Hack. ex Travis] M.J. Wilk), hard fescue (HD) (*Festuca brevipila* Tracey), Chewings fescue (CH) (*Festuca rubra* L. spp. *commutata* Gaudin, syn. *Festuca rubra* L. spp. *fallax* [Thuill.] Nyman), slender creeping red fescue (*Festuca rubra* L. spp. *littoralis* [G. Mey.] Auquier) and strong creeping red fescue (ST) (*Festuca rubra* L. spp. *rubra* Gaudin) are cool-season perennial grasses known for their ability to grow well under low-input management practices. These species can withstand long periods of deficit irrigations while maintaining superior turf quality (Breuillin-Sessoms et al., 2021), do not require high fertility compared to Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (PR) (*Lolium perenne* L.) (Hugie & Watkins, 2016), and are characterized by slow vegetative growth compared to other cool-season species (Van Huylbroeck et al., 1999). The fine fescues are promoted as alternatives for homeowners who wish to establish more sustainable lawns and several studies have revealed that homeowners are willing to buy and use these low input turfgrass species, despite being more expensive, because of their reduced resource input requirements (Hugie et al., 2012; Yue et al., 2021, 2017). While willingness to purchase these grasses is evident, turfgrass breeders and seed distributors rate the volume of seed sales as the most important factor when setting priorities (Yue et al., 2019), so while new markets for low-input turf continue to develop, innovation from private and public breeding programs has not yet translated into expansion of fine fescue acreage. Furthermore, those traits that might be important for seed producers (stand longevity, high yield in a seed production system, etc.) have not been prioritized in plant improvement programs.

Only three regions in the world are currently known for fine fescue seed production: Oregon (USA), the Peace River Region (Canada), and Denmark. Between 2010 and 2020, the most produced turfgrass species in Oregon were tall fescue (*Festuca arundinacea* Schreb.), PR, and Kentucky bluegrass for seed production (Table 1) (<https://cropandsoil.oregonstate.edu/seed-crops/oregon-grass-and-legume-seed-production>). These three species had either the highest percentage of area harvested (tall fescue > PR > Kentucky bluegrass), and/or the greatest increase in area harvested between 2010 and 2020 (Kentucky bluegrass > tall fescue). For the fine fescue taxa, only red fescue and CH showed an increase in the area harvested in Oregon between 2010 and 2020, but the acreage of harvested red fescue was always lower compared to PR, tall fescue, and Kentucky bluegrass (Table 1). Most importantly, the area harvested for HD was reduced in 2020 compared to 2010, despite possessing high value in both 2010 and 2020 and exhibiting increased yield across the 10-year timeframe (+42.22%).

Core Ideas

- Turfgrass stakeholders desire lower input options, resulting in the need to increase fine fescue seed production.
- In Northern Minnesota, establishing fine fescue in spring wheat, as is currently done with perennial ryegrass, is preferred by growers.
- Fine fescue stand, culm index, and yield are negatively affected when established with spring wheat.

Interestingly, using a 2010 hard fescue enterprise budget (<https://agsci.oregonstate.edu/enterprise-budgets/aeb0013>) and 2010 hard fescue seed price (2.00\$ kg⁻¹, Table 1), the positive return of Oregon seed producers would have occurred between yield of 784.6 kg ha⁻¹ priced 1.84\$ kg⁻¹ and yield of 672.5 kg ha⁻¹ priced at 2.11\$ kg⁻¹; hard fescue 2010 yield (979.75 kg ha⁻¹, Table 1) indicates that Oregon seed producers would have already obtained positive returns from growing hard fescue in 2010. Despite continuous high market value and increasing consumer demand, there is limited fine fescue seed production in Oregon, pointing to a need for fine fescue seed production to increase in other parts of the Northern United States.

The environment in the upper Midwest is advantageous for meeting the floral requirements of fine fescues. A review of the literature revealed that the exact photoperiod requirements for primary and secondary floral induction can vary tremendously between *Festuca* species and even between ecotypes of the same species. Fine fescue species require a dual induction to flower. Primary induction has been shown to require short days (<12 h), but this requirement can be modified by temperature (Heide, 1994). Secondary induction of floral development takes place under long days (>12 h) and with warmer temperatures (Heide, 1994). Both Northern and East-Central Minnesota have been shown to meet both the primary and secondary induction requirements (photoperiod and temperatures) in fall and spring, as fine fescue cultivars such as ‘Quatro’ sheep fescue, ‘Windward’ CH, ‘Cindy Lou’ ST, and ‘Shoreline’ Slender creeping red fescue were able to produce seed in Roseau, Becker, and St. Paul (Rodriguez Herrera, 2020).

Northern Minnesota, a location that already has extensive turfgrass seed production acreage, along with the necessary infrastructure for seed production, could serve as an ideal location for fine fescue seed production. Most turfgrass seed production in Minnesota is in the northwest part of the state, close to the Canadian border in Beltrami, Kittson, Koochiching, Lake of the Woods, Marshall, Pennington, Red Lake, and

TABLE 1 Oregon grass preliminary estimate in 2010 and 2020.

Species	Year	Area harvested (ha)	Yield (Kg ha ⁻¹)	Price (\$ kg ⁻¹)
Perennial ryegrass	2010	37,057.87	1794.72	1.09
	2020	25,431.00 (–31.37%) ^a	2022.28 (+12.68%)	1.87 (+71.72%)
Tall fescue	2010	47,381.63	1784.63	0.69
	2020	64,034.80 (+35.15%)	1927.00 (+7.98%)	1.72 (+147.77%)
Kentucky bluegrass	2010	5402.67	1381.07	2.12
	2020	10,202.35 (+88.84%)	1317.18 (–4.63%)	2.87 (+34.90%)
Chewings fescue	2010	3099.96	1421.43	1.20
	2020	3520.84 (+13.58%)	1571.64 (+10.57%)	2.25 (+86.85%)
Red fescue ^b	2010	3435.86	1437.12	1.25
	2020	4912.99 (+42.99%)	1300.36 (–9.52%)	2.29 (+83.23%)
Hard fescue	2010	1297.05	979.75	2.00
	2020	1125.05 (–13.26%)	1393.40 (+42.22%)	2.87 (+43.22%)

Note: Data were extracted from the 2010 and 2020 Oregon grass and legume seed production estimates (<https://cropandsoil.oregonstate.edu/seed-crops/oregon-grass-and-legume-seed-production>).

^aPercent change from 2010 data in brackets.

^bData were reported only as red fescue, which includes both ST and slender creeping red fescue, although slender creeping red fescue production is very limited.

Roseau counties. Perennial ryegrass is the main cool-season grass cultivated for seed production in these counties. In 2020, an estimated total of 24,281 hectares were in use for PR seed production (Wyse et al., 2020). The region is characterized by very cold winters with average temperatures below 0°C between November and March. Perennial ryegrass is known to be susceptible to winter injury and kill leading to reduced seed yield or complete crop failure (Hulke et al., 2008). The University of Minnesota has released a number of cultivars with improved winterhardiness, but this continues to be a major challenge.

Like most other turfgrasses, PR requires a full growing season before vernalization and will only produce seed during the next growing season, leaving farmers potentially without revenue during the establishment year. Seed growers have remedied the loss of cash revenue during the first growing season by intercropping PR with spring wheat (*Triticum aestivum* L.). Studies have demonstrated that this system works well because wheat growth and yield is not affected by the perennial ryegrass. The wheat provides a source of revenue for the first growing season and the wheat stubble that remains after harvest helps protect and insulate the PR stand by maintaining snow cover (Ehlke & Vellekson, 1998). Intercropping in agricultural systems can provide numerous benefits such as reduced nitrogen leaching and soil erosion, increased soil carbon sequestration, greater organic matter accumulation, and increasing soil microorganism biodiversity; however, competition for nutrient availability and light can negatively impact the yield of the undersown crop (Cheng et al., 2022; Huss et al., 2022).

Perennial ryegrass is not a shade-tolerant species but exhibits shade avoidance symptoms (Tegg & Lane, 2004)

under foliar shade which allows this species to survive when grown under the shade of wheat (Ehlke & Vellekson, 1998; Poudel et al., 2022). Furthermore, the ability of PR to quickly germinate (Braun et al., 2023), and its strong seedling vigor (Rozman et al., 2010) would allow a faster establishment before the development of very dense foliar shade under a wheat canopy. Fine fescue taxa are often marked as shade tolerant, but a recent study revealed variation in their response to shade with CH performing best, followed by ST and then HD (Petrella & Watkins, 2020). Fine fescue germination speed is lower than for PR with PR > ST ≥ slender creeping red fescue ≥ HD ≥ CH ≥ sheep fescue (Braun et al., 2023). Fine fescue seedling vigor is also lower than PR: Rozman et al. (2010) reported fine fescue seedling height between 4 and 5 cm at 18 days compared to the 8.7 cm at 18 days of PR (Rozman et al., 2010); the red fescue taxa are known to have better seedling vigor than taxa in the ovina complex (Braun et al., 2023). The slower germination and lower seedling vigor of fine fescues could counterbalance their shade tolerance when established with spring wheat.

Only a few studies mention red fescue undersown with other species such as winter barley (*Hordeum vulgare* spp. *vulgare*) (Kankanen & Eriksson, 2007) and winter wheat (Ghiloufi et al., 2010; Picard et al., 2010). Fine fescues have been tested for interseeding with winter small grains (barley and wheat) in Oregon (Chastain & Grabe, 1988a, 1988b) and resulted in contrasting results between establishment (reduction) and yield (no difference and reduction) but there is no information on the effect of a spring small grain crop on the fine fescue yield when grown in Northern Minnesota. Therefore, our objective was to compare seed production of several fine fescue cultivars with PR grown either

TABLE 2 Seeding and harvest dates for SP-2018, RO-2018, and RO-2019 field experiments.

	SP-2018	RO-2018	RO-2019
Wheat seeded	14 May 2018	23 May 2018	22 May 2019
Perennial grass seeded	15 May 2018	23 May 2018	22 May 2019
Wheat harvest	30 July 2018	08 August 2018	23 August 2019
Perennial grass harvest ^a	2 July 2019	10 July 2019	2 July 2020

^aDate indicates the beginning of the harvest for the different perennial grass cultivars.

alone or interseeded with wheat during the establishment year.

2 | MATERIALS AND METHODS

2.1 | Experimental setup

Experiments were established in Roseau County, MN at the Magnusson Research Farm in both 2018 (hereafter referred to as RO-2018) and 2019 (RO-2019) and at the Minnesota Agricultural Experimental Station in St. Paul, MN in 2018 (SP-2018) (Table 1). The trial was arranged as a split-plot with four replications. Cropping system (non-wheat and in wheat) was the whole-plot factor and turfgrass grass cultivar was the split-plot factor. The size of the split-plot varied between locations and measured 121.41 m² in RO-2018/2019 and 106.83 m² in SP-2018. Grass species tested included 'Arctic Green' PR, 'Chantilly' ST, 'Intrigue' and 'Radar' CH, and 'MNHD' HD. These cultivars were chosen because preliminary results from Petrella and Watkins (2020) indicated that they were more shade tolerant relative to other cultivars of the same taxa, although 'Intrigue' CH was not tested in that study. All entries were seeded at a rate of 6.72 kg of seed ha⁻¹; percentage of germination was tested of each cultivar and seeding rate was based on 90% pure live seed (PLS). Seed size and seed viability were not considered. Turfgrass cultivars were seeded perpendicular to the row of wheat for RO-2018 and SP-2018 or within the row of wheat for RO-2019 field experiment. For interseeded treatments, 'Linkert' spring wheat was seeded at a rate of 112.09 kg of seed ha⁻¹; this variety was chosen because of its shorter growth habit and lower amount of biomass, making it ideal for inter-seeding. Seeding and harvest dates are presented in Table 2. Weeds were controlled according to standard agronomic management practices for the different perennial grass species tested in the seedings. 2,4-D (2,4-dichlorophenoxyacetic acid) (Weedar[®] 64, 1.40 L ha⁻¹, Nufarm) combined with dicamba (3,6-dichloro-2-methoxybenzoic acid) (Sterling Blue[®], 0.88 L ha⁻¹, WinField United) was applied on 7 October 2018 to SP-2018. In Roseau, RO-2018 received two applications of herbicide, clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) and 2, 4-D (Curtail[®], 2.80 L ha⁻¹, Corteva) with dicamba (Sterling Blue[®], 0.88

TABLE 3 Fertilization regimes and application dates for SP-2018, RO-2018, and RO-2019 field experiments.

Experiment	Dates	Fertility applied (kg ha ⁻¹)		
		N	P	K
SP-2018	At seeding	89.7	0	0
	23 October 2018	100.9	0	0
	<i>Total received</i>	<i>190.6</i>	<i>0</i>	<i>0</i>
RO-2018	At seeding	156.9	19.6	37.1
	23 August 2018	12.3	24.5	46.3
	27 October 2018	100.9	0	0
	<i>Total received</i>	<i>270.1</i>	<i>44.1</i>	<i>83.4</i>
RO-2019	At seeding	156.9	19.6	37.1
	1 September 2019	56.0	24.5	46.3
	27 April 2020	44.8	0	0
	<i>Total received</i>	<i>257.7</i>	<i>44.1</i>	<i>83.4</i>

Note. In 2019, flooding of plots did not allow for regular late fall fertilization; as a result, the late fall fertilization for RO-2019 field experiment occurred in early spring 2020.

L ha⁻¹, WinField United) applied on 26 September 2018 and fluzifop-P-butyl (butyl (R)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoate) (Fusilade[®] DX, 0.88 L ha⁻¹, Syngenta) applied on 2 May 2019. 2, 4-D (Weedar[®] 64, 1.40 L ha⁻¹, Nufarm) combined with dicamba (Sterling Blue[®], 0.88 L ha⁻¹, WinField United) was applied on 9 September 2019 to RO-2019. No irrigation was added in any of the three seedings and during the whole experimental runs.

Despite a similar set-up for all field experiments, the fertilization regimes and application times were different for the three field experiments (Table 3). SP-2018 was established on a Waukegan silt loam with a pH of 6.5, initial concentration of 52 mg of P kg⁻¹ soil, 116 mg of K kg⁻¹ soil, 6.6 mg of N kg⁻¹ soil, 3.0% organic matter, and received a total of 190.6 kg N ha⁻¹ during the run of the experiment; no phosphate or potassium were added during this field experiment. Both RO-2018 and RO-2019 were established on a Zippel very fine sandy loam with pH 8.1, initial concentration of 10.7 mg of P kg⁻¹ soil, 99 mg of K kg⁻¹ soil, 8.9 mg of N kg⁻¹ soil, 3.4% organic matter, and received a total of 270.1 kg N ha⁻¹, 44.1 kg P ha⁻¹, and 83.4 kg K ha⁻¹ for RO-2018; a total of 257.7 kg N ha⁻¹, 44.1 kg P ha⁻¹, and 83.4 kg K ha⁻¹ for RO-2019.

2.2 | Data collection

2.2.1 | Early establishment data

Early establishment data were collected using a modified seedling vigor/establishment NTEP turfgrass rating (<https://www.ntep.org/reports/ratings.htm>). This initial visual rating was performed once within 3 weeks after seeding before the wheat canopy started to interfere with the observation, and considered emerging seedling and tiller presence, along with homogeneity of the stand within all rows. The rating ranged from 1 (no emerging seedlings within all rows of the plot), 2 (some emerging seedlings within all rows of the plot, no tillering seedling), 5 (all rows are covered with emerging seedlings, but very few tillering observed), 9 (all rows displayed tillering seedlings across all rows within the plot). Data was collected for SP-2018 on 1 June 2018 and for RO-2018 on 15 June 2018.

2.2.2 | Gridline stand count

Fall and spring stand counts were estimated similarly for all three experiments. Within each plot, a 96-intersection grid was placed on two random locations within the plot and the number of intersections with the presence of perennial grass leaves was recorded to determine percent establishment.

2.2.3 | Wheat harvest

Wheat was harvested from plots during the first year of each experiment and turfgrass seeds were harvested the following year as they require a winter vernalization period. Both wheat and turfgrass seeds were harvested by clipping all culms within two randomly placed 1 m² quadrats. The harvested biomass was dried for a week in a forced air drier at 90°C. Seed threshing and cleaning was performed following a methodology previously described (Koeritz et al., 2013), and seed yield was calculated as g m⁻².

2.2.4 | Culm index

Culm index was calculated to assess the vegetative or reproductive state of all fine fescue species because little to no flag leaves were seen in early summer observations in wheat plots; 'Arctic Green' PR was not included in this last data assessment, as we observed its flowering capacity was not impacted by the wheat presence. Several 15 cm² quadrats (four for RO-2018 and SP-2018; 3 for RO-2019) were placed at random locations within each plot and the entire aboveground plant biomass was harvested. Biomass was dried for a minimum

of 4 days at 90°C in an air dryer and weighed, and the number of culms for each sample was counted. Culm index was calculated as the number of culms g⁻¹ of dry biomass.

2.3 | Light parameters

Photosynthetic photon flux (PPF) in selected plots was monitored using photosynthetically active radiation (PAR) sensors (SQ-420 Smart Quantum Sensor, Apogee instruments, Logan, UT) powered by lithium-ion batteries (V44, Voltaic Systems, Brooklyn, NY), charged using 9 W solar panels (Voltaic Systems). One week after wheat germination, sensors were mounted 12.7 cm from the soil surface in non-wheat plots, or in the middle of wheat rows. Sensors were east–west center justified in all plots and were placed 4 m deep into the plots from the south or north edge. In 2018, two sensors were placed in wheat and two were placed in non-wheat in both St. Paul (installed on 22 May 2018, 7 days after seeding) and in Roseau (installed on 30 May 2018, 7 days after seeding); however, one wheat PAR sensor was damaged in both locations, leaving data for a total of two PAR sensors in wheat and four under non-wheat. In 2019, three PAR sensors were placed in wheat and three were placed under non-wheat in Roseau (installed on 22 May 2018, 8 days after seeding). One non-wheat sensor was damaged and unusable in 2019. PPF data from the PAR sensors were logged every 10 min and used to calculate the daily light integral (DLI; mol m⁻² day⁻¹) (Faust & Logan, 2018). To compare non-wheat and wheat DLI, daily DLI data were averaged weekly to smooth variation due to logging interval differences between sensors.

To examine the effects of solar elevation on the spectral energy distributions under spring wheat canopies, vertical (downward) spectral photon distribution data were acquired with a spectroradiometer (Apogee SS-110, Apogee instruments) 8.9 cm from the soil surface on a total of five cloudless days for SP-2018 only; data were acquired on 13 June, 2 July (after closure of wheat canopy), 6 July, and 30 July 2018 (after wheat harvest) at 9:00, 14:00, and 20:00 h (±10 min). Twelve independent scans were acquired in wheat, and six in non-wheat at each time point and on each date.

Spectral energy distribution data were used to calculate the red to far-red (R:FR) ratio (655–665/725–735 nm), and the phytochrome photoequilibria (PPE) to evaluate phytochrome and red/far-red light mediated shade avoidance responses (Gardner & Graceffo, 1982; Holmes & Smith, 1975; Sager et al., 1988). We also calculated the blue to green light (B:G) ratio as a means to evaluate cryptochrome activity and blue/green light mediated shade avoidance response (Sellaro et al., 2010). Spectral data were normalized to 780 nm and were plotted to examine large scale changes between data in wheat and non-wheat (Figures S1 and S2).

TABLE 4 Monthly average temperature (°C) and cumulative precipitation (mm) for SP-2018, RO-2018, and RO 2019 field experiments.

Month	Temperature (°C) ^a			Precipitation (mm) ^b		
	SP-2018	RO-2018	RO-2019	SP-2018	RO-2018	RO-2019
May	18.48	14.13	9.58	89.41	68.88	36.09
June	22.76	18.24	16.78	117.86	52.86	66.07
July	24.78	19.46	19.32	103.38	44.45	93.75
August	23.51	18.46	17.05	73.91	34.54	76.00
September	19.44	11.78	13.15	182.63	52.07	237.95
October	6.78	2.91	4.17	86.36	42.67	92.00
November	−3.52	−7.68	−6.09	35.81	0.00	0.00
December	−4.64	−9.96	−11.80	33.53	0.00	0.00
January	−10.47	−18.43	−12.97	9.14	0.00	0.00
February	−12.56	−18.50	−14.36	58.67	0.00	0.00
March	−3.27	−8.78	−5.86	53.09	0.00	0.00
April	7.48	3.46	1.42	85.60	6.86	17.53
May	11.53	9.58	10.60	163.58	36.09	29.46
June	19.56	16.78	18.22	72.39	66.07	197.00
July	22.49	19.32	20.97	120.65	93.75	150.22

Note: for SP-2018, temperatures and precipitation data were collected from the Minnesota Department of Natural Resources University of Minnesota St. Paul Campus Climate Observatory located approximately 900 m away from field experiment (<https://www.dnr.state.mn.us/climate/historical/daily.html>). For RO-2018 and RO-2019, temperatures and precipitation data were collected from the North Dakota Agricultural Weather Network Center from at the Magnusson Research Farm station, approximately 200 m away from the field experiments (<https://ndawn.ndsu.nodak.edu/>).

^aAverage temperature was calculated for each month of the study using the daily average temperature.

^bCumulative precipitation was calculated for each month of the study by summing daily precipitation observations.

2.4 | Statistical analysis

Due to differences in location, year of seeding, frequency of data collection, and differences in management practices, the three experiments were analyzed separately. Data were log-transformed when needed. Early establishment, stand counts (fall and spring), and seed yield (g m^{-2}) were subjected to an ANOVA using a mixed model with cropping system (CS; wheat presence), perennial grass cultivars (C), and their interaction ($\text{CS} \times \text{C}$) as fixed effects. Block, along with the interaction between block, CS, and C were treated as random effects. Means were compared using Tukey's honestly significant difference ($p = 0.05$) for significant treatment effects. All data were analyzed using JMP (JMP®, Version 16. SAS Institute Inc., Cary, NC, 1989–2023).

3 | RESULTS AND DISCUSSION

3.1 | Monthly temperature and precipitation during the experimental runs

Daily average temperatures followed similar trends (Figure S3) for the three experiments. Monthly average temperatures were higher for SP-2018 than either of the two experiments in Roseau (Table 4). The RO-2018 experiment experienced

a warmer establishment year and a colder second year than RO-2019. Daily precipitation was variable between the three experiments (Figure S3): SP-2018 had the highest monthly precipitation, and RO-2018 had the lowest average monthly precipitation. (Table 4 and Figure S3).

3.2 | Reductions in light intensity

Weekly average DLI in non-wheat plots ranged from approximately $35\text{--}50 \text{ mol m}^{-2} \text{ day}^{-1}$ in both St. Paul and Roseau during the 2018 season (Figure 1). These results are in line with the expected monthly average DLI in Minnesota for June, July, and August (Faust & Logan, 2018). Similar DLI data were observed with and without wheat during the 2 weeks after placing the sensors. However, at the beginning of the third week, a fast decline in DLI was observed in the wheat treatment (Figure 1) where the maximum reduction (85%–95%) in the weekly average DLI occurred 5–6 weeks after wheat germination, and weekly average DLI was $\leq 5 \text{ mol m}^{-2} \text{ day}^{-1}$ during this timeframe (Figure 1). There were no differences in the photoperiod between the in wheat and non-wheat plots during the time when wheat canopy was covering the fine fescue (data not shown). Photoperiodic responses have also been shown to only require very low light intensities, those observed at dusk and at dawn (Seaton et al., 2018), and would therefore not be interrupted by the presence of the

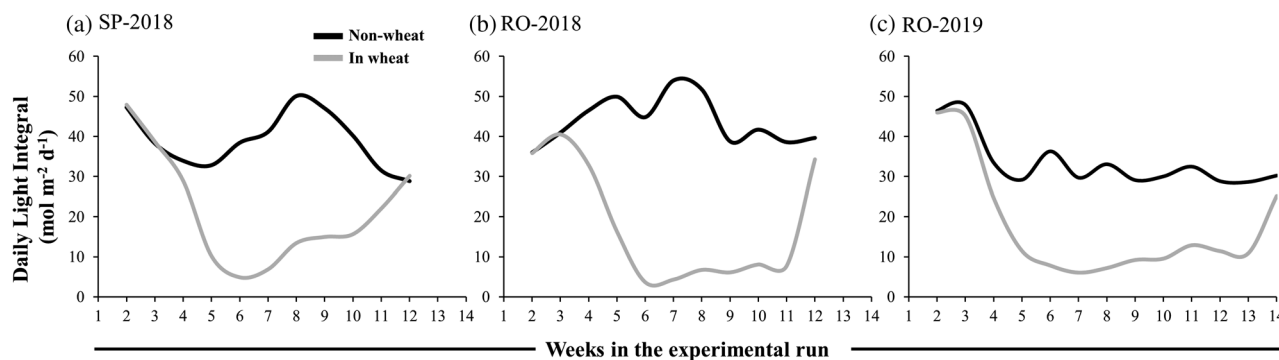


FIGURE 1 Weekly average daily light integral ($\text{mol m}^{-2} \text{ day}^{-1}$, DLI) data under non-wheat (black lines) and in wheat (grey lines) in a) St. Paul MN during the summer of 2018, in b) Roseau MN during the summer of 2018, and c) in Roseau MN during the summer of 2019. Data for DLI calculations were made from instantaneous photosynthetic photon flux (PPF) data collected from photosynthetic active radiation (PAR) sensors every 10 min at each site and in each year.

wheat, even if the photoperiod was slightly shorter under the wheat canopy.

For both RO-2018 and SP-2018, the weekly average DLI under the wheat canopy was below $15 \text{ mol m}^{-2} \text{ day}^{-1}$ for most of the time, exhibiting a minimum reduction in DLI of 50% relative to non-wheat for a large majority of the experiments in both locations. Across Minnesota, monthly averaged DLIs of $\leq 15 \text{ mol m}^{-2} \text{ day}^{-1}$ occur from October to February, and monthly average DLIs of $\leq 5 \text{ mol m}^{-2} \text{ day}^{-1}$ do not occur anytime during the year in Minnesota (Faust & Logan, 2018). While the period where light intensity was reduced under the wheat canopy was relatively short, this light reduction was similar to those observed under dense tree canopy (Petrella et al., 2022).

3.3 | Alterations to light quality in SP-2018

Phytochrome (R:FR) and cryptochrome (B:G) related spectral ratios data were quite different between the wheat and non-wheat treatments. On each date for SP-2018, the R:FR ratio collected in non-wheat plots did not present much variation during the day and between dates. However, this ratio changed significantly under the wheat canopy (Table 5). In wheat plots, the R:FR was always lower than in the non-wheat plots until wheat harvest (30 July). Overall R:FR ratios and the within-day changes observed in the R:FR ratio in wheat in these experiments were like what has been previously reported, ranging from approximately 0.20 to 0.40 at the soil surface (Chelle et al., 2007; Holmes & Smith, 1975). While there were larger differences in the R:FR ratio in wheat during the days and across dates, there was very little difference in the PPE (Table 5).

The B:G ratios in non-wheat plots were similar among days and between dates. However, in wheat plots, this ratio

decreased in wheat compared to non-wheat in the morning and in the afternoon, while increasing in the evening (Table 5). Even though the R:FR ratio was higher in the afternoon in wheat compared to the morning, the lower B:G in the afternoon ratio may counterbalance any potential positive benefits of the higher afternoon R:FR. Similarly, the increase in the B:G ratio in the evening hours in wheat may attenuate shade avoidance responses associated with the reduced R:FR ratios in the evening. Sellaro et al. (2010) clearly showed that higher B:G ratios lead to shorter hypocotyl length in *Arabidopsis*, and treatment with a B:G ratio of 0.50 more than doubled hypocotyl length of plants treated with a B:G ratio of 1.10 through cryptochrome action (Sellaro et al., 2010). To our knowledge, there is no published research examining the interaction between the B:G and the R:FR ratios, though the R:FR ratio has been suggested to have larger effects on plant response to shade compared to the B:G ratio (Sellaro et al., 2010). More research should be done to study the interaction at the end of the day for improved shade tolerance and to breed turfgrass cultivars more suited for intercropping.

3.4 | Overall results

For SP-2018 and RO-2018 early establishment, no cropping system $\times$ cultivar interaction was significant. A significant cultivar effect was observed for the SP-2018 and the RO-2018 early establishment (Table 6). For fall stand count, a cropping system $\times$ cultivar interaction was observed for all field experiments (Table 6); this could still be observed for the spring stand count for both RO-2018 and SP-2018, but not RO-2019. The cropping system $\times$ cultivar interaction was also significant for yield (Table 6).

TABLE 5 The red to far-red (R:FR) ratio and the blue to green (B:G) ratio in the morning, afternoon, and evening in SP-2018 on 13 June, 2 July, and 6 July 2018 in wheat or non-wheat cropping systems.

Cropping system	Date and weeks number	Time (h) ^a	Solar elevation (degrees) ^b	R:FR ^c	B:G ^d
Non-wheat	13 June 4.1 weeks ^e	9:00	34.84	1.14 ± 0.00 ^f	0.88 ± 0.01
		14:00	66.26	1.12 ± 0.01	0.87 ± 0.01
		20:00	8.56	1.18 ± 0.00	0.93 ± 0.02
	2 July 6.6 weeks	9:00	34.00	1.30 ± 0.00	0.88 ± 0.01
		14:00	66.35	1.23 ± 0.01	0.86 ± 0.01
		20:00	9.00	1.45 ± 0.01	0.88 ± 0.04
	6 July 7.3 weeks	9:00	33.65	1.21 ± 0.01	0.86 ± 0.00
		14:00	66.06	1.16 ± 0.00	0.86 ± 0.00
		20:00	8.85	1.34 ± 0.01	0.84 ± 0.01
In Wheat	30 July 10.6 weeks	14:00	62.1	1.13 ± 0.09	0.90 ± 0.10
	13 June 4.1 weeks	9:00	34.84	0.28 ± 0.08	0.80 ± 0.05
		14:00	66.26	0.57 ± 0.34	0.76 ± 0.08
		20:00	8.56	0.44 ± 0.09	0.94 ± 0.04
	2 July 6.6 weeks	9:00	34.00	0.21 ± 0.04	0.80 ± 0.05
		14:00	66.35	0.36 ± 0.18	0.70 ± 0.10
		20:00	9.00	0.44 ± 0.10	1.01 ± 0.08
	6 July 7.3 weeks	9:00	33.65	0.22 ± 0.02	0.83 ± 0.04
		14:00	66.06	0.34 ± 0.08	0.81 ± 0.03
		20:00	8.85	0.36 ± 0.04	0.95 ± 0.09
	30 July 10.6 weeks	14:00	56.16	1.12 ± 0.01	0.80 ± 0.00

Note: Wheat was seeded on 14 May 2018, and began heading on approximately 26 June 2018. Wheat was harvested on 30 July 2018 in SP-2018 field experiment. SPD data presented are the average of 12 independent scans in wheat, and 6 in non-wheat on each date. Data in wheat were collected in between rows, at least four rows in from plot edges, and were collected in randomly chosen locations within wheat plots on each date.

^aTime = Approximate time during the day spectral data were acquired, ±10 min.

^bSolar elevation = Angle of sun relative to the horizon. Determined with latitude, longitude, date, and time of the day using the NOAA sun position calculator (<https://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html>).

^cR:FR = 655–665/725–735.

^dB:G = 420–490/500–570.

^eNumber of weeks in the experiment calculated from 15 May 2018 when the fine fescue were seeded.

^fMean ± standard deviation.

TABLE 6 Level of significance for cropping system (CS), perennial grass cultivars (C), and their interaction (CS × C) on early establishment and stand counts (fall and spring), culm index and yield (g m⁻² and \$ ha⁻¹) from data collected in SP-2018, RO-2018, and RO-2019 experiments.

Location	Source	Pr > F			
		Early establishment	Stand count		Yield g m ⁻²
			Fall	Spring	
SP-2018	CS	NS	***	**	***
	C	*	***	***	***
	CS × C	NS	**	***	***
RO-2018	CS	NS	**	NS	NS
	C	***	***	***	*
	CS × C	NS	*	***	***
RO-2019	CS		***	NS	***
	C		**	NS	***
	CS × C	—	**	NS	***

Abbreviation: NS, nonsignificant.

*Significant at the 0.05 probability level.

**Significant at the .01 probability level.

***Significant at the 0.001 probability level.

TABLE 7 Average early establishment for all perennial grass cultivars tested in SP-2018 and RO-2018 experiments.

Species	Cultivar	Early establishment (1–9) ^a	
		SP-2018	RO-2018
PR	Arctic Green	6.0 A ^b	5.9 A
ST	Chantilly	3.0 B	3.5 B
CH	Intrigue	3.4 B	3.3 BC
	Radar	3.6 B	4.0 B
HD	MNHD	3.0 B	2.5 C

Note: Early establishment data were collected for SP-2018 on 1 June 2018 (16 days after seeding) and for RO-2018 on 15 June 2018 (23 days after seeding). Data were log-transformed prior to analysis.

Abbreviations: CH, Chewings fescue; HD, hard fescue; PR, perennial ryegrass; ST, strong creeping red fescue.

^a1 = no emerging seedlings within all rows of the plot; 2 = some emerging seedlings within all rows of the plot, no tillering seedling; 5 = all rows are covered with emerging seedlings, and little tillering is observed; 9 = all rows displayed tillering seedlings across within the plot.

^bWithin a column, values not sharing a common uppercase letter are significantly different at the 0.05 probability level. Mean separation was done with a student t test. All field experiments were analyzed separately.

3.5 | Early establishment

‘Arctic Green’ PR had a higher average early establishment for both SP-2018 and RO-2018 field experiments (Table 7) when compared to fine fescue cultivars. This higher observation could be attributed to the faster germination of perennial ryegrass. Perennial ryegrass seeds start to germinate in less than 10 days whereas fine fescue species require a longer time for germination, up to 12 days for CH and ST and up to 14 days for HD (Beard, 1973; Braun et al., 2023) and stronger seedling vigor. In SP-2018, no differences were observed between the fine fescue cultivars. ‘MNHD’ HD had a lower early establishment than other fine fescues, except for Intrigue CH, for RO-2018 (Table 7). The presence of wheat did not affect perennial grass early establishment; this could be explained by average daylight data (Figure 1), which showed that the light availability within the rows of wheat was not impaired during the first 3 weeks after seeding (the sensors were added 7 to 8 days after seeding).

3.6 | Fall stand counts

Wheat was harvested during the month of August for all experiments (Table 2). Perennial grass cultivars were grown with wheat during 77 days for SP-2018 and RO-2018 runs and during 93 days for the RO-2019 run. Perennial grasses fall stand count was assessed at 85, 71, and 55 days after wheat harvest for SP-2018, RO-2018, and RO-2019, respectively. Wheat harvest occurred later for RO-2019 than for RO-2018 (Table 2) due to the low precipitation experienced after seeding in 2019 (Figure S3) delaying germination and

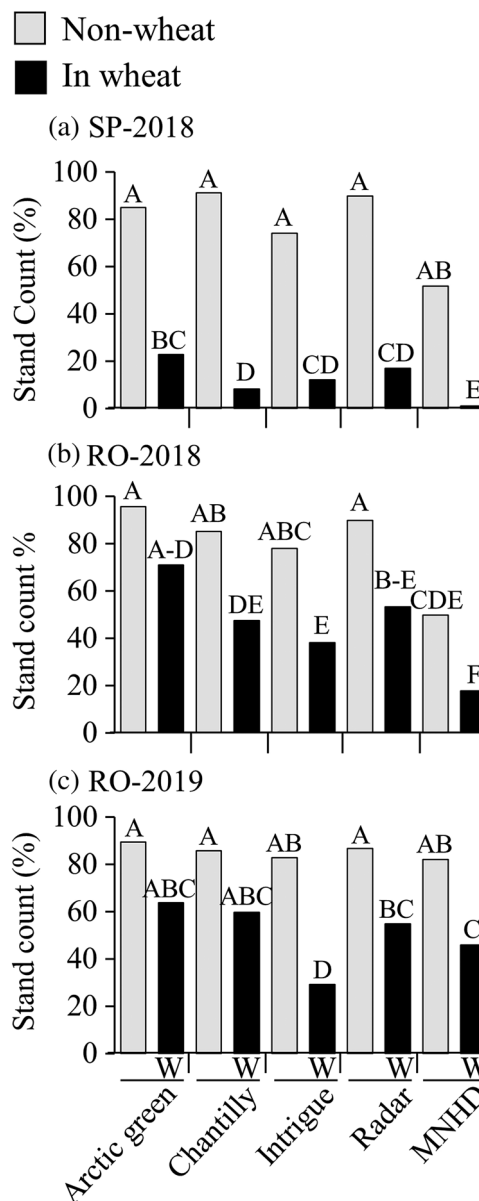


FIGURE 2 Average stand count in fall (a) for SP-2018, (b) RO-2018, and (c) RO-2019. Turfgrass cultivars in non-wheat cropping system are indicated in grey bars, and turfgrass cultivars in wheat cropping system are indicated in black bars. All stand counts were log-transformed prior statistical analysis; data were back-transformed for presentation. Within a graph, values not sharing a common uppercase letter are significantly different at the 0.05 probability level. All field experiments were analyzed separately.

initial growth. The fall stand count of cultivars seeded greatly varied between the three field experiments (Figure 2). In non-wheat, the fall stand counts of all perennial grasses were similar except for RO-2018, where HD was lower (Figure 2c). However, the fall stand counts of the cultivars seeded with wheat varied between the three field experiments (Figure 2 dark bars). In SP-2018, the fall stand counts for all cultivars in wheat were significantly lower in the non-wheat observa-

tions (Figure 2a) with ‘Intrigue’ and ‘Radar’ CH displaying fall stand counts similar to ‘Arctic Green’ PR in the wheat plots. However, these observations were different for Roseau locations where PR fall stand count was not affected by wheat for RO-2018 and RO-2019 while all other perennial turf grasses, except for ‘Chantilly’ ST in the RO-2019 trial, had lower fall stand count in wheat. ‘Radar’ CH and ‘Chantilly’ ST presented the highest fine fescue fall stand count in wheat plots for RO-2018 and RO-2019 and were never significantly different from the ‘Arctic Green’ PR in wheat fall stand count (Figure 2b,c). Interestingly for RO-2018 and RO-2019, when seeded in wheat, ‘Intrigue’ CH did have as high a fall stand count as ‘Radar’ CH. This difference in ‘Radar’ and ‘Intrigue’ response confirms cultivars from the same species can display a different response to shade. These observations are interesting because fine fescues are traditionally considered shade tolerant, whereas PR has been thought to not do well in these conditions (Fry & Huang, 2004). Shade is a very generic term, but reduction of light quantity and spectral quality can result in different molecular and physiological response of the plants; Petrella et al. (2022) grew 40 fine fescue entries under a 30% light reduction, and a R/FR ratio of 0.66/0.67 at solar noon and found CH entries were more tolerant to shade than ST entries, and HD entries were mostly shade intolerant (Petrella & Watkins, 2020). More importantly, that study pinpointed that cultivar tolerance to shade varied greatly within species. Three cultivars from the current study were included in the previous research: ‘Radar’ CH was one of the most shade tolerant, ‘Chantilly’ ST demonstrated medium shade tolerance response, and ‘MNHD’ HD was shade intolerant. Our field experiments resulted in more stringent foliar shade conditions (up to 95% light reduction with a R:FR < 0.40) and confirmed these observations.

3.7 | Second-year spring stand counts

We took spring stand count counts the second year to assess the ability of turfgrass cultivars of surviving the Minnesotan winter months with or without the presence of wheat residues. Second-year spring stand counts were measured 311, 294, and 271 days after wheat harvest for SP-2018, RO-2018, and RO-2019, respectively. None of the grasses used this study were killed during the winter period (Figure 3 and Figure S4) and personal observations showed that establishment was uneven within the plots that had wheat (Figure S4). Most cultivars showed a higher second-year spring stand count in wheat treatments (Figure 3). In RO-2018, PR second-year spring stand count in the non-wheat cropping system was reduced compared to the in wheat plots (Figure 3b). A previous study demonstrated the importance of wheat stubbles to greatly improve winter survival of PR (Ehlke & Vellekson, 1998) and these data confirm these observations. For

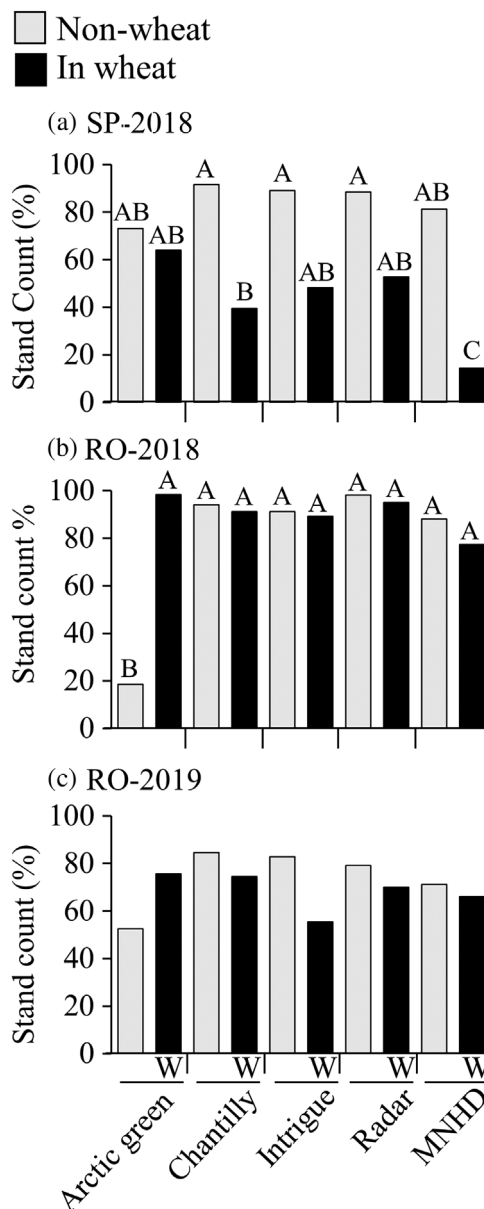


FIGURE 3 Average stand count in the following spring (a) for SP-2018, (b) RO-2018, and (c) RO-2019. Turfgrass cultivars establishment in non-wheat are indicated in grey bars, and turfgrass cultivars established in wheat are indicated in black bars. All stand counts were log-transformed prior statistical analysis; data were back-transformed for presentation. Within a graph, values not sharing a common uppercase letter are significantly different at the 0.05 probability level. All field experiments were analyzed separately.

both RO-2018 and RO-2019, no differences between the non-wheat and in wheat treatments were observed for all fine fescue cultivars (Figure 3b,c), indicating a full recovery of all fine fescue from the shade stress. For SP-2018, this was not the case (Figure 3a), which may be the result of the low fall stand counts (Figure 2a).

TABLE 8 Average culm index data for all fine fescue cultivars grown and without wheat in SP-2018, RO-2018, and RO-2019 experiments.

Species	Cultivars	Cropping system	Culm index (no. of culm g ⁻¹) ^a		
			SP-2018	RO-2018	RO-2019
ST	Chantilly	Non-wheat	5.01	4.45	3.94
		In wheat	1.77*	3.10*	1.24*
CH	Intrigue	Non-wheat	4.34	5.06	4.75
		In wheat	1.61*	2.79*	1.13*
	Radar	Non-wheat	5.26	5.18	6.16
		In wheat	3.38*	4.62*	2.72*
HD	MNHD	Non-wheat	5.88	8.65	7.43
		In wheat	1.53*	3.75*	4.99*

Abbreviations: CH, Chewings fescue; HD, hard fescue; ST, strong creeping red fescue.

*Significant at the 0.05 probability level. Each species was analyzed separately. Mean separation was performed with a non-parametric Wilcoxon test.

^aCulm index's least square mean. Culm index was calculated by dividing the number of culms with the total dry biomass harvested in a 15 cm² quadrat.

TABLE 9 Average yield (g m⁻²) for all perennial grass cultivars seeded alone or with wheat in SP-2018, RO-2018, and RO-2019 experiments.

Species	Cultivar	Cropping system	Yield (gm ⁻²)		
			SP-2018	RO-2018	RO-2019
PR	Arctic Green	Non-wheat	66.63 ABC ^a	38.63 CD	99.13 A
		Wheat	87.50 AB (+31.32%) ^b	114.38 A (+196.09%)	115.63 A (+16.64%)
ST	Chantilly	Non-wheat	124.00 A	85.25 AB	87.38 A
		Wheat	35.25 C (−71.57%)	55.25 BC (−35.19%)	26.13 C (−70.10%)
CH	Intrigue	Non-wheat	136.13 A	61.75 BC	108.00 A
		Wheat	48.75 BC (−64.19%)	43.25 CD (−29.96%)	27.13 C (−74.88%)
	Radar	Non-wheat	141.38 A	87.63 AB	116.75 A
		Wheat	76.63 ABC (−45.80%)	58.13 BC (−33.66%)	44.25 B (−62.10%)
HD	MNHD	Non-wheat	129.50 A	82.50 AB	101.75 A
		Wheat	5.50 D (−95.75%)	24.63 D (−70.15%)	27.50 BC (−72.97%)

Note: Data were log-transformed prior to analysis; data were back-transformed for presentation.

Abbreviations: CH, Chewings fescue; HD, hard fescue; PR, ryegrass; ST, strong creeping red fescue.

^aWithin a column, values not sharing a common uppercase letter are significantly different at the 0.05 probability level. All field experiments were analyzed separately.

^bPercent change from non-wheat data in brackets.

3.8 | Wheat yield

No difference in wheat yield were found for grass cultivar treatments for either RO-2018 or SP-2018 (data not shown); therefore, wheat harvest was not evaluated for RO-2019. Other researchers have also observed that PR has little or no effect on wheat yield (Poeplau et al., 2015; Poudel et al., 2022) but this is not the case for all small grains (Helander, 2004). While some fine fescues can suppress weeds and have been postulated as allelopathic (Bertin et al., 2009), these grasses did not affect wheat yield in our study; however, the low stand count of the fine fescue and unevenness of establishment observed in fall could explain why the wheat did not show any yield impact as previous observations have shown that well established red fescue can impact winter wheat yields (Picard et al., 2010). Wheat yield was lower for SP-2018 than RO-2018 (~2725 and 4885 kg ha⁻¹); these differences could be

attributed to the field location, weather, and/or management practices.

3.9 | Culm index

The culm index was always lower when fine fescues were established in wheat than in non-wheat (Table 8 and Figure S5). In cool-season grasses, yield will depend on several factors occurring prior to vernalization: overall establishment, density of tillers, and tiller maturity (Chastain & Young, 1998). A majority of cool-season perennial grasses required a dual induction for flowering. The first step, or primary induction, requires low temperatures (6–15°C) and/or short day length (<12 h) and the second step, or secondary also called floral initiation, occurs at longer days and with warmer temperatures (Heide, 1994). The length of primary induction and

floral initiation seems to be dependent on the species tested, the cultivar used, and its genetic diversity. In Roseau County, where most of the cool-season perennial grass seed production in Minnesota occurs, primary induction length (low temp with/without short days), would be very short around 1 September and ending mid-October. The lower culm index of the fine fescue plots established with wheat would indicate that these plots possessed fewer vegetative tillers, or even less mature tillers that could start to be primary induced in September. Taken together, our data suggest that in addition to the poor and uneven establishment, tiller number and/or maturity was not reached for fine fescue cultivars seeded in wheat.

3.10 | Seed yield

The presence of wheat had strong lasting effects on seed yield of all species. For PR, intercropping with wheat resulted in greater seed production in the second year. This is not surprising as the wheat stubble can serve as a snow catch providing insulation during the winter. Conversely, for all fine fescues, there was a drop in yield when seeded with wheat; this reduction was clearly significant for SP-2018 and RO-2019 for all fine fescue taxa (Table 9). The RO-2018 experiment showed similar trends for CH and ST, and a significant drop in yield for HD. The decline in yield for HD was the most severe. In general, the decline in fine fescue yield can be linked to poorer stand counts during the previous year, which were the result of difficulty of the slow-growing fine fescue grasses to compete with the fast-growing wheat during initial establishment. PR, on the other hand, establishes much more quickly, and can compete better with the wheat, even though PR lacks the superior foliar shade tolerance of CH and ST.

4 | CONCLUSIONS

We evaluated several perennial grass cultivars for their seed production parameters under spring wheat. Spring wheat canopy reduced light intensity and affected light quality to a large degree. Under these shade conditions fine fescues species struggled to establish, possibly due to their slower growth rate. This reduced establishment resulted in lower fine fescue seed yields; on the other hand, PR was not as affected by the wheat presence and its winter tolerance is improved due to the wheat stubble, leading to increased seed yield in wheat. While yields of PR are much higher than fine fescues, the dollar value of fine fescue seed is significantly higher, therefore, economic analysis should consider the entire 2-year cropping system when determining inputs and outputs. Plant breeders should develop fine fescues that are better able to establish

well when seeded with spring cropping systems, with emphasis on important traits such as improved foliar shade tolerance and a faster rate of establishment. This will allow expanded fine fescue seed production, meeting expected market needs as consumers seek more sustainable turfgrasses for home lawns and other managed landscapes.

AUTHOR CONTRIBUTIONS

Florence Breuillin-Sessoms: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; validation; visualization; writing—original draft; writing—review and editing. **Dominic P. Petrella:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—original draft; writing—review and editing. **Nancy J. Ehlke:** Conceptualization; funding acquisition; project administration; writing—review and editing. **Donn Vellekson:** Conceptualization; funding acquisition; methodology; project administration; supervision; writing—review and editing. **Eric Watkins:** Conceptualization; funding acquisition; investigation; methodology; project administration; supervision; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

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

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