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Effects of Carolina geranium (*Geranium carolinianum*) competition on strawberry growth and yield

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Research Article

Cite this article: Buzanini AC and Boyd NS (2024) Effects of Carolina geranium (*Geranium carolinianum*) competition on strawberry growth and yield. Weed Sci. **72**: 740–747. doi: 10.1017/wsc.2024.41

Received: 20 November 2023
Revised: 28 May 2024
Accepted: 14 June 2024

Associate Editor:
Caio Brunharo, Penn State University

Keywords:
Fruits; weed density; yield

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Abstract

Carolina geranium (*Geranium carolinianum* L.) growth in planting holes in commercial strawberry [*Fragaria* × *ananassa* (Weston) Duchesne ex Rozier (pro sp.) [*chiloensis* × *virginiana*]] fields is a serious problem in Florida. This study aimed to evaluate the effects of different *G. carolinianum* densities on strawberry growth and yield in plasticulture production systems. *Geranium carolinianum* densities were 0, 0.4, 0.8, 1.9, 2.7, and 3.8 plants m^{-2} equally distributed on the plastic-mulched bed top within the planting holes. *Geranium carolinianum* density did not affect plant height; however, seed production and season-end biomass were negatively correlated with density in Season I. There was a negative, linear correlation between weed density and berry yields. With each increase in *G. carolinianum* per square meter, the total annual yield was lowered by 554 and 935 kg ha^{-1}, in Seasons I and II, respectively. Our data clearly indicate that *G. carolinianum* emerging in the transplant holes of strawberry and competing throughout the season has a significantly negative effect on total berry yield.

Introduction

Strawberry [*Fragaria* × *ananassa* (Weston) Duchesne ex Rozier (pro sp.) [*chiloensis* × *virginiana*]] is an important crop in Florida. In 2022, the state harvested approximately 4,290 ha with an estimated value of US$511 million (USDA-NASS 2022). Strawberry is cultivated as a winter annual crop in raised beds that are covered with polyethylene plastic mulch (Yu et al. 2018). In Florida plasticulture systems, the raised bed is formed, fumigated, and covered with plastic mulch 13 to 30 d before transplanting to control weeds and other soil pathogens. The plasticulture system provides excellent broadleaf and grass weed control on the bed, but weeds emerge in the planting holes created for the transplants and compete directly with the crop (Sharpe et al. 2018a; Whitaker et al. 2014). Weeds in the planting holes are typically managed with preemergence herbicides applied under the plastic mulch or by hand weeding. Oxyfluorfen, napropamide, flumioxazin, and sulfentrazone are all registered for use under the plastic mulch (Daugovish et al. 2008; Gilreath and Santos 2005; Samtani et al. 2012; Stall et al. 1995). Postemergence herbicides can also be used during the season, but very few active ingredients are registered for use postemergence broadcast. Sethoxydim and clethodim can be used for grasses (Fennimore and Boyd 2019; Manning and Fennimore 2001), but clopyralid is the only registered option for broadleaf weeds with efficacy on problem species such as Carolina geranium (*Geranium carolinianum* L.) and black medic (*Medicago lupulina* L.) (Sharpe et al. 2016).

Limited research has examined the competitive interaction between strawberries and weeds. Pritts and Kelly (2001) reported that weed competition in the first 2 mo after planting in a matted row system had the greatest impact on berry yield, with 20% and 65% yield reductions after 1 to 2 mo of competition, respectively. Pritts and Kelly (2004) reported that season-long uncontrolled weed growth in a mature matted row system reduced productivity by 51%, but yield losses are likely to be much less at lower weed densities. The weed species, time of emergence, weed location in comparison to the crop, and weed density all influence the competitive interaction, as has been observed in other crops grown in similar production systems (Gilreath and Santos 2004; Morales-Payan et al. 2003; Motis et al. 2003).

According to a survey conducted in 2019 and 2020, the most common weeds found in Florida's strawberry production are goosegrass [*Eleusine indica* (L.) Gaertn.], cutleaf evening primrose (*Oenothera laciniata* Hill), *G. carolinianum*, common ragweed (*Ambrosia artemisiifolia* L.), and eclipta [*Eclipta prostrata* (L.) L.]. These weeds were found in 83%, 63%, 58%, 58%, and 46% of all fields surveyed, respectively (Boyd and Reuss 2022). *Geranium carolinianum* is a cool-season annual or biennial broadleaf weed that is particularly problematic in Florida strawberry (Webster 2014; Linex 2020). The seeds of *G. carolinianum* are not adequately controlled by fumigants or preemergence herbicides, and seedlings emerge in the planting holes of commercial strawberry fields approximately 2 wk after transplant. As a result,

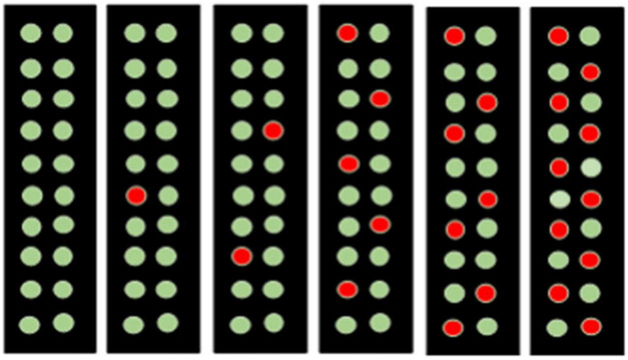

Figure 1. Carolina geranium planting configuration in the field trials. The red dots represent strawberry plants with Carolina geranium in the same transplant hole and the green dots represent strawberry plants with no Carolina geranium. From left to right, the densities would be 0, 0.4, 0.8, 1.9, 2.7, and 3.8 Carolina geranium plants m^{-2}.

G. carolinianum weeds compete with the strawberry crop for limited resources, including nutrients, sunlight, and water for most of the season; and this competitive interaction is likely to reduce berry yield and berry physiochemical attributes (Sharpe et al. 2018a; Yu et al. 2018). As noted previously, there are very few studies evaluating weed competition in strawberry fields, with even fewer done in plasticulture systems.

The objective of this research was to determine the effect of season-long competition of *G. carolinianum* at varying densities on strawberry growth and yield.

Materials and Methods

Two field research trials were conducted at the Gulf Coast Research and Education Center (27.76°N, 82.22°W) in Wimauma, FL, USA (Season I: August 2020 to March 2021; Season II: August 2021 to March 2022) to evaluate the effects of *G. carolinianum* competition on strawberry plant growth and yield. The soil type for both trials is classified as a Myakka fine sand (sandy, siliceous hyperthermic Oxyaquic Alorthod) with a pH of 6.5 and 0.7% organic matter.

The plot size was 7.62 m of a single raised bed. Raised beds were formed using standard bed-pressing equipment (Kennco Manufacturing, Ruskin, FL, USA) on 1.22-m centers. The beds were 30.5-cm high and 68-cm wide. After the beds were formed, they were fumigated with 336 kg ha^{-1} 1,3 dichloropropene+ chloropicrin (Pic-Clor 60, Soil Chemicals Corporation D/B/A Cardinal Professional Products, Hollister, CA, USA). A single drip tape (2.22-cm diameter, 0.254-mm thick) with emitters every 30 cm and a flow rate of 0.95 L min^{-1} was installed at 2.5 cm below the bed top-soil surface. Raised beds were covered with impermeable opaque film (TIF, Berry Plastics, Evansville, IN, USA).

The experimental design was a randomized complete block with four replications. Treatments included 0, 0.4, 0.8, 1.9, 2.7, and 3.8 *G. carolinianum* plants m^{-2} and a weed-free control (Figure 1). Two rows of bare-root strawberry ('Brilliance') transplants were planted per bed with 38-cm spacing between plants and 30-cm spacing between rows. This is the standard spacing used by commercial growers in central Florida. Twenty strawberry plants per plot were transplanted on October 6, 2020, and October 6, 2021. *Geranium carolinianum* seedlings were transplanted 2 wk after strawberry transplanting. One seedling was transplanted per strawberry planting hole (8-cm length by 1-cm width) according to the density schemes shown in Figure 1. The timing for transplanting the weed seedlings was determined in order to replicate the time when the *G. carolinianum* seedlings usually started to emerge in strawberry crops in Florida. Crop management followed standard practices in the region, including sprinkler irrigation after planting for plant acclimatization. Fungicides and insecticides were used as needed to control pests. During both seasons, 5-2-8 liquid fertilizer (Chemical Dynamics, Plant City, FL, USA) was applied through drip irrigation (fertigation) at a rate of 1.12 kg N ha^{-1} day^{-1}, with no preplant N. Fertigation occurred for 1 h twice a day.

Throughout the experimental period, average, minimum, and maximum air temperatures were similar across seasons (Table 1). However, in Season I, rainfall was higher compared with Season II, especially during November, December, and February. During the cropping period in Season I, the fields received a total accumulated precipitation of 466.3 mm, while precipitation was 303.8 mm in Season II.

One randomly selected strawberry plant per plot with a *G. carolinianum* plant growing in the same planting hole was tagged using a plastic stake for data collection. A single strawberry plant adjacent to the tagged plant mentioned with no *G. carolinianum* growing in the same transplant hole was also tagged. Marketable strawberries were harvested from the entire plot twice per week from January 5, 2021, to March 3, 2021, and January 13, 2022, to March 3, 2022, for Seasons I and II respectively. Strawberries from the two tagged plants in each plot were harvested separately. Strawberry photosynthetic rate was measured on February 1, 2022, in Season II, with a Li-Cor 6400 photosynthesis meter (Li-Cor Biosciences, Lincoln, NE, USA) on a separate strawberry plant on the north side of a strawberry plant with a Carolina geranium in the same transplant hole. Strawberry shoot biomass was collected by cutting the one tagged plant with *G. carolinianum* and the tagged plant without *G. carolinianum* at the soil surface for a total of two plants per plot. The plants were collected on March 1, 2021, and March 3, 2022, dried at 60 C for 7 d, and weighed. All fruits were removed before drying.

Geranium carolinianum shoot height, seed pod number per plant, total seeds per plant, and shoot biomass were collected in both years. In Season I, the *G. carolinianum* height was measured in 2020 on December 7 and 18, and in 2021 on January 4, 11, and 19, February 2 and 16, and March 1. For Season II, heights were measured every 14 d after the transplanting day from November 22, 2021, to February 21, 2022. The height was measured with a graduated scale from the base to the longest stem of *G. carolinianum* plants. The *G. carolinianum* biomass and seed counts were collected at the end of the season, on March 8, 2021, and March 11, 2022, in Seasons I and II respectively. *Geranium carolinianum* shoot biomass, pod number per plant, and seeds per plant were measured using the tagged *G. carolinianum* shoot in each plot and one additional randomly selected *G. carolinianum* plant. The total number of seed pods was counted on each shoot, and the number of seeds within five randomly selected pods was counted to estimate total seed production per plant. Shoot biomass was measured by cutting the shoot at the soil surface. All samples were dried at 60 C for 7 d and weighed.

Statistical Analysis

Data of *G. carolinianum* height and strawberry biomass were subject to ANOVAs with PROC MIXED in SAS (v. 9.4, SAS Institute, Cary, NC, USA). The density was considered a fixed factor, while the block was considered a random factor. The two iterations of the experiment were analyzed separately, as data

https://doi.org/10.1017/wsc.2024.41 Published online by Cambridge University Press

Table 1. Monthly weather data at the Gulf Coast Research and Education Center in Wimauma, FL, in 2020–2021 (Season I) and 2021–2022 (Season II).[a]

	Month	Average air temperature	Minimum air temperature	Maximum air temperature	Rainfall
		C			mm
Season I (2020–2021)	October	25.2	14.2	34.2	59.7
	November	21.8	10	32	186.9
	December	15	0.2	28.3	72.9
	January	15.6	3.3	29.5	22.1
	February	18.8	−0.7	31.3	100.3
	March	20	4.8	33	24.4
Total					466.3
Season II (2021–2022)	October	24.2	13.5	35	53.3
	November	18.1	6.5	30	93.5
	December	19.4	5.8	29.9	36.8
	January	15	−3.9	28.8	31.8
	February	18.3	3.5	31.3	16.8
	March	21	2.3	33	71.6
Total					303.8

[a]The weather station is part of the Florida Automated Weather Network.

collection occurred on different dates. Constant variance and normality were examined. *Geranium carolinianum* height data were collected on multiple dates, and the data were subject to repeated-measures analyses with the PROC MIXED model. The months were considered to be the time factor. Treatment means were separated using Tukey's multiple-means comparisons at $P \leq 0.05$. SigmaPlot (v. 14.5, Systat Software, San Jose, CA, USA) was used for linear regression analyses:

$$f = y_0 + a^* x \quad [1]$$

where x is the explanatory variable (density) and f is the dependent variable. The slope of the line is a, and y_0 is the intercept (value of y when $x = 0$). Nonlinear regression was used to examine the correlation between *G. carolinianum* density and *G. carolinianum* seed production, *G. carolinianum* biomass, strawberry fruit yield, and photosynthetic rate.

Table 2. *Geranium carolinianum* height by month at the Gulf Coast Research and Education Center in Wimauma, FL, in 2020–2021 (Season I) and 2021–2022 (Season II).

	G. carolinianum height[a]	
Month	Season I	Season II
	cm plant^{-1}	
December	10 a[b]	13 a
January	14 b	21 b
February	52 c	49 c
P-value[b]	<0.0001	<0.0001

[a]Means within a column followed by the same letter are not significantly different according to Tukey's test ($P \leq 0.05$).
[b]The value refers to the factor time from the repeated-measures analyses.

Results and Discussion

Geranium carolinianum

Weed density had no effect on *G. carolinianum* height ($P = 0.5449$ and 0.0329 for Seasons I and II, respectively). As expected, *G. carolinianum* height increased over the season, with the most rapid growth occurring in January and February (Table 2). Slow early-season growth is one of the reasons this weed is typically not detected during early establishment in commercial fields. A strong linear correlation between *G. carolinianum* density and *G. carolinianum* biomass and seed production (Table 3) was noted in Season I but not in Season II (Figures 2 and 3). *Geranium carolinianum* densities ranging from 0.8 to 3.8 plants m^{-2} reduced *G. carolinianum* seed production by 11% to 49%. For each unit increase in *G. carolinianum* density, weed biomass decreased by 24.5 g ($R^2 = 0.88$) in Season I. However, during Season II, this relationship was much weaker, with no clear correlation between density and weed growth parameters. We cannot adequately explain the lack of correlation observed in Season II nor can we distinguish inter- and intraspecific competition. The management routines for both seasons were the same for both irrigation and fertilization, and there were no differences in growing degree days between years (data not shown). We conclude that intraspecific competition occurred in at least 1 of 2 yr and that interspecific competition likely occurred in both years, although not measured.

It is also important to note that even low densities of *G. carolinianum* can negatively impact strawberry production in ways that increase management costs or lower yields. For example, hand weeding or clopyralid applications for *G. carolinianum* control increase production costs. If not adequately controlled, *G. carolinianum* plants may alter the humidity levels in the strawberry canopy and block fungicide penetration. Both variables can lead to increased disease incidence. Moreover, the presence of *G. carolinianum* on strawberry beds can pose challenges during harvest, as the weed's foliage and stems may intertwine with the strawberry plants and hamper workers' visibility and access to the fruits. At the end of the season, the presence of large shoots and thick stems hinders plastic removal and increases costs associated with this activity. Additionally, the failure to control *G. carolinianum* can lead to an increase in the seedbank and dramatic increases in weed density in the following seasons (O'Donovan 1996). *Geranium carolinianum* plants in Florida strawberry fields produce approximately 5 seeds per fruit (Dubay and Murdy 1983) and potentially produce more than 20,000 seeds per plant (Figure 3).

Strawberry

There was a significant negative linear correlation between *G. carolinianum* density and total strawberry yield, with reductions ranging from 6% to 26% in Season I and 2% to 40% in Season II at weed densities ranging from 0.4 to 3.8 weeds m^{-2} (Table 4; Figure 4). Strawberry yield was not negatively correlated with *G.*

Table 3. Regression results of the relationship between *Geranium carolinianum* density and *G. carolinianum* seed and biomass production in Wimauma, FL, in 2020–2021 (Season I) and 2021–2022 (Season II).

Season	*G. carolinianum*	R^2	P-value[a]	SE of estimate	y_0[b]	a[c]
I	Seed production	0.94	0.027*	570.9	10,142.6	−1,539.2
	Biomass	0.88	0.02*	15.1	180.5	−24.5
II	Seed production	0.15	0.52	3,996.6	1,7043.5	1,056.2
	Biomass	0.12	0.57	14.9	189.5	−3.46

[a]An asterisk (*) indicates the significance levels of the linear regression equations at the $P \leq 0.05$.
[b]y_0, the intercept (value of y when $x = 0$) in the linear regression equation (Equation 1).
[c]a, the slope of the line in the linear regression equation (Equation 1).

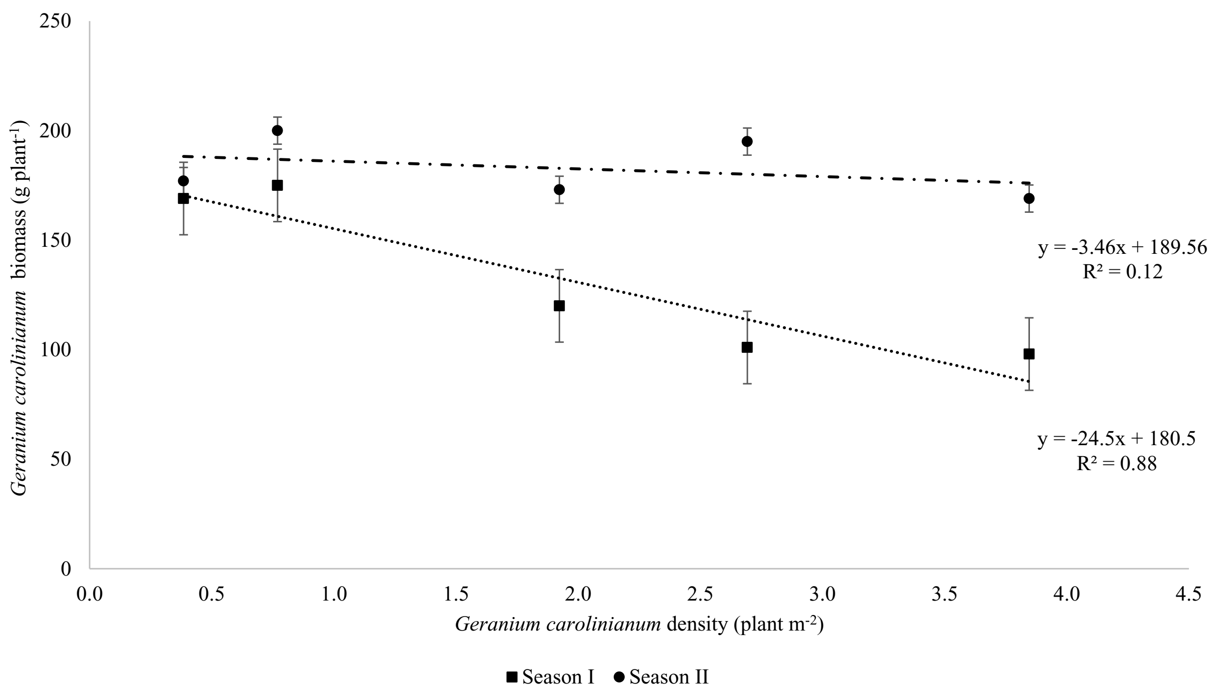

Figure 2. The linear regression between Carolina geranium biomass and Carolina geranium density in a strawberry field in Wimauma, FL, during the 2020–2021 season. Error bars represent the standard error of the mean.

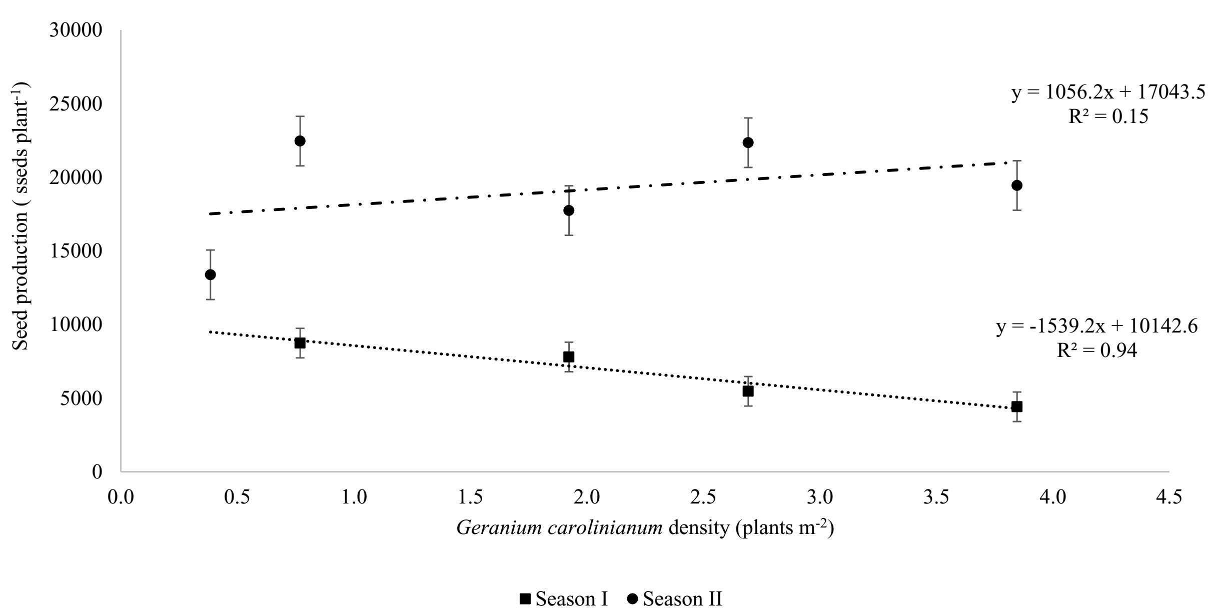

Figure 3. The linear regression between Carolina geranium seed production and Carolina geranium density in a strawberry field in Wimauma, FL, during the 2020–2021 season. Error bars represent the standard error of the mean.

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Table 4. Regression results of the relationship between *Geranium carolinianum* density and strawberry yield and photosynthetic rate at Wimauma, FL, in 2020–2021 (Season I) and 2021–2022 (Season II).

Season	Date	R^2	P-value[a]	SE of estimate	y_0[b]	a[c]
I	January	0.20	0.36	466.7	1,895.2	−146.1
	Feb	0.65	0.05*	307.6	5,799.8	−255.2
	March	0.85	0.01*	106.6	1,110.5	−152.2
	Total	0.59	0.07**	746.5	8,805.5	−553.7
II	Jan	0.24	0.32	400.8	2,659.4	−138.3
	Feb	0.58	0.08**	952.6	6,801.1	−686.9
	March	0.62	0.06**	139.5	731.8	−109.6
	Total	0.55	0.09**	1,362.4	10,192.1	−934.8
	Photosynthesis	0.77	0.021*	0.711	27.3	−0.803

[a]Asterisks indicate the significance levels of the linear regression equations at $*P \leq 0.05$ and $**P \leq 0.1$, respectively; $n = 6$.
[b]y_0, the intercept (value of y when $x = 0$) in the linear regression equation (Equation 1).
[c]a, the slope of the line in the linear regression equation (Equation 1).

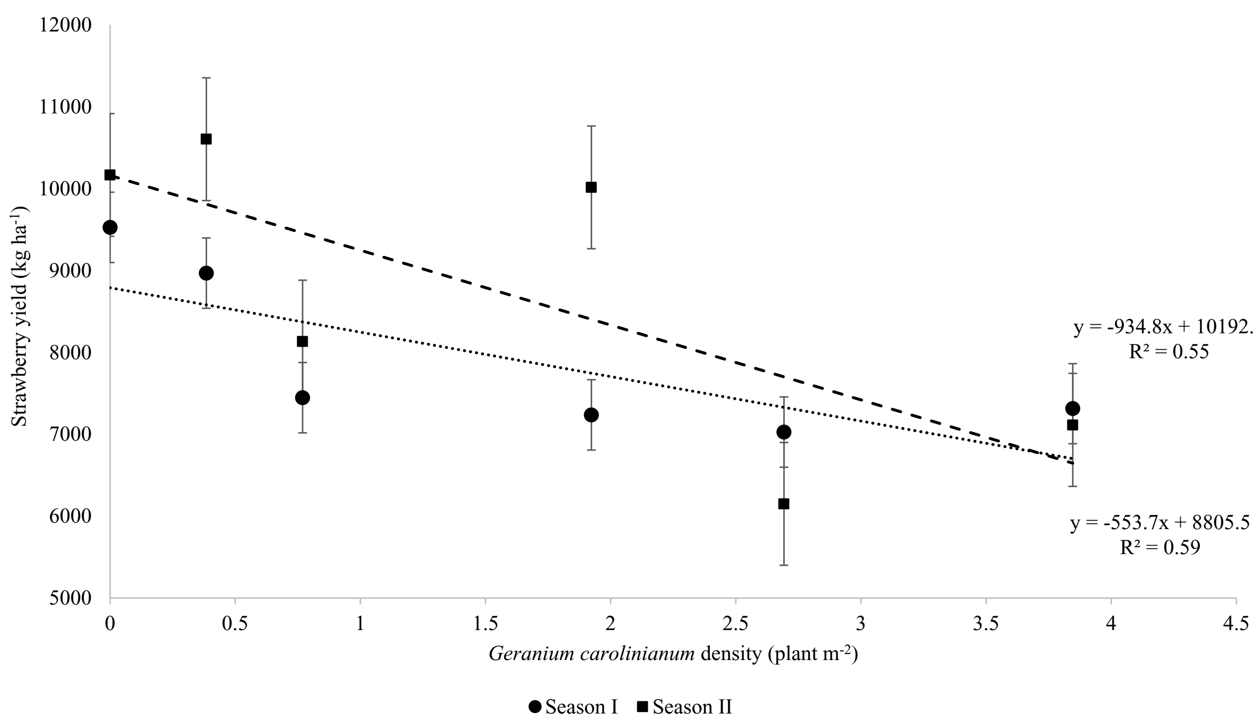

Figure 4. The linear regression between total strawberry yield harvested from January to March and Carolina geranium density at Wimauma, FL, during the 2020–2021 and 2021–2022 seasons. Each point is the mean of four replicates for each year. Error bars represent the standard error of the mean.

carolinianum density early in the harvest season (January) but was significantly correlated during the middle and late harvest season (February and March) in both years (Figures 5 and 6). The lack of difference early in the season is most likely attributed to the seasonal growth pattern of *G. carolinianum*. In commercial strawberry fields in central Florida, *G. carolinianum* tends to grow slowly early in the season with rapid growth and subsequent overtopping of the strawberry canopy in February and March, as can be observed in the height data (Table 2). As a result of this growth pattern, *G. carolinianum* is often not detected and consequently not removed by hand or sprayed with clopyralid early in the season when the weeds are most susceptible (Sharpe et al. 2018b). Therefore, our data indicate that *G. carolinianum* has a limited effect on early-season berry yields when berry prices are at a premium but can have a significant impact on mid- and late-season berry yields. Further research is needed to enhance our understanding of the potential economic impacts of this weed species over a range of berry prices.

Geranium carolinianum forms a large rosette and a dense canopy that may reduce sunlight penetration. In Season II, we measured strawberry photosynthesis at peak harvest. One *G. carolinianum* plant per square meter decreased the photosynthetic rate by an average of 7% (Figure 7). Moreover, the presence of two *G. carolinianum* plants per square meter caused a 12% reduction in photosynthetic rate. In a study conducted by Choi et al. (2016), the researchers examined the yield of strawberry plants grown in a high bench system under different light and bed positions. They found that plants grown under higher light conditions produced more fruit than those grown under lower light conditions. Specifically, in March, the light intensity in the upper beds was reported to be 19.54 mol m^{-2} d^{-1}, while in the bottom beds, it was reported to be 7.35 mol m^{-2} d^{-1}. Our results should be interpreted with caution, as we only have 1 yr of photosynthetic rate data. However, we included the data because they suggest that shading later in the season by weeds is likely to reduce strawberry photosynthesis, and therefore the reduction in available

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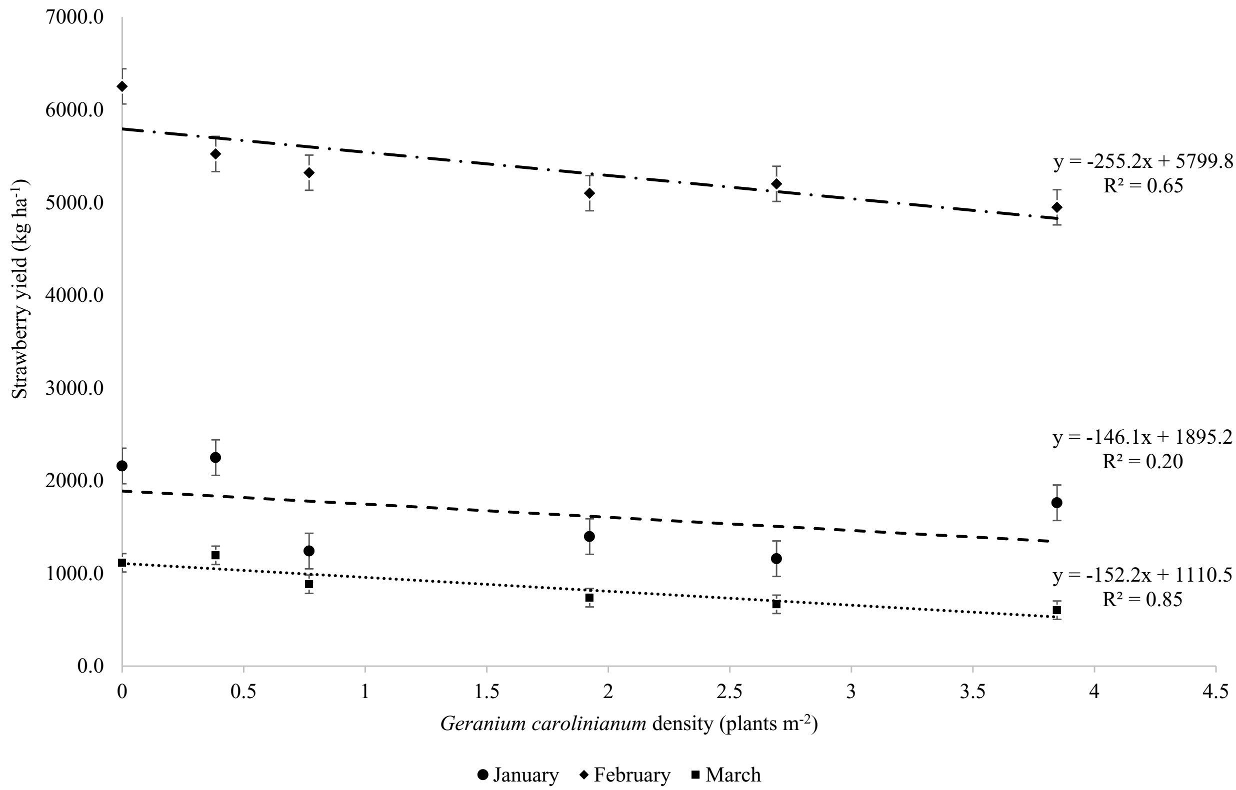

Figure 5. The linear regression between monthly strawberry yield and Carolina geranium density in Season I (2020–2021). Each point is the mean of four replicates. Error bars represent the standard error of the mean.

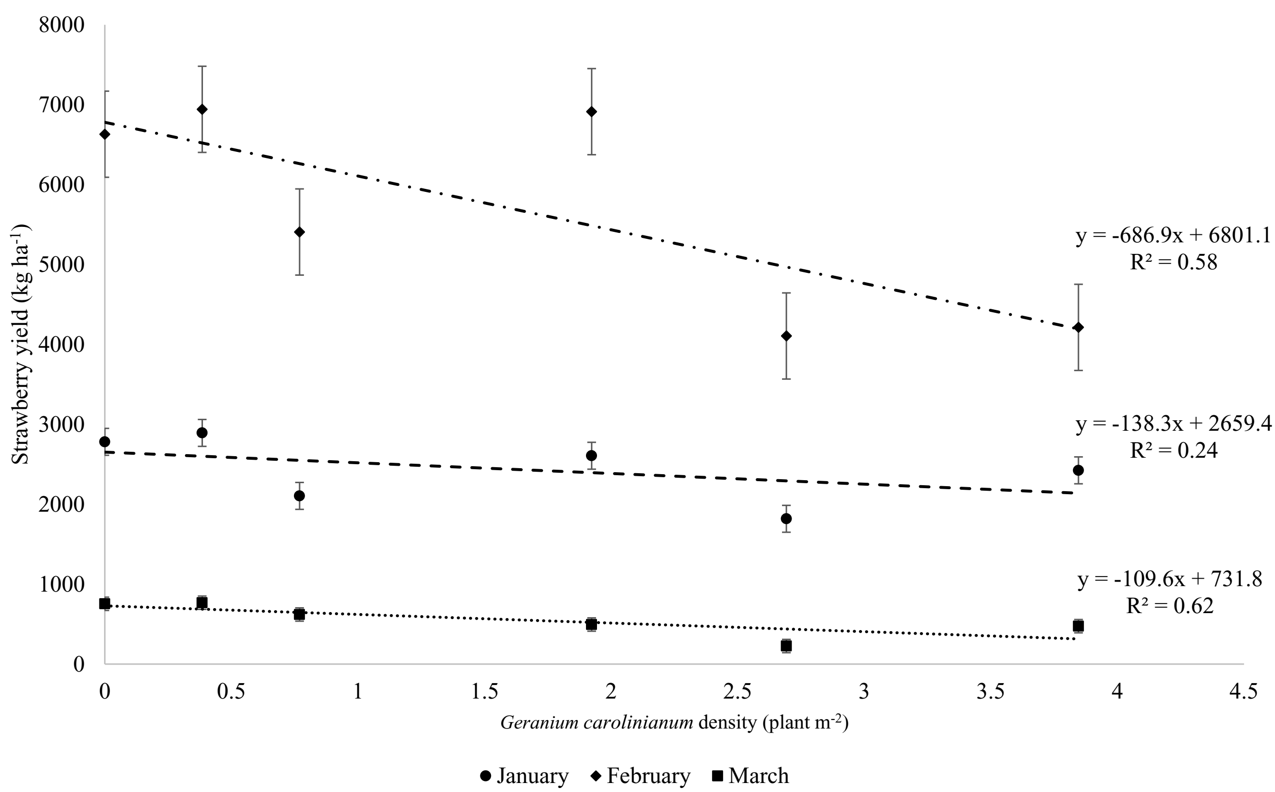

Figure 6. The linear regression between strawberry yield and Carolina geranium density on monthly yield (January to March) in Season II (2021–2022). Each point is the mean of four replicates. Error bars represent the standard error of the mean.

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Table 5. Effects of *Geranium carolinianum* density on strawberry biomass in Wimauma, FL, in 2020–2021 (Season I) and 2021–2022 (Season II).

	Strawberry biomass			
	With *G. carolinianum*[a]		Without *G. carolinianum*[b]	
Density	Season I	Season II	Season I	Season II
plants m^{-2}	g $plant^{-1}$			
0	35	36	41	38
0.4	25	20	50	39
0.8	43	29	41	46
1.9	35	22	43	34
2.7	20	30	25	35
3.8	31	32	31	40
P-value	0.4257	0.0899	0.255	0.4772

[a]One randomly selected tagged strawberry plant per plot with a *G. carolinianum* plant growing.
[b]A single strawberry plant adjacent to the tagged strawberry plant with no *G. carolinianum* growing in the same transplant hole.

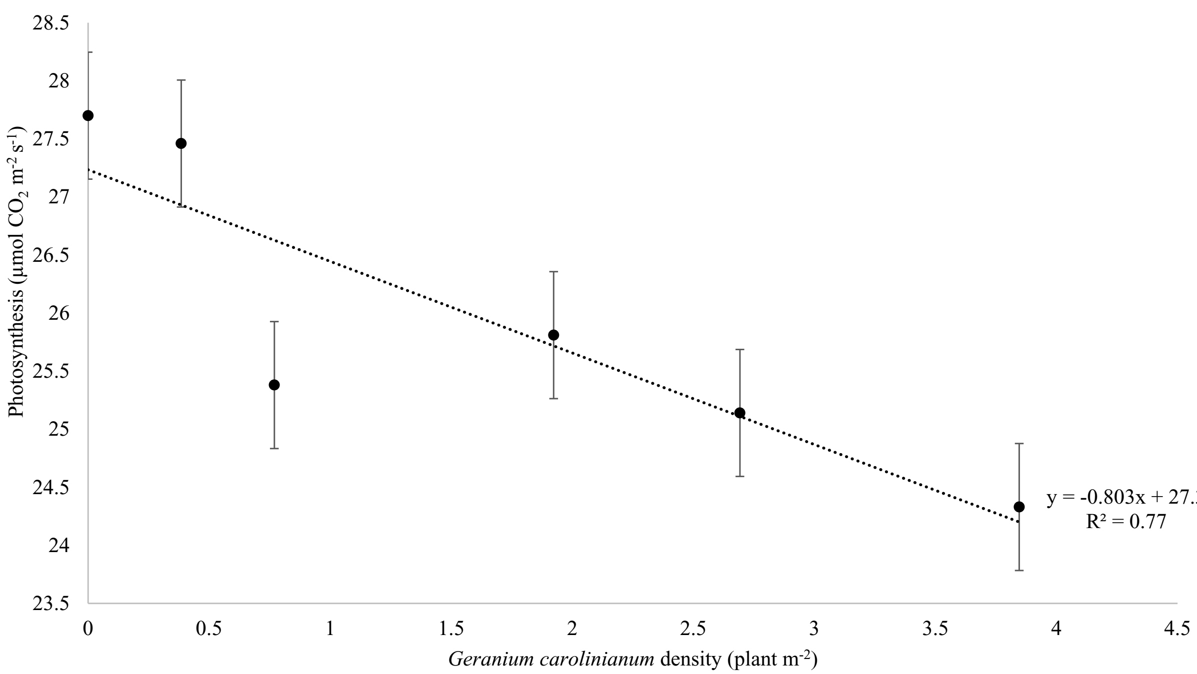

Figure 7. Effect of Carolina geranium on strawberry shoot photosynthetic rate in Season II (2021–2022). Each point is the mean of four replicates for density.

photosynthate for fruit production may partially explain the yield reductions observed in our study.

The presence of *G. carolinianum* did not significantly affect the end-of-season strawberry biomass in both seasons (Table 5). Choi (2021) reported that plants allocate energy synthesized through photosynthesis to produce more biomass, increase fruit yields, or maintain basic homeostasis. If light intensity is insufficient, the strawberry plant consumes relatively large amounts of energy to synthesize photosynthetic pigments to absorb more light to maintain biomass levels (Choi 2021). We elucidate that this may explain why fruit but not biomass was affected by the presence of *G. carolinianum*.

We conclude that the presence of *G. carolinianum* can negatively affect strawberry yield with a reduction of 554 to 935 kg fruits ha^{-1} with each increase of one *G. carolinianum* per square meter. Adequate control of *G. carolinianum* is crucial to prevent an increase in seedbanks, losses in strawberry yield, and difficulties during harvest. Future studies are needed to determine both the mechanism of competition between strawberry and *G. carolinianum* and the optimal time to remove the weeds to minimize competitive interactions.

Acknowledgments. We acknowledge the technical assistance of Mike Sweat, Laura Reuss, Emily Witt, Cecilia Lopez, and the farm crew at the Gulf Coast Research and Education Center for assistance with crop management.

Funding statement. The research was partially funded by the Florida Strawberry Research and Education Foundation.

Competing interests. The authors declare no conflicts of interest.

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