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Light partitioning strategies impact relative fitness of weeds and cover crops when drill-interseeding in corn

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Abstract

Drill-interseeding cover crops into corn (*Zea mays* L.) is an emerging establishment method in northern U.S. production regions. However, cover crop performance in interseeded systems remains variable, and creating environments that are conducive to cover crop but not weed growth is challenging. Cultural practices that partition resources between corn and interseeded cover crops have potential to improve performance if weeds are adequately managed. This study evaluated interactions among corn hybrids differing in leaf architecture (upright, pendulum), corn row spacing (76 cm, 152 cm), and interseeding timing (V3, V6) on light transmittance, relative fitness of cover crop species (cereal rye [*Secale cereale* L.], annual ryegrass (*Lolium multiflorum* Lam), red clover [*Trifolium pratense* L.]) and weeds, and corn grain yield at three U.S. Northeast locations. Results showed that light transmittance through the corn canopy was greater in 152-cm row spacing compared with 76-cm row spacing at the V6 growth stage, with the magnitude of difference increasing at the V10 corn growth stage. Corn hybrids had a marginal effect on light transmittance. The effect of row spacing and interseeding timing on fall cover crop biomass varied across cover crop species and locations. In 76-cm rows, interseeding earlier (V3) increased cover crop biomass production. The relative fitness of cover crops was greater than that of weeds in each combination of cultural practices that included narrow spacing (76 cm), whereas the relative fitness of weeds was greater than that of cover crops when interseeding in wide rows (152 cm). The effect of row spacing on corn yield varied among locations, with higher yields observed in 76-cm row spacing compared with 152-cm at two of three locations. Our results show that interseeding early (V3) on 76-cm row spacing can balance cover crop and corn production management goals, while placing cover crops at a relative fitness advantage over weeds.

Introduction

Drill-interseeding cover crops between corn (*Zea mays* L.) rows is a strip-relay intercropping practice designed to overcome narrow establishment windows for overwintering cover crops in the northern United States (Curran et al. 2018; Noland et al. 2018; Rusch et al. 2020). However, field studies of drill-interseeding report high levels of variability in cover crop performance across soil–environment conditions (Curran et al. 2018; Moore and Mirsky 2020; Noland et al. 2018). Inconsistent performance limits the adoption potential and intended conservation benefits of drill-interseeding cover crops, which include increased water infiltration (Schomberg et al. 2023), reduced soil erosion (Rabin et al. 2023), improved nitrogen (N) scavenging (Isbell et al. 2022; Wallace et al. 2021), increased microbial abundance (Isbell et al. 2022), and carbon accumulation (Mohammed et al. 2020). Cultural management practices that reduce competition through resource partitioning between corn and interseeded cover crops are needed to improve performance (Brooker et al. 2015; Bybee-Finley and Ryan 2018).

In a strip-relay intercropping system, competition is likely to be reduced by increasing spatial and temporal partitioning of light (Donald 1958; Harbur and Owen 2004; Little et al. 2021). Light partitioning strategies designed for cover crop establishment will also mediate weed–crop competition (Lindquist and Mortensen 1999; Rajcan and Swanton 2001). Weed management systems based on the critical period of weed control (Hall et al. 1992; Knezevic et al. 2002) are designed to create a size hierarchy between crops and weeds that results in size-asymmetric competition for light, whereby crops preempt light resources from weeds emerging after the critical period (Gallandt and Weiner 2015), and to limit resource-independent weed interference (Horvath et al. 2023). Consequently, weed management goals (i.e., critical period) may constrain adoption of cultural practices designed to improve interseeding performance via increased light partitioning.

Cultural practices for increasing spatial partitioning of light include selection of leaf architecture traits in corn hybrids, manipulation of corn population density, or widening row spacing to increase transmission of photosynthetically active radiation (PAR) to the soil surface. Youngerman et al. (2018) reported that decreasing corn density on 76-cm row spacing had a positive direct effect on cover crop biomass when interseeding at the V5 growth stage, with cover crop biomass levels mediated by indirect effects of light transmittance (+) and weed biomass (−). Flex-ear corn hybrids were used in this study, which are characterized by indeterminate ear size that compensates for variation in plant density (Thomison and Jordan 1995). Flex-ear hybrids typically have pendulum leaf architecture that increases sunlight interception and decreases water loss by evaporation, particularly at lower population densities (e.g., defensive hybrid; Andrade et al. 1999; Tetio-Kagho and Gardner 1988). In contrast, corn hybrids with determinate ear size are more likely to have upright leaf architecture that optimizes light transmission into the canopy to maximize photosynthesis, particularly at higher population density (e.g., offensive hybrid). Increasing corn density and spatial uniformity in corn leaf architecture has been shown to increase weed suppression (Marin and Weiner 2014; Teasdale 1998). Thus, without additional weed control measures, increased weed fitness is expected when manipulating corn density or hybrid selection to partition light to cover crops.

Widening corn row spacing from 76 to 152 cm to partition light to interseeded cover crops is a novel cultural practice for facilitating grazing or harvesting cover crops for forage (Kremer and Deichman 2014). On-farm evaluation of this practice has shown that wide row spacing reduces corn grain yield but can increase cover crop biomass and forage quality, and such gains in productivity can offset 12% of the economic loss from reduced grain yields (Black et al. 2023). However, information is lacking about how wide-row corn spacing mediates competitive interactions between interseeded cover crops and weeds. Weed suppression in this system will also be challenging, because most herbicide labels do not permit crops interseeded between the V3 and V6 growth stages to be used as a forage crop. Consequently, understanding the relative fitness of cover crop species and summer annual weed species under higher light resource conditions will be necessary to determine the viability of this practice for forage production.

Drill-interseeding before the V5-V6 corn stages is one of the few strategies to manage light partitioning temporally. Interseeding at the V5-V6 stage has been the standard recommendation to (1) reduce risk of corn yield loss to cover crop competition; (2) permit cover crop establishment before corn canopy closure; and (3) facilitate other agronomic operations before interseeding, such as side-dressing with N and postemergence herbicide applications. Interseeding at the V3 growth stage has the potential to improve cover crop productivity without compromising corn yield, compared with interseeding at the V5-V6 (Brooker et al. 2020a; Curran et al. 2018). However, interseeding at the V3 stage may create additional weed management challenges. If soil-applied residual herbicides are applied at corn planting to reduce early-season weed recruitment, there will be greater risk of cover crop injury and reduced establishment due to a shorter period for herbicide degradation or movement below the seedling emergence zone (Brooker et al. 2020b; Stanton and Haramoto 2019; Tharp and Kells 2000; Wallace et al. 2017). Alternatively, if no soil-applied residual herbicides are used preemergence, and a postemergence application is used just before interseeding, it is more likely that cover crop establishment at V3 will overlap with emergence periods of some summer annual weed species, thereby increasing competition intensity between cover crops and weeds (Rajcan and Swanton 2001).

Development of cultural practices that increase spatial or temporal light partitioning to increase performance of interseeding systems requires consideration of crop production and conservation goals. Although grower perceptions of short- and long-term return on investments vary (CTIC 2020), any change in cultural practices for corn management to improve cover crop performance ought to have negligible to marginal impacts on crop production and weed management goals. We conducted a study to: (1) quantify the effects of alternative cultural practices for drill-interseeding on light partitioning, cover crop performance, weed abundance, and corn yield; and (2) characterize the relative fitness of cover crop and weed species under alternative cultural practices.

Materials and Methods

Experimental Design

A field experiment was conducted at three locations spanning U.S. Northeast production regions within the 2020 growing season. Locations included the Pennsylvania State University Southeast Agricultural Research and Extension Center (SEARC) near Landisville, PA (40.118056°N, 76.427778°W), the Pennsylvania State University Russell E. Larson Agricultural Research Center (RELARC) near Rock Springs, PA (40.11833°N, 76.427500°W), and the Cornell University Musgrave Research Farm near Aurora, NY (42.735568°N, 76.656112°W). Soils were Duffield silt loam (fine-loamy, mixed, active, mesic Ultic Hapludalfs) with 2.7% organic matter at Landisville, PA; Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalfs) with 2.4% organic matter at Rock Springs, PA; and Lima silt loam (fine-loamy, mixed, semiactive, mesic Oxyaquic Hapludalfs) with 3.6% organic matter at Aurora, NY. Each experiment was established in crop rotations following full-season soybean and managed with no-till practices.

Experiments were designed as a four-factor randomized complete block factorial with four replicates. Treatments were imposed using a split-split-plot structure. Two treatment factors, each with two treatment levels, were randomly imposed at the main plot level, resulting in a factorial of corn row spacing (76 cm, 152 cm) and hybrid selection (upright, pendulum). The first split-plot treatment was interseeding timing relative to corn growth stage (V3, V6). These growth stages represent early and late timings, respectively, for drill-interseeding cover crops based on previous field studies (Curran et al. 2018). The split-split-plot treatment was cover crop species, with three treatment levels: cereal rye [*Secale cereale* (L.) 'VNS'; 100 kg ha^{-1}], annual ryegrass (*Lolium multiflorum* Lam 28 kg ha^{-1}), and medium red clover [*Trifolium pratense* (L.) 'VNS, coated'; 17 kg ha^{-1}].

Wide-row corn spacing (152 cm) treatments were imposed by shutting off every other planter row-unit while holding corn seeding rate constant across treatments on an areal basis (81,250 seeds ha^{-1}), resulting in a doubling of intrarow density in wide-row treatments. Corn hybrid selection was held constant across experimental locations. The determinate hybrid (ZS9598, Local Seeds®) was selected for its upright leaf architecture (hereafter, upright) and the flex-ear hybrid (LC0057 VT2PRIB, Local Seeds®)

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was selected for its pendulum leaf architecture (hereafter, pendulum).

At the PA locations, main plots were 45 by 12 m, split plots were 45 by 6 m, and split-split plots were 15 by 6 m. At the NY location, main plots were 80 by 24 m, split plots were 80 by 12 m, and split-split plots were 80 by 3 m.

Field Operations

Experimental fields were soil sampled the previous fall at the block level and amended with P, K, and lime based on soil fertility test recommendations. Glyphosate (1.3 kg ae ha^{-1}) + 2,4-D LVE (0.6 kg ae ha^{-1}) + AMS (2.5% v/v) was applied as a preplant burndown treatment approximately 7 d before corn planting. Corn was planted using a John Deere 7200 MaxEmerge no-till planter (Deere & Company, Moline, IL) equipped with an electric drive seed-metering system (Precision Planting, Tremont, IL) at PA locations and a John Deere 1755 MaxEmerge5 no-till vacuum planter with an electric drive seed-metering system (Graham Electric Planter, Sterling, CO) at Aurora, NY. Urea ammonium nitrate (UAN, 30-0-0) was banded beside the row and calibrated to deliver 40 kg N ha^{-1}. Starter fertilizer (10-34-0) was applied in-furrow at planting and calibrated to deliver 6 kg N ha^{-1}. Nitrogen was side-dressed at the V3 corn growth stage using a tractor-mounted sprayer with drop nozzles calibrated to deliver UAN at 155 kg N ha^{-1}. Just before interseeding at the V3 corn growth stage, glyphosate (1.3 kg ae ha^{-1}) + AMS (2.5% v/v) was applied to control emerged weeds across all experimental plots. Cover crops were interseeded at a 1.25-cm depth with a two-row high-clearance grain drill equipped with a cone-seeder at the PA locations and with a four-row high-clearance grain drill at the NY location. Interseeding grain drills at both locations were designed to seed three cover crop rows on 19-cm row spacing between the 76-cm corn rows. This configuration was also employed for the 152-cm row-spacing treatments. Consequently, no cover crop was seeded in the skip corn row.

Data Collection

PAR was measured at the V6 and V10 corn growth stage with use of a line quantum sensor (LI-190, Li-Cor, Lincoln, NE) and point sensor (LI-191, Li-Cor) between 10 AM and 2 PM on days with minimal cloud cover. PAR measurements were taken at two locations within the middle two rows of each split-split plot. Point sensors were held above the corn canopy and line quantum sensors were held on the soil surface in the between-row area at a diagonal angle with each end at a corn row. At the later sampling dates, emerged cover crops were flattened in the area where line quantum sensors were placed to prevent cover crop interference with PAR measurements. At each sampling point, the PAR measurement of the line sensor was divided by the PAR measurement of the point sensor to quantify light transmittance through the corn canopy.

Cover crop and weed biomass was sampled at the VT (tasseling) corn growth stage at the PA locations and approximately 10 to 14 d before grain harvest across all locations in one representative and randomly placed 0.5-m^2 quadrat (66 by 76 cm) per split-plot. Quadrats were centered between corn rows in the 76-cm row-spacing treatment and between the northern corn row and skip row in the 152-cm row-spacing treatment. Biomass samples were oven-dried at 65 C for 7 d and weighed to estimate dry matter biomass production (kg ha^{-1}). Corn populations were assessed at the V5 growth stage by counting a 5.33-m length of row in two side-by-side rows of each split-plot. Corn yields were evaluated at the split-split-plot level by harvesting the middle four rows using two passes with a two-row small plot harvester and then correcting moisture to 15.5%.

Statistical Analysis

Data were analyzed in R v. 3.6.1 (R Core Team 2021). Light transmittance data were analyzed separately by sampling date (V6, V10) using linear mixed effects models with the *lme* function in the NLME package (Pinheiro et al. 2019). Before analysis, light transmittance data were first averaged at the main plot level ($n = 6$), and models were fit using row spacing, corn hybrid, location, and two- and three-way interactions as fixed effects with block as a random factor.

Cover crop and weed biomass collected before corn harvest were analyzed separately by fitting generalized linear mixed-effect models (GLMMs) with a Tweedie response distribution in the GLMMTMB package (Brooks et al. 2017). This distribution is in the exponential family and is characterized by having a point mass at zero and a skewed positive distribution for observations greater than zero. To facilitate analysis of alternative combinations of light partitioning strategies, we combined corn hybrid, interseeding timing, and row-spacing treatments into a single factor (hereafter, cultural practice) with eight treatment levels. Data were then analyzed in GLMMs using cultural practice, cover crop species, location, and two- and three-way interactions as a fixed effect and block, main plot (row spacing by hybrid) nested within block, and interseeding timing nested within main plots as random effects. Significance of fixed effects was evaluated using log-likelihood ratio tests (Wald χ^2) to compare full versus reduced models using the *anova* function.

To evaluate effects of cultural practices for interseeding on the relative fitness of cover crop species and weeds, we used a response comparison index (RCI) described by Williams et al. (1998), which the authors adapted from indices that measure absolute competition intensity (Grace 1995). A relative response index (RRI) was first independently calculated for each cover crop species and weed community by block and location. The RRI standardizes cover crop and weed responses across locations to a control treatment. We used the narrow row (76 cm), pendulum hybrid, and V6 interseeding timing as the control treatment, because this combination of cultural practices resulted in the lowest mean light transmittance, creating a directional comparison to treatments with greater light partitioning. Moreover, interseeding on 76-cm row spacing and the V5-V6 growth stage is currently the standard management recommendation.

For each cover crop species, the RRI was calculated as:

$$\mathrm{RRI} = \left(P_{\mathrm{std}} - P_{\mathrm{cp}}\right) / \left(P_{\mathrm{std}} + P_{\mathrm{cp}}\right) \qquad [1]$$

where P_{std} represents plant biomass in the standard (pendulum/76/V6) treatment, and P_{cp} is plant biomass in alternative ($n = 7$) cultural practice treatments. RRI values greater than zero indicate that the alternative cultural practice for interseeding increased plant fitness. The RCI value is used to compare the relative response of cover crop species and weeds, where:

$$\mathrm{RCI} = \mathrm{RRI}_{\mathrm{weeds}} - \mathrm{RRI}_{\mathrm{CC\ spp}} \qquad [2]$$

$\mathrm{RRI}_{\mathrm{weeds}}$ is the RRI of weeds and $\mathrm{RRI}_{\mathrm{CC\ spp}}$ is the RRI of the cover crop species in the same sampling quadrat. Consequently, cultural practices for interseeding that increase cover crop fitness more

Table 1. Cumulative precipitation (mm) and growing degree days (GDD) using 4C as base temperature by month across experiment locations throughout the 2020 corn growing season.[a]

	May	June	July	August	September	October	Total
				Cumulative precipitation mm			
Landisville, PA	69	84	125	291	61	156	786
Rock Springs, PA	65	138	29	49	62	75	418
Aurora, NY	121	39	102	58	172	77	569
				Cumulative GDD_{4C}			
Landisville, PA	325	498	650	592	419	265	2,749
Rock Springs, PA	278	454	593	546	358	202	2,431
Aurora, NY	262	450	599	544	372	191	2,418

[a]Precipitation and GDD data from nearby weather stations accessed via the Network of Environment and Weather Applications (NEWA) portal (https://newa.cornell.edu).

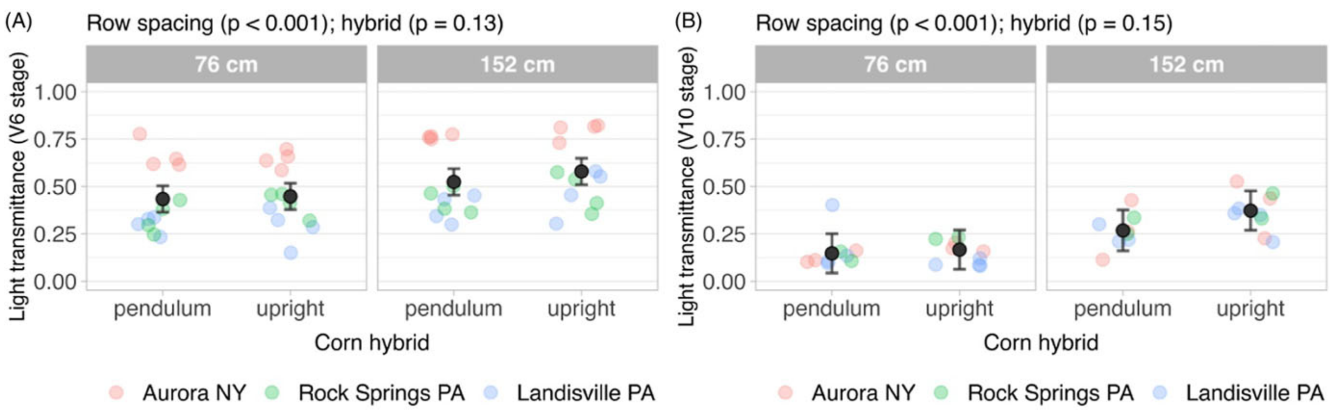

Figure 1. Main effect of corn row spacing (76 cm, 152 cm) on the proportion of photosynthetically active radiation (PAR) transmitted through the corn canopy (i.e., light transmittance) at the (A) V6 and (B) V10 corn growth stages. Data are estimated marginal means (±1 SE) of the two-way interaction between row spacing and corn hybrid (pendulum, upright) to visualize the magnitude of effects between corn management tactics and averaged over experiment location and replications, shown in color-coded scatter plot.

than weed fitness compared with standard practices will have RCI values greater than zero. Conversely, an RCI value less than zero indicates that the alternative interseeding cultural practice is increasing the relative fitness of the weed community more than the cover crop species, likely diminishing the utility of the practice due to shifting the competitive advantage toward weeds.

To assess temporal differences in the relative response of interseeded cover crops and weed communities to alternative cultural practices for interseeding, we analyzed RCI data from biomass samples collected between VT and R2 corn growth stages (August) at the two PA locations and before corn grain harvest (October) at all locations. To facilitate inferences across sampling periods, weed biomass data were restricted to summer annual or perennial species that would be competing for resources during the corn growing season and excluded winter annual weeds that emerged in early fall close to corn grain harvest. For each sampling date, RCI data were analyzed by fitting cultural practice, cover crop species, location, and two- and three-way interactions as fixed effects, with block, main plot (row spacing by hybrid) nested within block, and interseeding timing nested within main plots as random effects. The main effect of location and interactions was not significant. Consequently, we used a revised model with location specified as a random effect to generate population-level estimates of treatment factors.

Corn yield data were modeled at the split-split-plot level. Row spacing, corn hybrid, interseeding timing, cover crop species, location, and all two- through five- way interactions were fit as fixed effects. Block, main plot (row spacing by hybrid) nested within block, and interseeding timing nested with main plots were fit as random effects. The EMMEANS package was used to obtain least-square means on the response scale and pairwise comparisons for significant interactions in all models (Lenth 2019).

Results and Discussion

Environmental Conditions

Growing conditions during the corn establishment phase (May) approximated 30-yr averages at all experimental locations (Table 1). However, temperatures were above average (1 to 2 C) during the cover crop establishment period (June to August) across all locations. Precipitation levels were near the 30-yr average at Landisville, PA, during this period (June to August), but precipitation at Aurora, NY, and Rock Springs, PA, was 25% and 50% below 30-yr averages, respectively, resulting in periods of moderate drought. Drought stress was most pronounced and likely had the greatest impact on crop and weed interactions at the Rock Springs, PA, location.

Light Transmittance

At the V6 corn growth stage, light transmittance differed between corn row spacing treatments ($F(1, 33) = 25$; $P < 0.001$) and location ($F(2, 33) = 102$; $P < 0.001$), but the effect of row spacing did not differ among corn hybrids or locations (Figure 1A). Light transmittance increased from 44% in 76-cm rows to 55% in 152-cm rows, a 25% relative increase when averaged across hybrids and locations. Averaged across treatments, light transmittance was

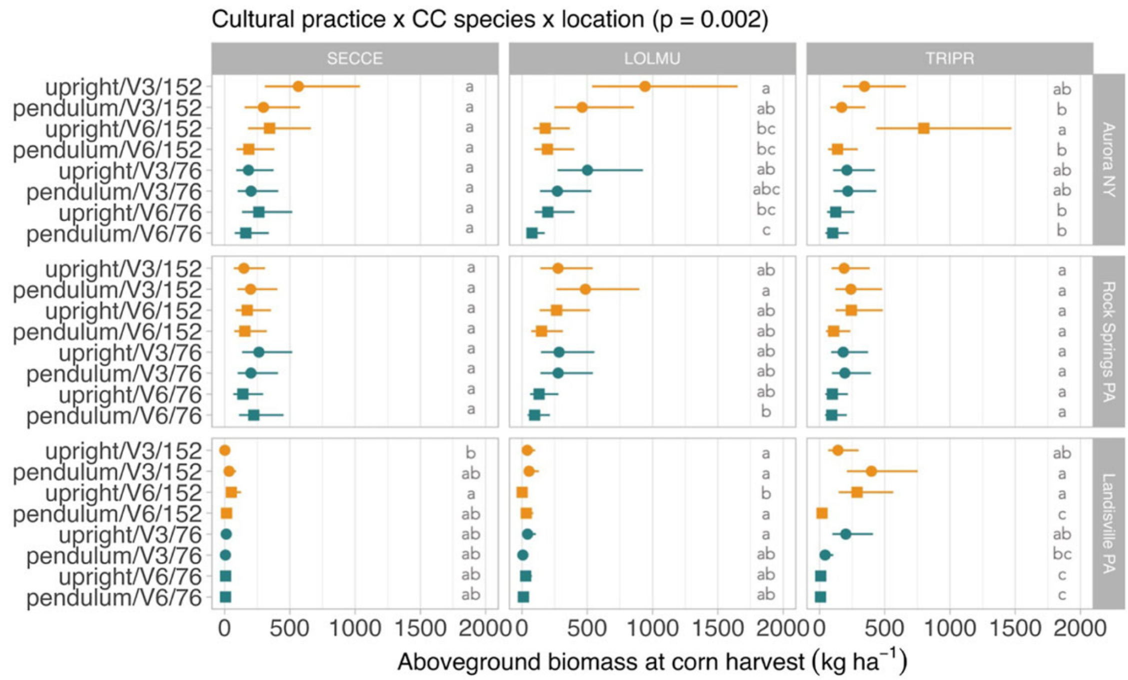

Figure 2. Effect of cultural practice (corn hybrid/interseeding timing/row spacing) on aboveground cover crop biomass (kg ha^{-1}) at corn grain harvest by cover crop species and experiment location. Data are estimated marginal means (±95% confidence interval, CI) on the response scale. Means labeled with the same letter within each panel are not significantly different ($P > 0.05$). Cover crop (CC) species include: SECCE, cereal rye; LOLMU, annual ryegrass; TRIPR, medium red clover. Cultural practices are factorial combinations of upright or pendulum hybrids, interseeding at V3 or V6 corn growth stages, and use of 76- or 152-cm corn row spacing.

greater at Aurora, NY (71%) compared with the PA locations (36% to 41%).

No differences were observed in light transmittance among locations at the V10 corn growth stage, but a significant effect of row spacing persisted ($F(1, 20) = 27$; $P < 0.001$; Figure 1B). Wide-row corn spacing (152 cm) resulted in a 2-fold increase in mean light transmittance relative to 76-cm rows (16% to 32%) when averaged across corn hybrids and locations. Though no interaction was observed ($F(1, 20) = 2.65$; $P = 0.11$), trends suggest that the use of pendulum hybrids in 152-cm rows decreased light transmittance by 30% compared with upright hybrids, whereas marginal differences were observed in 76-cm row spacing and at earlier corn growth stages.

Light transmittance results at the V6 and V0 growth stages provide a snapshot of light partitioning during the cover crop establishment phase (i.e., 3- to 4-wk period) for the V3 and V6 corn growth stage treatments, respectively. Previous studies indicate that reaching a 50% reduction in light transmittance may approximate the end of the critical period for weed control in corn (Hall et al. 1992; Teasdale 1998) and correspond to increased intensity of size-asymmetric competition (Schwinning and Weiner 1998). It is reasonable to assume that interseeding at V3 partitioned light to cover crops across row-spacing treatments during the establishment phase, given that light transmittance was near 50% across treatments at the V6 corn growth stage. In comparison, interseeding at the V6 corn growth stage likely resulted in greater size-asymmetric competition in 76-cm rows compared with 152-cm rows at the onset of cover crop establishment as the corn canopy rapidly closed.

Fall Cover Crop Biomass

The effect of cultural practices on biomass production of cover crop species varied among locations ($\chi^2 = 53$; $P = 0.002$). Mean biomass among cultural practice and cover crop species treatments ranged from 80 to 940 kg ha^{-1} at Aurora, NY, 100 to 490 kg ha^{-1} at Rock Springs, PA, and <10 to 400 kg ha^{-1} at Landisville, PA. Rank order of cultural practice treatments are reported by cover crop species and location (Figure 2).

At Aurora, NY, no differences in cereal rye biomass production were detected among cultural practices. Within annual ryegrass treatments, interseeding early (V3) into the upright hybrid in wide row spacing (152 cm) resulted in greater biomass than interseeding later (V6) in narrow and wide row spacing. When interseeding early (V3), annual ryegrass biomass did not differ among alternative corn management (row spacing, hybrid) tactics. Within red clover treatments, interseeding later (V6) into an upright hybrid in wide row spacing (152 cm) resulted in greater biomass compared with other corn management (row spacing, hybrid) tactics.

At Rock Springs, PA, few differences were observed in cover crop biomass production among cultural practices for interseeding, with no significant differences observed for cereal rye and medium red clover. Within annual ryegrass treatments, interseeding at the V3 corn growth stage into the pendulum hybrid on wide row spacing resulted in greater biomass production than interseeding at the V6 growth stage into pendulum hybrids on 76-cm row spacing.

At Landisville, PA, treatment interactions were observed for cereal rye and annual ryegrass biomass, but productivity was low (<200 kg ha^{-1}) among all treatments, resulting in few meaningful differences when the magnitude of effects is considered. Within medium red clover treatments, fall biomass was lower when interseeding later (V6) into pendulum hybrids on wide row spacing (152 cm) compared with other wide row spacing combinations. Interseeding red clover at the V3 corn growth stage into the upright hybrid on narrow row spacing resulted in

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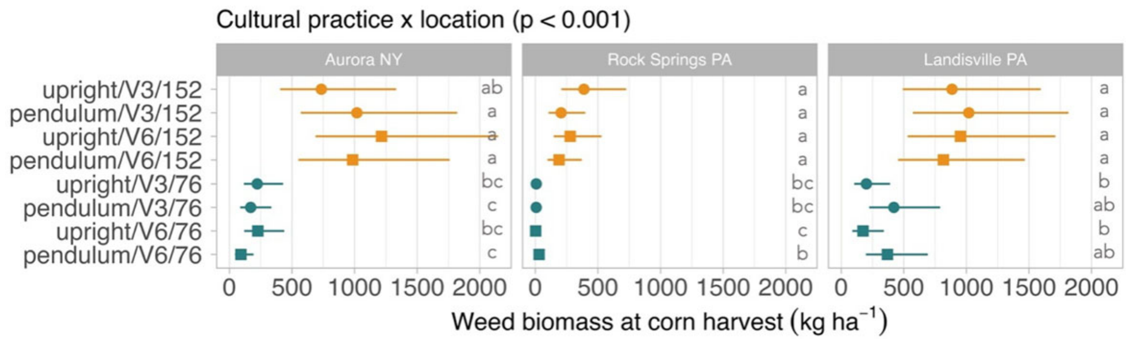

Figure 3. Effect of cultural practice (corn hybrid/interseeding timing/row spacing) on weed biomass (kg ha^{-1}) at corn grain harvest by experimental location. Data are estimated marginal means (±95% confidence interval, CI) on the response scale. Means labeled with the same letter within each panel are not significantly different ($P > 0.05$). Cultural practices are factorial combinations of upright or pendulum hybrids, interseeding at V3 or V6 corn growth stages, and use of 76- or 152-cm corn row spacing.

biomass production comparable to that of interseeding early into either hybrid on wide row spacing.

On-farm trials on 76-cm row spacing within the U.S. Northeast have resulted in similar fall biomass levels (<400 kg ha^{-1}) of annual ryegrass and grass–legume mixtures compared with our observations across both row spacings (Curran et al. 2018; Moore and Mirsky 2020). Few studies have documented relationships between fall cover crop biomass and ecosystem services within interseeded systems. Recent experiments within the U.S. Northeast region have indicated that 200 kg ha^{-1} of annual ryegrass biomass at corn harvest can result in greater N scavenging in fall compared with cereal rye planted postharvest (Isbell et al. 2022). Previous studies have also shown that interseeding can result in winter annual weed suppression in fall and spring (Wallace et al. 2021), but few studies have characterized cover crop and weed interactions within the corn growing season in drill-interseeded systems. It is important to note that evaluation of treatment effects concluded at corn grain harvest, and cover crop biomass production is expected to increase postharvest in late fall and spring. Previous on-farm research trials within the Northeast region report an asymptotic relationship between spring and fall biomass for interseeded annual ryegrass and ryegrass–legume mixtures (Curran et al. 2018).

Weed Biomass and Relative Fitness

The effect of cultural practices for interseeding on aboveground weed biomass before corn grain harvest varied across locations ($\chi^2 = 51.4$; $P < 0.001$; Figure 3). General trends show significantly greater weed biomass in 152-cm spacing compared with 76-cm row spacing when averaged among other treatments. However, the magnitude of difference between row-spacing treatments was comparatively lower at the Rock Springs, PA, that at other locations, which we attribute to summer drought conditions that likely limited weed growth. No differences were observed among alternative practices that used 152-cm row spacing at each location or among cultural practices that used 76-cm row spacing at each location.

Based on this finding, we evaluated the relative proportion of grass and broadleaf weed species among row-spacing treatments and locations. Relative proportion of taxonomic groups differed by location ($\chi^2 = 91$; $P < 0.001$; Figure 3) but not by row spacing ($P > 0.05$). Grass species represented 73% and 81% of total weed biomass at Aurora, NY, and Rock Springs, PA, but only 21% at Landisville, PA. The most frequently occurring species at Aurora, NY, were fall panicum (*Panicum dichotomiflorum* Michx.), witchgrass (*Panicum capillare* L.), and redroot pigweed

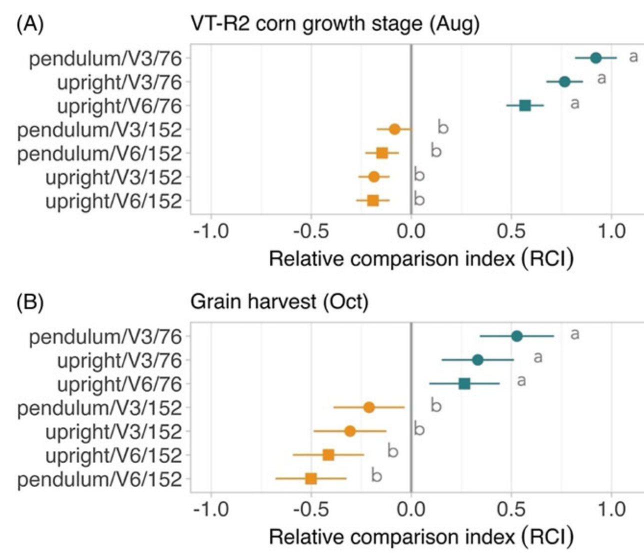

Figure 4. Effect of cultural practice (corn hybrid/interseeding timing/row spacing) on the relative comparison index (RCI) at the (A) VT-R2 corn growth stage and (B) before corn grain harvest. RCI values are standardized to the pendulum/V6/76 treatment. Cultural practices that increase cover crop fitness more than weed fitness compared with the standard will have an RCI value that is greater than zero. RCI values less than zero indicate that the cultural practice is increasing the relative fitness of the weed community more than the cover crop species. Data are estimated marginal means (±1 SE) on the response scale. Means labeled with the same letter within each panel are not significantly different ($P > 0.05$). Cultural practices are factorial combinations of upright or pendulum hybrids, interseeding at V3 or V6 corn growth stages, and use of 76- or 152-cm corn row spacing.

(*Amaranthus retroflexus* L.). The most frequently occurring species at Rock Springs, PA, were *P. dichotomiflorum*, large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and *A. retroflexus*. The most frequently occurring species at Landisville, PA, were eastern black nightshade (*Solanum ptychanthum* Dunal), *A. retroflexus*, and *P. capillare*. These species are known to either have prolonged or delayed emergence periods in the U.S. Northeast (Cordeau et al. 2017).

Cultural practices for interseeding had a significant effect on RCI values at both the VT-R2 corn growth stage ($F(6, 41) = 31$; $P < 0.001$; Figure 4A) and before corn grain harvest ($F(6, 65) = 13$; $P < 0.001$; Figure 4B). RCI values describe the relative fitness of cover crops and weeds in alternative management scenarios. Results indicate that row spacing determined the relative fitness advantage across the corn growing season. Other cultural practices,

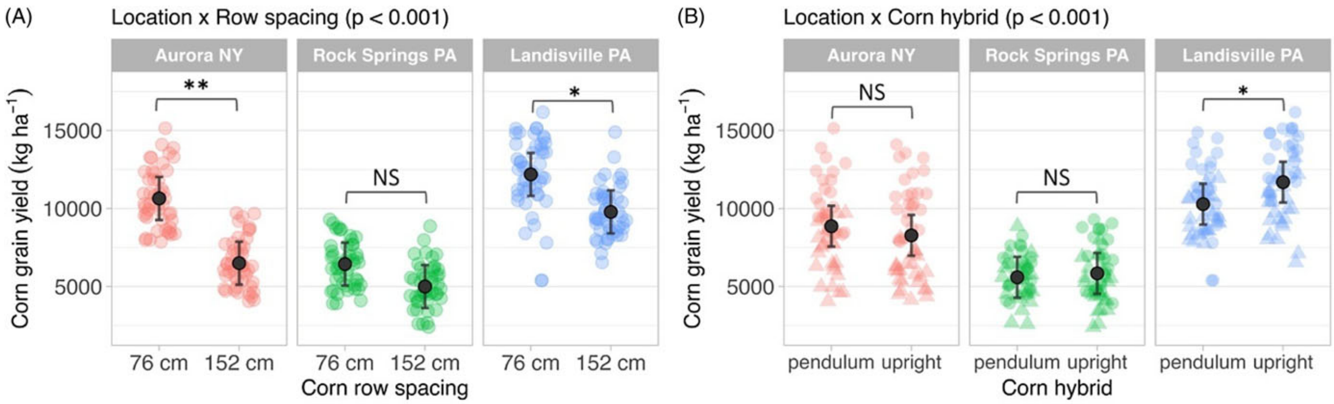

Figure 5. Interaction between (A) corn row spacing (76 cm, 152 cm) and experiment location and (B) corn hybrid selection (upright, pendulum) and experiment location on corn grain yield (kg ha^{-1}). Data are estimated marginal means (±1 SE) averaged over other treatment factors and replicates.

including interseeding timing and hybrid selection, produced smaller mediating effects on relative fitness. The relative fitness of cover crops was greater than that of weeds (RCI > 0) and significantly different from zero (P < 0.05) in each combination of cultural practices that included narrow spacing (Figure 4A). Conversely, the relative fitness of weeds was greater than that of cover crops (RCI < 0) but not significantly different from zero (P > 0.05) when interseeding in wide rows regardless of interseeding timing or hybrid selection (Figure 4B).

Corn Yield

Interactions with interseeding timing and cover crop species treatments were not observed (P > 0.05) in analysis of corn grain yields, indicating that cover crop responses to alternative corn row spacing and hybrid selection had little impact on corn yield. The effect of row spacing on corn yield varied among locations (F(2, 192) = 19; P < 0.001; Figure 5A), with higher yields observed in 76-cm row spacing compared with 152-cm row spacing at Aurora, NY, and Landisville, PA, and no row-spacing effect detected at Rock Springs, PA. The lack of corn yield response at the Rock Springs, PA, location may be attributed, in part, to drought conditions that resulted in low corn yields across treatments. The effect of corn hybrid on grain yield also varied among locations (F(2, 192) = 10; P < 0.001; Figure 5B), where the upright hybrid produced higher yields at Landisville, PA, but did not differ from the pendulum hybrid at other locations. It is important to note that this study did not have replicated no–cover crop control treatments across factorial treatment combinations. Consequently, yield impact inferences are limited to comparisons among alternative cover crop and corn cultural management practices within an interseeded system. Previous research has shown no negative corn yield impact when interseeding annual ryegrass or ryegrass–legume mixtures between the V3 and V6 corn growth stage, though trends suggested that the combination early-interseeding (V2-V3) and high levels of weed competition has the potential to influence corn grain yield (Curran et al. 2018).

Management Implications

Results of this research show that interseeding cover crops on 76-cm row spacing may have advantages over wider row spacing (152 cm) for balancing cover crop, weed management, and corn production goals. Reduction in corn yield observed within wider row treatments was not consistently offset by a significant increase in cover crop performance due to increased weed competition with the cool-season cover crop species (cereal rye, annual ryegrass, medium red clover) used in this study.

Our results show that interseeding at the V3 corn growth stage in 76-cm row spacing lengthens the establishment period before rapid corn canopy closure compared with interseeding at the V6 growth stage and may increase the relative fitness advantage of cover crops over weeds. However, additional studies are needed to characterize corn yield impacts when interseeding at the V3 corn growth stage across a range of soil–environment conditions and weed communities. Differences in leaf architecture produced marginal effects on light transmittance when using 76-cm rows and played a limited role in mediating cover crop and weed interactions. Greater understanding of herbicide tolerance differences among cover crop species could result in the extension of residual weed control from soil-applied herbicides through the cover crop establishment phase (Wallace 2023), which would increase the relative fitness advantage of interseeded cover crops across a broader range of weed communities than evaluated in this study.

More research is needed to understand competitive interactions between weeds and interseeded cover crops in wide-row (152 cm) corn systems. When wide-row systems are employed to increase forage productivity or grazing potential, it will likely be necessary to use forage species that have established herbicide control options, such as glyphosate-tolerant alfalfa (*Medicago sativa* L.) (Chu et al. 2022; Osterholz et al. 2020), that are compatible with corn production. Alternatively, use of cover crop mixtures that include warm-season species with higher relative growth rates and more competitive traits (Bybee-Finley et al. 2016) than the cool-season species used in this research (cereal rye, annual ryegrass, and red clover) may help to increase cover crop competition with weeds and increase forage productivity. Finally, more research is needed to understand how manipulating corn density, soil nutrient availability, and different row-spacing arrangements (e.g., 76–152–76–skip-row system) mediates cover crop and weed competition within wide-row corn systems to balance crop production, conservation, and weed management goals.

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References

Andrade FH, Vega C, Uhart S, Cirilo A, Cantarero M, Valentinuz O (1999) Kernel number determination in maize. Crop Sci 39:453–459

Black KL, Wells S, Johnson GA, Lazarus WF, Kraus A (2023) Interseeding wide row corn with forage cover crops: investigating system potential for expanded economic opportunities in corn production systems. Agronomy 13:307

Brooker AP, Renner KA, Sprague CL (2020a) Interseeding cover crops in corn. Agron J 112:139–147

Brooker AP, Sprague CL, Renner KA (2020b) Interseeded annual ryegrass, oilseed radish, and crimson clover tolerance to residual herbicides commonly used in corn. Weed Technol 34:35–41

Brooker RW, Bennett AE, Cong WF, Daniell TJ, George TS, Hallett PD, Hawes C, Ianetta PP, Jones HG, Karley AJ, Li L, McKenzie BM, Pakeman RJ, Paterson E, Schob C, *et al.* (2015) Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phytol 206: 107–117

Brooks ME, Kristensen K, van Benthem KJ, Magnusson A, Berg CW, Nielsen A, Skaug HJ, Maechler M, Bolker BM (2017) glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. R J 9:378–400

Bybee-Finley KA, Mirsky SB, Ryan MR (2016) Functional diversity in summer annual grass and legume intercrops in the northeastern United States. Crop Sci 56:2775–2790

Bybee-Finley KA, Ryan MR (2018) Advancing intercropping research and practices in industrialized agricultural landscapes. Agriculture 8:80

Chu SAD, Cassida KA, Singh MP, Burns EE (2022) Critical period of weed control in an interseeded system of corn and alfalfa. Weed Sci 70:680–686

[CTIC] Conservation Technology Information Center (2020) 2019–2020 CTIC Cover Crop Survey. http://www.sare.org/Learning-Center/Topic-Rooms/Cover-Crops/Cover-Crop-Surveys. Accessed: May 1, 2023

Cordeau S, Smith RG, Gallandt ER, Brown B, Salon P, DiTommaso A, Ryan MR (2017) How do weeds differ in their response to the timing of tillage? A study of 61 species across the northeastern United States. Ann Appl Biol 171: 340–352

Curran WS, Hoover RJ, Mirsky SB, Roth GW, Ryan MR, Ackroyd VJ, Wallace JM, Dempsey MA, Pelzer CJ (2018) Evaluation of cover crops drill interseeded into corn across the Mid-Atlantic region. Agron J 110:435–443

Donald CM (1958) The interaction of competition for light and for nutrients. Aust J Agric Res 9:421–435

Gallandt ER, Weiner J (2015) Crop-weed competition. *In* Encyclopedia of Life Sciences. doi: 10.1002/9780470015902.a0020477.pub2.

Grace JB (1995) On the measurement of plant competition intensity. Ecology 76:305–308

Hall MR, Swanton CJ, Anderson GW (1992) The critical period of weed control in grain corn. Weed Sci 40:441–447

Harbur MM, Owen MD (2004) Light and growth rate effects on crop and weed responses to nitrogen. Weed Sci 52:578–583

Horvath DP, Clay SA, Swanton CJ, Anderson JV, Chaio WS (2023) Weed-induced crop yield loss: a new paradigm and new challenges. Trends Plant Sci 28:567–582

Isbell SA, Alonso-Ayuso M, Bell TH, Bradley B, Rowles T, Kaye JP (2022) Nitrogen services provided by interseeded cover crops in organic corn systems. Agron J 114:2458–2472

Knezevic SV, Evans SP, Blankenship EE, Van Acker RC, Lindquist JL (2002) Critical period for weed control: the concept and data analysis. Weed Sci 50:773–786

Kremer RJ, Deichman CLR (2014) Introduction: the solar corridor concept. Agron J 106:1817–1819

Lenth R (2019) emmeans: Estimated Marginal Means, aka Least-Squares Means. R Package Version 1.4.1. https://CRAN.R-project.org/package=emmeans. Accessed: May 1, 2023

Lindquist JL, Mortensen DA (1999) Ecophysiological characteristics of four maize hybrids and *Abutilon theophrasti*. Weed Res 39:271–285

Little NG, DiTommaso A, Westbrook AS, Ketterings QM, Mohler CL (2021) Effects of fertility amendments on weed growth and weed-crop competition: a review. Weed Sci. 69:132–146

Marin C, Weiner J (2014) Effects of density and sowing pattern on weed suppression and grain yield in three varieties of maize under high weed pressure. Weed Res 54:467–474

Mohammed YA, Matthees HL, Gesch RW, Patel S, Forcella F, Aasand K, Steffl N, Johnson BL, Wells MS, Lenssen AW (2020) Establishing winter annual cover crops by interseeding into maize and soybean. Agron J 112:719–732

Moore VM, Mirsky SB (2020) Cover crop biomass production across establishment methods in mid-Atlantic corn. Agron J 112:4765–4774

Noland RL, Wells MS, Shaeffer CC, Baker JM, Martinson KL, Coulter JA (2018) Establishment and function of cover crops interseeded into corn. Crop Sci 58:863–873

Osterholz WR, Dias J, Grabber JH, Renz M (2020) PRE- and POST- applied herbicide options for alfalfa interseeded with corn silage. Weed Technol 35:1–26

Pinheiro J, Bates D, Debroy S, Sarkar D (2019) nlme: Linear and Nonlinear Mixed Effects Models. R Package Version 3.1-140. https://CRAN.R-project.org/package=nlme. Accessed: May 1, 2023

Rabin KC, Johnson GA, Strock JS, Jordan NR, Garcia y Garcia A (2023) Tillage and cover crop mixtures interseed in maize-soybean in the upper Midwest. Agron J 115:1188–1201

Rajcan I, Swanton CJ (2001) Understanding maize–weed competition: resource competition, light quality and the whole plant. Field Crop Res 71:139–150

R Core Team (2021) R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org

Rusch HL, Coulter JA, Grossman JM, Johnson GA, Porter PM, Garcia y Garcia A (2020) Towards sustainable maize production in the U.S. upper Midwest with interseeded cover crops. PLoS ONE 15:e0231032

Schomberg HH, White KE, Thompson AI, Bagley GA, Burke A, Garst G, Bybee-Finley KA, Mirsky SB (2023) Interseeded cover crop mixtures influence soil water storage during the corn phase of corn-soybean-wheat no-till cropping systems. Agric Water Manag 278, 10.1016/j.agwat.2023.108167

Schwinning S, Weiner J (1998) Mechanisms determining the degree of size asymmetry in competition among plants. Oecologia 113:447–455

Stanton VL, Haramoto ER (2019) Environmental factors may influence interseeded annual ryegrass and red clover establishment and growth more than soil residual herbicide applications. Weed Technol 33:296–302

Teasdale JR (1998) Influence of narrow row/high population corn (*Zea mays*) on weed control and light transmittance. Weed Technol 9:113–118

Tetio-Kagho F, Gardner F (1988) Responses of maize to plant population density. I. Canopy development, light relationships, and vegetative growth. Agronomy J 80:930–935

Tharp BE, Kells JJ (2000) Effect of soil-applied herbicides on establishment of cover crop species. Weed Technol 14:596–601

Thomison PR, Jordan DM (1995) Plant population effects on corn hybrids differing in ear growth habit and prolificacy. J Prod Agric 8:394–400

Wallace JM (2023) Can relative sensitivity of cover crops species to chloroacetamide and pyrazole herbicides be exploited to design interseeding mixtures? Weed Technol 37:100–107

Wallace JM, Curran WS, Mirsky SB, Ryan MR (2017) Tolerance of interseeded annual ryegrass and red clover cover crops to residual herbicides in Mid-Atlantic corn cropping systems. Weed Technol 31:641–650

Wallace JM, Isbell S, Hoover R, Barbercheck M, Kaye J, Curran WS (2021) Drill and broadcast establishment methods influence interseeded cover crop performance in organic corn. Renew Agric Food Syst 36:1–9

Williams MM, Mortensen DA, Doran JW (1998) Assessment of weed and crop fitness in cover crop residues for integrated weed management. Weed Sci 46:595–603

Youngerman CZ, DiTommaso A, Curran WS, Mirsky SB, Ryan MR (2018) Corn density effect on interseeded cover crops, weeds, and grain yield. Agron J 110:1–10