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DOI: 10.1017/wet.2024.73

Short title: Rye termination for AMAPA

Cereal Rye Cover Crop Termination Management for Palmer Amaranth (*Amaranthus palmeri*) Suppression in Soybean

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Abstract

Palmer amaranth is a troublesome weed species displaying the ability to adapt and evolve resistance to multiple herbicide modes of action, and there is a need for additional weed suppression tactics. Growing interest in the use of cover crops (CC) has led to questions regarding the most appropriate forms of CC management prior to cash crop planting in order to maximize weed suppression benefits. Experiments were conducted between 2021 to 2023 to test: 1) cover crop termination timing (i.e., green or brown), 2) CC biomass amount and 3) CC termination method (i.e., rolled or left standing) on Palmer amaranth suppression. Treatments included "planting brown" (cereal rye terminated two weeks before soybean planting), "planting green" (cereal rye terminated at soybean planting), and a no CC (winter fallow) check. Palmer amaranth emergence was evaluated at 4 and 6 weeks after soybean planting, and yield was calculated at harvest. CC reduced Palmer amaranth emergence when compared to the no CC check, and more suppression was observed as CC biomass increased. This decrease in emergence is potentially due to a decrease in light penetration reaching the soil surface and physical suppression as CC biomass increased. Yield, however, was unaffected by any CC management practice, indicating that growers can tailor CC termination practices for weed suppression. This information will provide better recommendations for farmers interested in using cover crops for weed suppression. Overall, the importance of CC biomass accumulation to achieve weed suppression is highlighted in our findings. Additionally, we add to the growing body of documentation that soybean yield may be variable from year to year as a result of CC presence.

Nomenclature: Palmer amaranth, *Amaranthus plameri* S. Watson; Cereal rye, *Secale cereale* L.; soybean, *Glycine max* (L.) Merr.

Key words: photosynthetic active radiation (PAR), planting green, photosynthetic photon flux density (PPFD)

Introduction

Adoption of cover crops (CC) has steadily increased over the years in response to challenges facing farmers (Zhou et al 2022), some of which include herbicide resistant weeds and government-mandated herbicide restrictions (Zilberman et al. 1991; Peterson et al. 2018). The use of CC has grown due mainly to the soil health and nutrient related benefits such as increased inorganic nitrogen and soil erosion prevention, but also for the weed suppressive capabilities (Dabney et al. 2007; Norsworthy et al. 2012; Myers and Watts 2015). Best practices to maximize CC benefits is largely dependent on the goal of the CC. For the purposes of weed suppression, the accumulation of heavy biomass has proven to be one of the most important factors (MacLaren et al. 2019).

Biomass accumulation of a CC is largely dependent on timely planting and the time at which it is terminated (Ruis et al. 2019). To accumulate biomass, some growers have been experimenting with planting into a "green" living CC, which means delaying CC termination until right before or just after planting the cash crop. More commonly, the CC is terminated prior to cash crop planting into a "brown" or dead CC. These two practices are both used by growers currently, but there is no clear consensus on whether one practice provides more benefits than the other. Maintaining a green canopy for longer may delay germination and emergence of small seeded weeds as they are typically sensitive to light quality germination cues (Baskin and Baskin, 1977; Jha et al. 2010). Conversely, there are concerns with soil moisture reduction via transpiration of the longer established CC leaving dryer conditions at cash crop planting (Meyer et al. 2020).

Similarly, management practices such as rolling the CC prior to cash crop planting have also been questioned in their effectiveness and need. Although some growers roll a CC after termination, it is unclear whether rolling more effectively suppresses weeds compared to a CC that is left standing and terminated only chemically. A rolled CC may provide suppression through smothering, physical interference of weed emergence, and light interception. Standing CC, although not physically suppressing weeds, can also provide suppression by interfering with light availability to weed seeds; particularly small-seeded weeds such as Palmer amaranth (Gallager and Cardina, 1998; Jha et al. 2010). The standing CC could potentially reduce light penetration for longer due to tall residue left in the field intercepting light from the seeds and seedlings in the lower canopy.

Though these are complex systems with many factors, the importance in solidifying CC termination strategies lies in the economic implications that this information provides. Knowing best management practices at the time of termination could result in reduced labor associated with pesticide application and increased efficiency. Therefore, to answer these questions for CC growers in the Mid-Atlantic, an experiment was established to answer 2 main questions across a range of CC biomass: 1) does rolling a CC or leaving it standing affect weed suppression and soybean yield, and 2) does planting into a green CC provide any weed suppression or soybean yield benefits that planting into a brown CC would not.

Materials and Methods

Field Experiment

Field experiments were conducted between 2021 and 2023 at the Southern Piedmont Agricultural Extension Station (SPAREC) near Blackstone, VA (37.087024, -77.956284), and at Kentland Farm near Blacksburg, VA (Kentland) (37.200091, -80.563504). Average temperatures for the experimental locations are -1 to 32°C, and -4 to 29°C, for SPAREC and Kentland respectively. Average rainfalls are 114 cm and 101 cm, at the two locations, respectively.

Treatments were arranged in a four by two by two factorial design, for a total of 16 treatments, with four target levels of CC biomass (none, low, medium, or high), rolled vs standing, and planted "green" vs "brown". Plots measured three by nine meters with four replications per treatment arranged in a randomized complete block design. In the fall of 2021 and 2022, cereal rye CC (variety 'Elbon': Green 79 Cover Seeds, Bladen, NE) was planted to initiate the experiment at both locations. Cereal rye was planted at 84 kg seed ha^{-1} to a depth of approximately 2.5 cm using a 1.5 m wide drill with 18 cm row spacing. Cereal rye planting dates were staggered to achieve a low, medium, and high CC biomass gradient. The first planting for the high biomass level took place around the last week of October of each year. The second planting followed three weeks later, and the final planting for the low biomass took place three weeks after the second planting. The CC was allowed to overwinter until two weeks prior to soybean planting at which point the "brown" termination treatments were sprayed with glufosinate ammonium at 656 g ai ha^{-1} (Interline® UPL NA Inc. Mumbai, Maharashtra) + AMS at 2.5% v v^{-1} (GROWMARK Bloomington, Illinois, United States) and glyphosate at 1.3 kg ae ha^{-1} (Roundup Powermax 3®, Bayer CropScience). All chemical applications were applied using a CO_2 -pressurized backpack sprayer with a four-nozzle boom with 46-cm spacing. The boom was fitted with TeeJet® Flat Fan XR 11002 nozzles (Spraying Systems Co., Wheaton, IL) and calibrated to deliver 147 L ha^{-1} at 275.79 kPa. Soybean planting took place the first week of May for all experimental years. Green termination treatments were sprayed the day of soybean planting using the aforementioned methodology. Rolled treatments were established the day of soybean planting using a 1.5m roller, while standing treatments were only passed over by the planter. XtendFlex® (Bayer

CropScience, Research Triangle Park, NC) soybean seed was planted at 222,300 seeds ha^{-1} for the 2 years of the study using a 2-row planter on 76 cm spacing (Kinze Evolution Series, Williamsburg, IA). Due to the size of the planter, some of the standing cereal rye was inevitably rolled down by the planting equipment and tractor wheels, but this also occurs with commercial scale equipment. To allow for harvest, glufosinate at 656 g ai ha^{-1} + AMS at 2.5% v v^{-1} was applied at 4 and 6 weeks after planting to control the Palmer amaranth present.

Data Collection

Total above ground CC biomass was collected at the time of respective CC termination for every plot using a randomly placed 0.5m^{-2} quadrat. At the time of CC biomass collection all above ground CC biomass was collected and clipped at the soil surface using hand shears. Individual plot bags were collected to isolate the treatment samples. Sample bags were then dried at 52°C for 4 days to collect dry weight. Palmer amaranth emergence was recorded by counting emerged plants within a single, randomly placed, 0.25 m^{-2} quadrat for each plot at 4 and 6 weeks after planting prior to the herbicide applications.

Light penetration was measured at 2, 4, and 6 weeks after planting using a LiCor LI-191R Light Quantum Sensor (Li-Cor Biosciences, Lincoln, NE). Light penetration was measured on the photosynthetic active radiation spectrum (PAR) as photosynthetic photon flux density (PPFD), expressed as μmol s^{-1} m^{-2}, over a 1-meter length. To observe light reaching the soil surface (emerging weeds) and above the soil (established weeds), PPFD was collected at 0 cm (at soil surface but below CC residues), 15 cm, and 30 cm above the soil surface. To avoid rolled CC residue from tractor tire tracks, PPFD readings were collected in the middle rows. At the conclusion of the trial, soybean yield was calculated from the two middle rows of each plot by collecting grain using a plot combine (Classic Plus Combine, Wintersteiger, Ried im Innkreis, Austria). Yield for each plot was calculated by using total weight and adjusting for moisture.

Statistical analysis

Palmer amaranth emergence and soybean yield data were analyzed using JMP Pro 16 (JMP®, Version 16. SAS Institute Inc., Cary, NC) to evaluate the main effects of termination timing, rolled or standing, and CC biomass at termination. Means were separated using Fisher's protected LSD (α= 0.05). Replication was considered a random effect while site year, location, and treatments were considered fixed effects. Soil level PPFD data were compared across treatments, while PPFD at 15 and 30 cm above ground was compared only for the standing treatments as rolled CC residue was below these heights and no reductions in PPFD were observed. Palmer amaranth emergence, soybean yield, and PPFD were fitted to quadratic, exponential decay, and hyperbolic decay models across CC biomass, as was performed in similar studies (Ma et al.

2015; Pacala and Winer, 1991) in SigmaPlot 15 (Systat Software, San Jose, CA) depending on the best fit for each model.

Greenhouse Study

A greenhouse study was conducted in three experimental runs from 2021 through 2023, to further understand the effects of CC termination timing and cereal rye biomass on Palmer amaranth emergence. These studies were established the second week of May of each experimental year, and were carried out for four weeks after initiation. Greenhouse day/night temperatures were 21°C to 32°C for the duration of the trial, and no supplemental lighting was provided.

Trays measuring 54.5 by 27.8 by 6 cm were filled with Moisture Control Potting Mix (ScottsMiracle-Gro, Marysville, Ohio) and each tray contained 100 Palmer amaranth seeds that were mixed into the top 0-2 cm of the soil profile of the tray. Each tray and seeds were covered with cereal rye biomass according to a designated treatment (0, 2242 kg ha^{-1}, 4483 kg ha^{-1}, 6725 kg ha^{-1}, 8967 kg ha^{-1}, and 11209 kg ha^{-1}) for both ‘green’ and ‘brown’ CC residue type to resemble the trial established in the field. Trays were arranged in a completely randomized design with four replications per treatment. CC biomass was collected on the day of trial initiation from the field where both “brown” dead CC and “green” living CC were cut and transported to the greenhouse. In 2021 and 2022, weights of the CC were wet weights. However, in 2023 accounting for the difference in water weight was implemented. Therefore, after testing for moisture (BHT6071, Silage, Crop, Hay Moisture Tester. Best Harvest, USA) of both brown and green CC, the difference in water weight was accounted for and CC residue amount was based on dry biomass.

Light penetration readings were measured, using the aforementioned Light Quantum sensor equipment, by placing the same levels of green and brown CC biomass on top of plexiglass upheld by a wooden box. Boxes measuring 59.7 by 12.7 cm were created to allow for the Light Quantum Sensor to slide below the plexiglass top. The boxes were enclosed to exclude light entering the box except for through the plexiglass top. Each level of CC biomass represented in the trays was also represented in the plexiglass wooden boxes to determine changes in PPFD as a result of CC biomass and termination timing. Boxes were arranged in a completely randomized design with two replications per treatment.

Greenhouse data collection

Newly emerged Palmer amaranth seedlings were counted and removed weekly for four weeks after trial initiation. PPFD measurements were also recorded on a weekly basis for the duration of the trial.

Greenhouse statistical analysis

Emergence and light penetration data were analyzed using JMP Pro 16 (JMP®, Version 16. SAS Institute Inc., Cary, NC, 1989–2022). ANOVA was used to evaluate differences in Palmer amaranth emergence and light penetration as a result of biomass quantity, as well as the effect of biomass type (green or brown) and appropriate means were separated using Fisher's protected LSD (α= 0.05). Year was considered a random effect while treatment, which included CC biomass and termination timing, were considered fixed effects. Fisher's protected LSD using an α= 0.05 level of significance was used to determine significant differences and mean separation for main effects. Emergence and PPFD data were subjected to nonlinear regression across CC biomass levels in SigmaPlot 15 using the aforementioned methodology.

Results and Discussion

Cover crop biomass

There was a site year by CC termination timing interaction for biomass (p=0.041) (Table 1). Generally, the green terminated CC treatments had greater biomass accumulation across site years with the exception of Blacksburg in 2023 where there was no difference between brown and green treatments. The trend of greater biomass in the green treatments was most likely a result of the green termination timing accumulating more growing degree days than the brown timing (Mischler et al. 2010).

Palmer amaranth emergence 4 weeks after planting

Emergence data indicated a two-way interaction between site year and weeks after planting (p<0.001), therefore, data were subsequently analyzed by site year. At four weeks after planting (WAP) in Blackstone 2022 a two-way interaction between CC biomass and rolled or standing was significant (p=0.002). The rolled treatments decreased Palmer amaranth emergence as the CC biomass increased, but CC biomass did not reduce Palmer amaranth emergence in the standing plots (Figure 1).

There was a three-way interaction between termination timing, rolled or standing, and CC biomass (p=0.003) at the Blacksburg 2022 site year, but only differences below 1500 kg ha^{-1} in Palmer amaranth emergence were evident. At greater CC biomass amounts, no differences in Palmer amaranth emergence were present (Figure 1). At the Blacksburg site in 2023, the main effects of CC biomass and termination timing were significant (p=0.003 and p=0.001 respectively). Regression analysis indicated Palmer amaranth emergence decreased as CC biomass increased (Figure 1). Termination timing main effect showed the brown termination treatment having the greatest Palmer amaranth emergence (μ=201 plants m^{-2}) compared to the green termination treatment (μ=137 plants m^{-2}). The accumulation of at least 2000 kg ha^{-1} CC biomass is necessary to receive observed benefits in weed suppression (Figures 1). It is also important to note that under a rolled CC, the weeds are suppressed as long as they are under the CC biomass, but at low CC biomass levels the soil is not completely covered. However, up to 1500 kg ha^{-1} the standing plots showed less Palmer amaranth emergence, but at greater CC biomass levels, the rolled plots showed greater suppression. This interaction indicates at greater biomass levels, rolled CC can provide greater suppression, but at lower biomass levels, the difference in Palmer amaranth emergence is insufficient to warrant CC rolling. Previous work by Mischler et al. (2010) showed weed suppressive effects of a rolled CC as being comparable to that of an early postemergence herbicide. Although the results in Mischler et al. (2010) are possible, as their study reports, they are not always consistent across sites and are dependent on CC biomass.

Palmer amaranth emergence 6 weeks after planting

At 6 WAP there was a three-way interaction between CC termination timing, rolled or standing, and CC biomass (p=0.045) at Blackstone 2022. More Palmer amaranth emerged when CC biomass was below 500 kg ha^{-1} particularly under the rolled brown treatment, but at greater CC biomass accumulations, there was no difference in emergence when compared to the other treatments (Figure 2). The same three-way interaction was observed at Blacksburg in 2022 (p=0.018) where low CC biomass levels showed greater emergence for the green rolled and brown standing treatments, but at greater CC biomass levels there was no separation between treatments (Figure 2). A two-way interaction between termination timing and rolled or standing was significant in both Blacksburg 2023 (p=0.049) and Blackstone 2023 (p=0.033) (Table 2). At Blackstone in 2023, the brown rolled treatments had greater Palmer amaranth emergence (μ=26 plants m^{-2}), while the green standing (μ=12 plants m^{-2}), green rolled (μ=11 plants m^{-2}), and brown standing (μ=11 plants m^{-2}) had the least Palmer amaranth emergence (Table 2); however, the brown rolled and green standing did not differ at this site. Similarly, at Blacksburg in 2023, the brown rolled treatments had the greatest Palmer amaranth emergence (μ=37 plants m^{-2}) while the green rolled treatments had the least (μ=7 plants m^{-2}). The brown standing and green standing were not different when compared to any of the other treatments (μ=20 plants m^{-2} and μ=15 plants m^{-2}, respectively) at this site. Overall, the effects of Palmer amaranth suppression by the CC treatments did not separate consistently by treatments at 6 WAP.

When compared to the 4 WAP data, the trends at 6 WAP were not consistent across the interactions. It is important to note that glufosinate was applied at 4 WAP and thus these 6 WAP data are from a separate emergence cohort. Since the CC residue was all dead at this time, it is logical that there were no differences in termination timing (i.e., green versus brown). Additionally, the decomposition of the CC over time, particularly for the rolled brown treatments, may have reduced treatment effects. With less biomass and more time as nonliving residue, it is likely that the brown rolled treatments allowed for more Palmer amaranth emergence due to less biomass present. This information is in agreeance with Pittman et al. (2020) where greater CC biomass leads to more weed suppression. Consistently, in this study and others (MacLaren et al. 2019; Mirsky et al. 2011), the importance of sufficient CC biomass accumulation is highlighted, and agree that it is perhaps the most important factor in suppressing weeds.

Field PPFD

At soil level, PPFD data indicated a three-way interaction between termination timing, rolled or standing, and CC biomass ($p=0.006$) (Figure 3). There was also a two-way interaction between WAP and CC biomass ($p<0.001$). The three-way interaction did not show differences amongst treatments, but an overall trend of reduced PPFD with increasing CC biomass was observed (Figure 3). The two-way interaction at soil level showed greater light penetration at 2 and 4 WAP, but a decrease in light penetration at 6 WAP. The decrease in PPFD at 6 WAP could potentially be displaying the light interception via the soybean canopy as the crop developed.

Standing plots comparing different heights of PPFD data indicated a two-way interaction between termination timing and CC biomass ($p<0.001$), as well as an interaction of WAP and CC biomass ($p<0.001$) (Figure 4). The two-way interaction of termination timing and CC biomass did not show light penetration differences until the biomass was greater than 7,000 kg ha^{-1}. At biomass less than 7,000 kg ha^{-1}, there was no difference in PPFD between brown and green. The two-way interaction of WAP and CC biomass indicated similar trends to the soil level PPFD data: greater light penetration at 2 and 4 WAP, and decreased light penetration at 6 WAP. The main effect of height was also significant ($p<0.001$). Height data showed greatest PPFD at the 30 cm height ($\mu=1059$ µmol s^{-1} m^{-2}), followed by the 15 cm height ($\mu=968$ µmol s^{-1} m^{-2}), with the lowest PPFR at soil level ($\mu=794$ µmol s^{-1} m^{-2}) indicating that there is a reduction in light through CC canopy that is left standing. This light reduction could potentially explain the reduction in weed emergence observed by Rector (2019) in standing CC compared to rolled CC at the soil surface. With light penetration decreasing as it intercepts the CC canopy, reduction in light as well as potential changes in red to far red ratios from green versus brown CC residues may be changing both the quantity and quality of light reaching seeds in at the soil surface. The interception of light through the canopy is not present in a rolled crop, therefore that light would only encounter the rolled barrier at the soil surface.

Overall, this trend is consistent with other studies that have documented light reduction under the presence of a CC (Wayman et al. 2015). The reduction in light under greater CC biomass accumulation could explain some of the reduction in weed emergence at greater CC biomass that was also observed in our experiment. However, further research would be beneficial in understanding the differences in quality of light as a result of CC species selection, and changes in red to far red ratios affecting troublesome weed species. Additionally, more information is needed to identify differences in the rate of decomposition between the green terminated and brown terminated CC and its effect on small seeded weeds such as Palmer amaranth.

Yield

Due to herbivory damage caused by deer and groundhogs, the Blacksburg 2022 site was unable to be harvested for yield data. The remaining site years did not show significant main effects or interactions within each site year; yield data indicated site year as significant ($p<0.001$). These results indicate that yield was unaffected by any of the CC treatments of termination timing, rolled or standing, or CC biomass. However, yield effects have been reported to be variable under CC presence (Shoup el at. 2017; Singer and Kohler, 2005). Average yield was 1687 kg ha^{-1} for Blackstone 2022, 807 kg ha^{-1} for Blackstone 2023, and 1805 kg ha^{-1} for Blacksburg 2023. Although research has shown slight increases in yield under CC treatments (Cordeiro et al. 2021; Seifert et al. 2018), there are many contingencies including soil type, previous crop, and annual environmental conditions. Conversely, there are also multiple studies in which CC did not improve crop yields, similar to the observed results of this study (Nascente and Crisciol, 2012). It is clear that there are no consistent results on the impact of soybean yields under CC rotations. Studies by Fernando and Shrestha (2023) discuss that weed competition can be potentially suppressed through the use of a CC. There was no complete success between weed reductions and CC biomass, but greater weed suppression is often associated with greater CC biomass (Fernando and Shrestha, 2023). Other studies, however, document the potential reduction in soybean yield as a result of CC use (Deines et al. 2023). Deines et al. (2023) does mention that this reduction in soybean yield is largely dependent on seasonal weather variations, effect of CC on nitrogen dynamics, and soil conditions. Additionally, the issue of herbivory that CCs often attract is a known risk (DeYoung et al. 2019) that also played an important role in this experiment. It is documented that the access of high quality foods for deer species will lead to more selective grazing by these herbivores (DeYoung et al 2019). Therefore, the availability of CC in the fall and crops such as soybeans in the summer may invite yet another pest to manage on farm. The variable results in soybean yield effects as a result of CC use are therefore to be expected in a large scale field experiment, and the results of our study are therefore not unlike those found in other forms of CC literature.

Greenhouse emergence

There was a three-way interaction between year, termination timing, and CC biomass on Palmer amaranth emergence ($p<0.001$). Due to the Palmer amaranth emergence data being cumulative, the results at 4 WAI were chosen to represent the total emergence from weeks 1-4 given that the significant treatment effects were the same. At 4 WAI in 2021 both CC biomass ($p=0.037$) as well as termination timing ($p=0.020$) were significant. The green termination timing showed greater cumulative emergence ($\mu=290$ plants m^{-2}) when compared to the brown termination timing ($\mu= 218$ plants m^{-2}). The CC biomass main effect, showed the 2,000 kg ha^{-1} treatment had the greatest cumulative emergence ($\mu=323$ plants m^{-2}) while the 10,000 kg ha^{-1} had the least ($\mu=158$ plants m^{-2}), which is reflected by the negative relationship in Palmer amaranth emergence as CC biomass increased shown in the quadratic and hyperbolic decay models (Figure 5).

At 4 WAI the interaction of CC biomass and termination timing on Palmer amaranth emergence was significant ($p=0.001$) for 2022. The greatest emergence was observed in the 2,000 kg ha^{-1} brown treatment ($\mu=462$ plants m^{-2}) after which point the general emergence trend began to decrease with increasing biomass (Figure 5). Up to 8,000 kg ha^{-1} the green and brown treatments did not differ, but at CC biomass levels greater than 8,000 kg ha^{-1} the green treatments showed greater Palmer amaranth emergence.

In 2023 at 4 WAI, the same interaction between CC biomass and termination timing was significant ($p=0.003$). The same pattern observed in 2021 and 2022 was also present at 4 WAI where the greater biomass treatments showed the greatest suppression, as the 8,000 kg ha^{-1} and 10,000 kg ha^{-1} green plots had the least Palmer amaranth emergence ($\mu= 85$ and 33 plants m^{-2} respectively) (Figure 5). Generally, the green treatments had less emergence, but did not separate from the brown treatments until after 8,000 kg ha^{-1} was accumulated.

Overall, there was a clear pattern in the greater CC biomass treatments reducing Palmer amaranth emergence while the lesser CC biomass treatments had more emergence. This information is in accordance with previous work such as the findings from Mirsky et al. (2017) that found increases in CC biomass reduce weedy populations. Additionally, with the exception of 2021, both main effects of CC biomass and termination timing in the greenhouse are consistent with the field results that indicate greater CC biomass increases Palmer amaranth suppression, and although not consistently, the green terminated treatments also reduced Palmer amaranth emergence when compared to the brown terminated treatments. It is possible that this inconsistency between experimental runs in the greenhouse is due to the biomass amounts not accounting for moisture in 2021 and 2022 as compared to 2023. Although emergence trends observed were similar, it is important to continue research with biomass accounting for moisture weight consistently to accurately compare between treatments.

Greenhouse light penetration

Light penetration data showed a year by biomass by termination timing interaction (p=0.001). The average PPFD data for 2021 indicated a clear relationship between PPFD and CC biomass (Figure 5). As the CC biomass increased there was a decrease in PPFD penetrating through the CC biomass. The same patterns were observed for 2022 and 2023 (Figure 3). The main effect of termination timing was only significant in 2021 when the brown treatments had greater light intensity compared to the green treatments (µ=261 and 249 µmol s^{-1} m^{-1}, respectively). However, the effect of CC biomass was consistently the significant main effect that affected PPFD reaching the soil top layer. One important detail concerning the PPFD data in both the field and greenhouse study, is these data do not speak to the quality of light penetrating the CC biomass. It is known that actively growing plants or CC in this case, would reduce the red to far red ratio (Batlla and Benech-Arnold, 2014). This change in quality of light can also impact weed seed germination. Additionally, Teasdale and Mohler (1993) determined that dead plant residues do not affect these red to far red ratio, however, living plant material could lead to different emergence cues for weedy species. Further research documenting the changes in red to far red ratios under various CC termination timings is therefore necessary to have a more wholistic understanding as to the changes in biological cues that CC management is having on weed seed emergence.

Practical Implications

Results suggest that CC management did not influence soybean yield. Although CCs can be another tool for weed suppression, sufficient biomass must be accumulated in order to reap Palmer amaranth suppression benefits. These results indicate that earlier plantings as well as later termination timings would allow farmers to accumulate biomass for results to be beneficial. This research shows the importance of CC biomass accumulation, as well as the variability with green and brown termination in terms of weed suppression. Although planting into a green CC may produce more biomass, this may not always provide more weed suppression. Therefore, from year to year, if biomass accumulation can be accomplished by other means, there would not be a strong incentive to delay CC termination.

Acknowledgements

The authors specifically acknowledge all the undergraduate assistants for field help on this project. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement. No conflicts of interest have been declared.

Funding

Funding was provided in part by the Virginia Soybean Board and the USDA National Institute of Food and Agriculture, Hatch project 1026160.

Competing interests

The authors declare none.

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Table 1. Total cover crop biomass by site and termination timing from experiments conducted in Virginia between 2019 and 2021. The no cover crop comparison treatment was excluded from this analysis.

	Cover crop termination timing			
Location	Planting brown[a]		Planting green	
	-------------------- Cover crop biomass (kg ha^{-1}) --------------------			
Blackstone 2022	1636	B[b]	2283	A
Blacksburg 2022	2566	B	4356	A
Blackstone 2023	1633	B	2656	A
Blacksburg 2023	4125	A	4957	A

[a] Brown planting refers to cover crop terminated two weeks prior to planting while green planting refers to cover crop terminated at the time of planting.

[b] Letters indicate significant differences ($p<0.05$) in cover crop biomass within each site.

Table 2. Palmer amaranth emergence at 6 weeks after planting for significant interactions of rolled versus standing CC when planted green versus brown in Virginia in Blackstone 2023 and Blacksburg.

Blackstone 2023				Blacksburg 2023			
Planting brown		Planting green		Planting brown		Planting green	
rolled	standing	rolled	standing	Rolled	standing	rolled	standing
-------------------------------- Palmer amaranth (plants m^{-2}) ----------------------------------							
26 A[a]	11 B	11 B	12 AB	37 A	20 AB	7 B	15 AB

[a] Brown planting refers to cover crop terminated two weeks prior to planting while green planting refers to cover crop terminated at the time of planting.

[b] Letters indicate significant differences ($p<0.05$) in Palmer amaranth plant counts within each site.

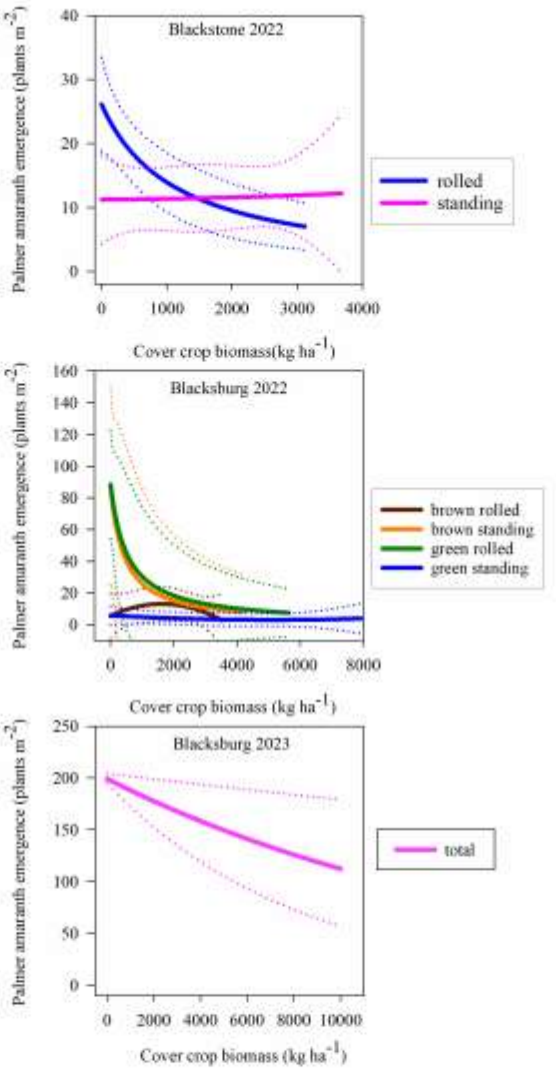

Figure 1. Palmer amaranth emergence for significant sites and interactions at 4 weeks after planting (WAP) across cover crop (CC) biomass for experiments conducted across Virginia between 2020 and 2023. Top graph shows the relationship between Palmer amaranth emergence for the rolled and standing treatments across the CC biomass gradient. The middle graph shows the 3-way interaction relationship for Palmer amaranth emergence as a result of termination timing (brown: CC terminated two weeks prior to planting, green: CC terminated at the time of planting), rolled and standing, and the CC biomass gradient. The bottom graph shows total Palmer amaranth emergence across the main effect of CC biomass. Dotted lines of same color indicate 95% confidence intervals (see Table 3 for equation parameters).

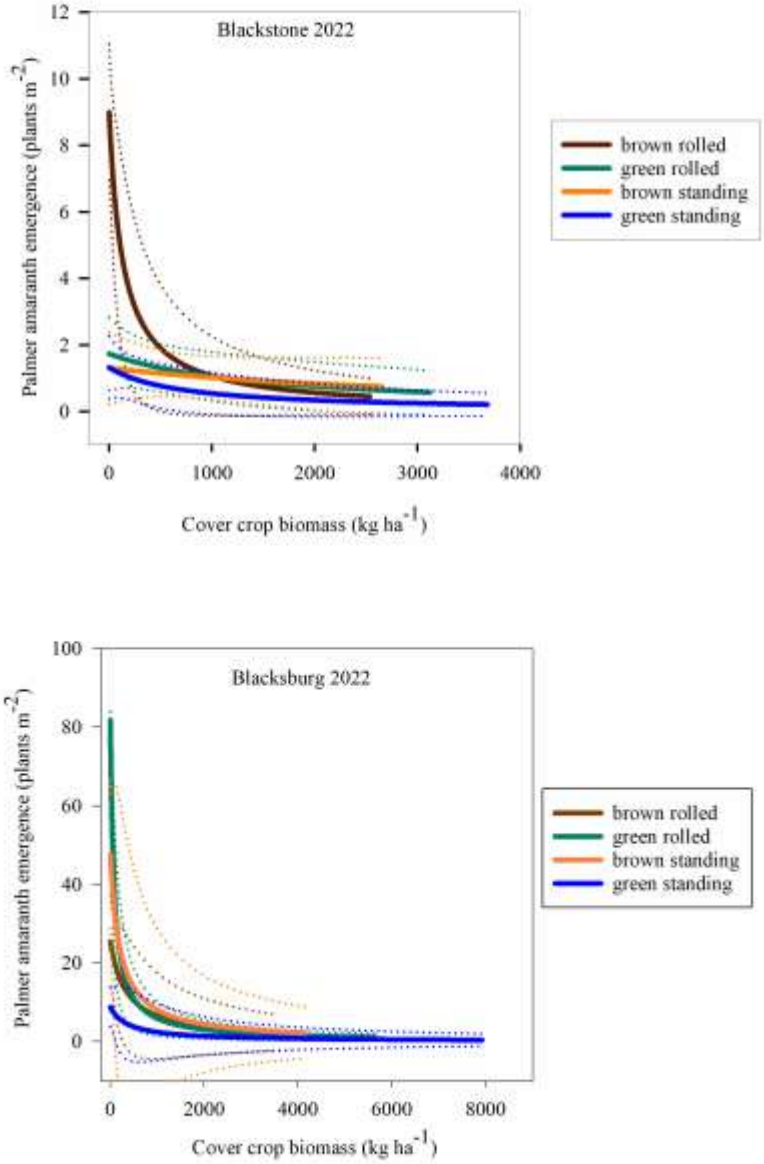

Figure 2. Regressions of significant three-way interactions at 6 weeks after planting (WAP) for Palmer amaranth emergence as a result of cover crop (CC) termination timing (brown: CC terminated two weeks prior to planting, green: CC terminated at the time of planting), as well as rolled or standing, regressed across CC biomass for experiments conducted in Virginia between 2020 and 2023. Dotted lines of same color indicate 95% confidence intervals (see Table 3 for equation parameters).

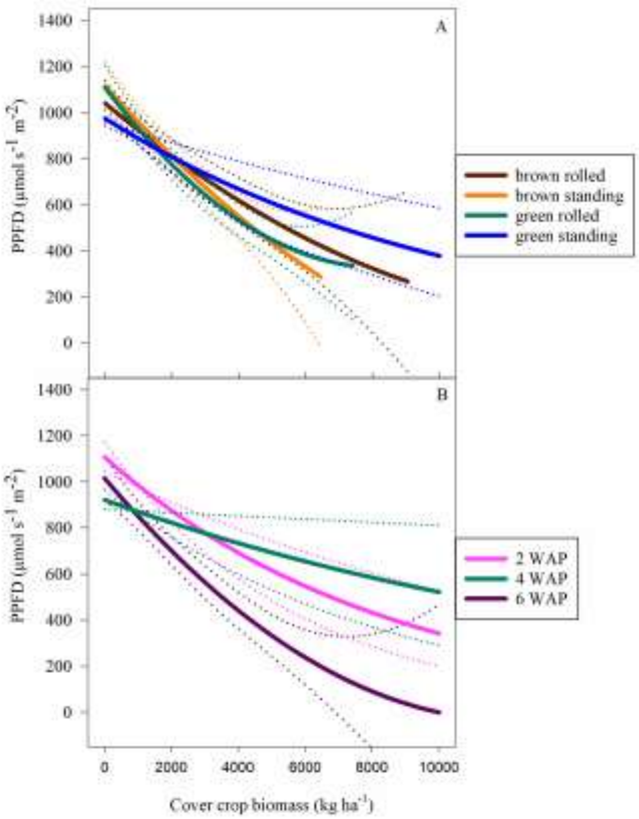

Figure 3. Photosynthetic photon flux density (PPFD) at soil level for trials conducted in Virginia between 2020 and 2023. Graph A shows PPFD at the soil surface level as a result of three way interactions between termination timing (brown: CC terminated two weeks prior to planting, green: CC terminated at the time of planting), rolled or standing, and the cover crop (CC) biomass gradient. Graph B shows PPFD as a result of two-way interactions between weeks after planting (WAP) and CC biomass. Dotted lines of same color indicate 95% confidence intervals (see Table 3 for equation parameters).

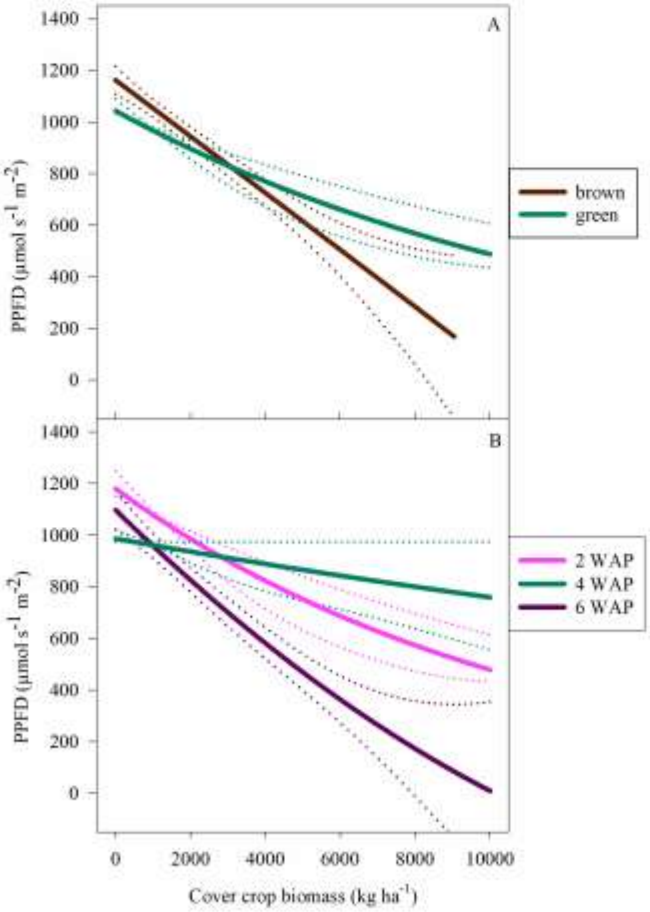

Figure 4. Photosynthetic photon flux density (PPFD) for all standing plots including soil level, 15 cm, and 35 cm above soil level for experiments conducted in Virginia between 2020 and 2023. Graph A shows the two-way interaction between termination timing (brown: CC terminated two weeks prior to planting, green: CC terminated at the time of planting) and cover crop (CC) biomass. Graph B shows the two-way interaction between weeks after planting (WAP) and CC biomass. Dotted lines of same color indicate 95% confidence intervals (see Table 3 for equation parameters).

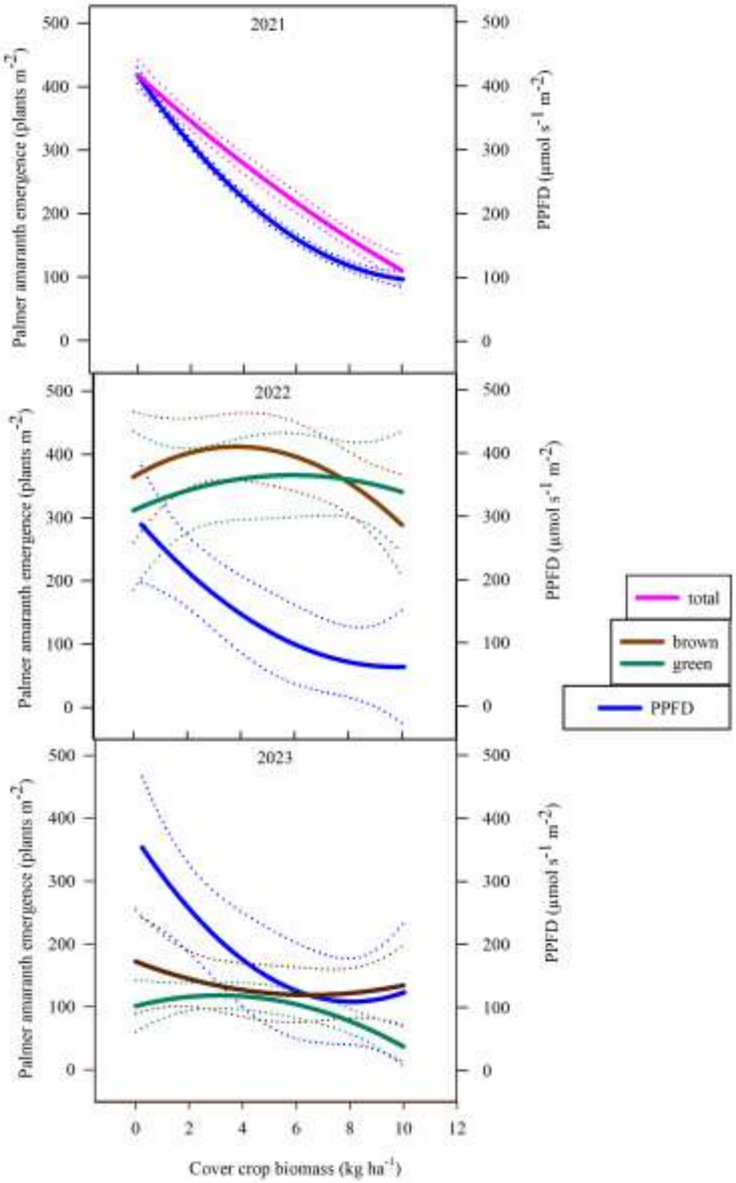

Figure 5. Greenhouse cumulative Palmer amaranth emergence for each experimental run from initiation to 4 weeks after initiation (WAI) (left axis) with average photosynthetic photon flux density (PPFD) (right axis) regressed across total CC biomass for experiments conducted between 2020 and 2023. 2021 shows the main effect of CC biomass on total Palmer amaranth emergence while 2023 and 2023 show the two-way interaction between termination timing (brown: CC terminated two weeks prior to planting, green: CC terminated at the time of planting) and CC biomass. Dotted lines of same color indicate 95% confidence intervals (see Table 3 for equation parameters).

Table 3. Summary of equation parameters in figures for trials conducted in Virginia between 2020 and 2023.

Figure	Title	Equation	R^2
Figure 1. Blackstone 2022	rolled	$y=24.12-0.0118*x+2.1162e-006*x^2$	0.34
	standing	$y=11.23+6.9174e-005*x+5.1434e-008*x^2$	0.01
Figure 1. Blacksburg 2022	brown rolled	$y=6.05-0.0067*x+1.9194e-006*x^2$	0.45
	green rolled	$y=1.68-0.0009*x+2.1275e-007*x^2$	0.12
	brown standing	$y=1.14+0.0007*x+-3.8853e-007*x^2$	0.13
	green standing	$y=1.26-0.0008*x+1.3762e-007*x^2$	0.22
Figure 1. Blacksburg 2023	total	$y=199*^{(5.72e-005*X)}$	0.54
Figure 2. Blackstone 2022	brown rolled	$y=(8.99*134)/(134+x)$	0.82
	green rolled	$y=(1.73*1540)/(1540+x)$	0.12
	brown standing	$y=(1.31*3585)/(3585+x)$	0.05
	green standing	$y=(1.32*694)/(694+x)$	0.24
Figure 2. Blacksburg 2022	brown rolled	$y=(25.5*346)/(346+x)$	0.46
	green rolled	$y=(81.7*77.5)/(77.5+x)$	0.99
	brown standing	$y=(47.7*204)/(204+x)$	0.55
	green standing	$y=(8.75*380)/(380+x)$	0.41
Figure 3. Soil level	brown rolled	$y=1041-0.12*x+3.9910e-006*x^2$	0.166

	brown standing	$y=1116-0.16*x+5.3440e-006*x^2$	0.22
	green rolled	$y=1108-0.18*x+1.1549e-005*x^2$	0.33
	green standing	$y=975*^{(9.4601e-005*X)}$	0.86
Figure 3. Weeks after planting (WAP)	2 WAP	$y=1107*^{(-0.0001*X)}$	0.80
	4 WAP	$y=921*^{(5.68e-005*X)}$	0.87
	6 WAP	$y=1015-0.17*x+6.9952e-006*x^2$	0.26
Figure 4. Standing plots	brown	$y=1161-0.108*x+-1.2039e-007*x^2$	0.14
	green	$y=1042*^{(7.593e-005*X)}$	0.16
Figure 4. Weeks after planting (WAP)	2 WAP	$y=1180*^{(-9.0289e-005*X)}$	0.88
	4 WAP	$y=986*^{(-2.6153e-005*X)}$	0.62
	6 WAP	$y=1097-0.142*x+3.3754e-006*x^2$	0.21
Figure 5. 2021	total	$y=417-37.33*x+0.66*x^2$	0.95
	PPFD	$y=416-58.9*x+2.69*x^2$	0.99
Figure 5. 2022	brown	$y=364.2-24.9*x-3.25*x^2$	0.47
	green	$y=311.2+18.8*x-1.59*x^2$	0.07
	PPFD	$y=287-46*x+2.4*x^2$	0.92
Figure 5. 2023	brown	$y=172.1-16.3*x+1.25*x^2$	0.14
	green	$y=101+10.8*x-1.72*x^2$	0.71
	PPFD	$y=353-61*x+3.8*x^2$	0.90