

Article

Sunflower and Sunn Hemp Potential as Summer Cover Crops in Southern Texas

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Abstract: The strategic incorporation of low-cost management practices, such as cover crops (CCs), to citrus production in southern Texas could add valuable ecosystem services that increase trees' resilience to changing climatic conditions. To provide insight into how producers can manage CCs to optimize ecosystem services, we conducted a study in controlled conditions to examine the potential of adding three annual summer CCs species: common buckwheat (*Fagopyrum esculentum*), sunflower (*Helianthus annuus* L.), and sunn hemp (*Crotalaria juncea* L.) as monocultures growing in two representative soil types of the citrus region in Texas, and receiving one of these irrigation volumes based on calculated daily water losses [i.e., evapotranspiration (ET)] corresponding to 100, 75, 50, and 25% field capacity replenishment. Sunflower and sunn hemp produced the highest aboveground dry matter, which was on average 338 and 342% greater than buckwheat. Sunn hemp emerged faster than the other CCs, and mortality was relatively uniform across CCs, but buckwheat exhibited the highest sensitivity to drought and heat distress. Sunn hemp exhibited superior aboveground biomass accumulation, height, and chlorophyll content. All CCs performed similarly in both experimental soils, under native fertility conditions, and without the addition of mineral fertilizers. Irrigation at 75 and 100% ET levels were conducive to enhanced plant growth, which indicates that a minimum of 86.4 mm (75% ET) is required during CCs lifespan, but sunn hemp and sunflower were also capable of tolerating medium (50% ET) drought stress. Overall, our findings suggest that sunflower and sunn hemp exhibited traits desirable for incorporation as CCs to a perennial citrus production system. The primary benefit was the addition of organic matter with minimum management; however, both CCs' performance was dependent on planting timing, successful early establishment, and favorable environmental conditions.

Keywords: *Crotalaria juncea* L.; buckwheat; sunflower; drought; southeastern U.S.



Academic Editors: Yoshiharu Fujii and Wei Wu

Received: 21 February 2025

Revised: 7 April 2025

Accepted: 16 April 2025

Published: 20 April 2025

Citation: Alapati, D.K.; Ancona, V.; Sétamou, M.; Donato, C.; Nelson, S.D.; Reyes-Cabrera, J. Sunflower and Sunn Hemp Potential as Summer Cover Crops in Southern Texas. *Agronomy* **2025**, *15*, 986. <https://doi.org/10.3390/agronomy15040986>

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1. Introduction

The Lower Rio Grande Valley (LRGV) located in the southern Texas plains is a productive agricultural region [1]. Its subtropical location and semiarid climate are suitable for the commercial production of citrus crops, with a value estimated at USD 65 million and cultivated in ~16,000 hectares [2]. Due to the perennial nature of citrus trees, they are continuously and concurrently exposed to a myriad of challenging climatic conditions,

and pests that progressively undermine their yield potential, requiring more external inputs to sustain profitable yield. Consequently, horticultural practices tailored to increase the resilience and sustain the yield of this high-value specialty crop are being constantly evaluated.

For example, Simpson et al. [3,4] assessed the combination of raised beds and ground covers in new citrus plantings to foster a soil microenvironment free of weeds, and conducive to minimum soil evaporation. Their results indicated that reducing evaporation could represent annual water savings of 11,000 L while maintaining fruit yield and quality. Recently, De Leon et al. [5] tested the annual application of compost to stimulate root growth, and reduce the progressive decline of mature orchards after a freezing event. They reported benefits on fruits' internal quality and root growth, which were not observed in the control treatment receiving the standard horticultural practices. Management practices like those tested by Simpson et al. [3,4] and De Leon et al. [5] aimed to support the continued cultivation of citrus under rapidly changing climatic conditions by improving soil health indicators (e.g., soil organic matter, reducing erosion, and evaporative water loss) with indirect benefits on desirable marketable traits such as fruit size, external appearance, and yield [6,7].

An additional low-cost management practice that could be beneficial for citrus trees in this region is the strategic incorporation of cover crops (CCs) to provide ecosystem services such as ground cover, organic matter, nitrogen (N) fixation, and weed suppression. Cover crop is a term to denote that a specific crop is cultivated to benefit the land where it is growing and is not for sale [8]. Cover crops are heralded as a climate-smart management practice to build more resilient agroecosystems [9], and maintain producers' incomes while enhancing their ability to adapt farming operations to a changing climate [7]. As the environmental and financial distresses of traditional farming systems intensify, CCs adoption must be carefully examined before deployment in the field. Increasing the diversity of plant species in commercial, large-scale citrus production in southern Texas has both potential benefits and drawbacks. Cover crops are deliberately selected to provide specific ecosystem services depending on the needs of the land where the cash crop (i.e., citrus) is produced.

For instance, common buckwheat (*Fagopyrum esculentum*, hereafter 'buckwheat') is a pseudo-cereal primarily cultivated in Asia, which was reported to solubilize inorganic phosphorus (Pi) present in poorly mobile Pi pools, and produce superior biomass compared with other summer CCs in subtropical regions [10,11]. Another annual species with potential as a cover crop is the domesticated sunflower (*Helianthus annuus* L.), which was reported to produce high biomass, and exhibit resilient performance under environmental stresses, spanning from mild to severe water deficit, which are common during the growing season in subtropical regions [12,13]. Similarly, sunn hemp (*Crotalaria juncea* L.) is a legume previously reported to fix $>70 \text{ kg ha}^{-1} \text{ yr}^{-1}$ of atmospheric nitrogen (N), which can be incorporated into the soil as green manure, decompose, and nutrients released for the concurrent or subsequent crop uptake [14–16], thereby supplying a percentage of the cash crop N demands, and simultaneously reducing the quantity of mineral fertilizer required. All of these CCs were reported to exhibit desirable traits with promising potential to maintain the resilience of citrus orchards in southern Texas.

However, there are concerns associated with CCs suitability in semiarid areas due to drought, and which tolerance strategy to implement, i.e., desiccation postponement (short-term capacity to maintain tissue hydrated) or desiccation tolerance, i.e., the ability to continue functioning while suffering dehydration [17]. Soils in southern Texas exhibit unique physical and chemical properties that make them challenging for the sustainable incorporation of CCs. Therefore, cover crop species must be able to establish and grow

in these soil types with minimum management. The incorporation of CCs in Texas citrus orchards is an actionable strategy that requires meticulous testing to minimize significant changes to a producer operation.

Therefore, in order to determine CCs viability to withstand the climate and native soil fertility of citrus production in Texas as well as their capacity to offer complementary benefits to these perennial trees, we conducted an experiment in controlled conditions. The objectives of this study were to (i) evaluate CCs fitness to environmental conditions common in southern Texas, (ii) determine the potential contribution of each CC to soil health, and (iii) quantify the minimum water requirement of each CC. Our hypothesis was that some CCs will exhibit superior adaptability to the growing conditions, and native soil fertility without full replenishment of their daily water losses.

2. Materials and Methods

2.1. Experimental Design

A study in controlled conditions (shade house) was conducted during 2022 and 2023 at the Texas A&M University–Kingsville Citrus Center located in Weslaco, TX (26°9′58.91″ N, 97°57′24.97″ W). Climate in the region is subtropical, with average annual cumulative precipitation of 592 mm and mean temperature of 30.0 °C [3]. The study site belongs to the Cfa climate zone (warm temperate, fully humid, hot summer) according to the Köppen–Geiger climate classification [18]. The experimental soil used for this study was taxonomically classified as sandy loam (fine-loamy, mixed, active, hyperthermic Typic Calciustolls). However, we collected soil from two locations with different physical and chemical properties (Table 1). Soil 1 (S1) was obtained from a mature grapefruit orchard in the South Research Farm (SRF, 26°8′3.16″ N, 97°57′5.67″ W) located 5 km south of the Citrus Center campus, whereas soil 2 (S2) was obtained from a young orchard planted at the Citrus Center campus (26°09′42.63″ N, 97°57′20.58″ W). Results of mineral analysis for both experimental soils are presented in Table 1. The experiment was a factorial arranged in a completely randomized design with three replications and was conducted twice (repetition 1 and 2). The first factor was cover crop species: buckwheat, sunn hemp, and sunflower. The second factor was application of four irrigation levels equivalent to 25, 50, 75, and 100% of soil-specific field capacity reference levels, which is called evapotranspiration (ET) subsequently in the text. Each irrigation level was maintained by irrigating daily and keeping each pot weight at their assigned gravimetric water content in correspondence to the ET treatment. The third factor was soil type (i.e., S1 and S2). The experiment had a total of 72 experimental units (i.e., pots).

In order to reduce variability in both soil physical properties associated with soil horizons, a uniform section of soil was collected from the upper 0 to 0.30 m soil layer, and sieved through a <2.0 mm mesh to remove large debris and organic matter with different levels of decomposition. Both soils were air dried for 11 d, homogenized, and weighed to fill pots (0.16 m diameter, 0.16 m height, 201.1 cm² area). The soil was carefully and uniformly packed in all pots. The bottom of each pot had a drainage system that allowed excess water to drain. We did not correct any nutrient deficiency because our goal was to evaluate the performance of each cover crop only with the native fertility present in each experimental soil. This methodological approach served the first step of producing relevant information to a citrus producer operation in the LRGV. Cultural practices to control insects were completed throughout the lifespan of each experimental unit. Weed control was performed manually on a regular basis. Environmental conditions (i.e., air temperature and relative humidity) inside the shade house were monitored and recorded daily for the duration of each experiment with a thermometer/hygrometer (Fisher Scientific, Pittsburgh,

PA, USA). Radiation was measured twice per day using a light meter (LightScout DLI 100, Spectrum Technologies, Inc., Aurora, IL, USA).

Table 1. Physical and chemical properties of experimental soils used in this study.

Property	SRF ^a	Citrus Center ^b
pH	7.9	8.0
P ^c	34	76
K	300	541
Ca	6200	5630
Mg	518	654
S	46	55
B	1.9	3.0
Zn	1.2	4.6
Mn	67	115
Fe	21	35
Cu	3.3	14.5
Na	247	265
Cl	48	25
SOM ^d (%)	1.1	1.7
Sand (%)	57.5	42.5
Silt (%)	29.8	46.8
Clay (%)	12.7	10.7

^a South Research Farm soil location: 26°8′3.16″ N, 97°57′5.67″ W. ^b Citrus Center soil location: 26°09′42.63″ N, 97°57′20.58″ W. ^c Macro and micronutrients are Mehlich-3 extractable levels, expressed in mg of the element by kg of soil. ^d Soil organic matter.

Planting occurred on 30 August 2022, and 22 June 2023. Five seeds of each cover crop were planted per pot, and shoot emergence was monitored and recorded daily for the subsequent ten days. Plants were thinned to one representative plant per pot on 9 and 19 days after planting (DAPs) for repetition 1 (2022), and repetition 2 (2023), respectively. Afterwards, there was a period of ten days where all plants received similar irrigation volume to ensure proper establishment. Irrigation treatments were initiated on 16 and 25 DAPs for repetition 1 (2022) and 2 (2023), respectively. Soil moisture content loss due to plant transpiration and soil evaporation (herein ‘ET’) was measured gravimetrically (i.e., pots were weighed) daily, and water was added if necessary to return the soil moisture content to the target level associated with each irrigation treatment.

2.2. Above and Belowground Plant Traits

Several phenotypical traits of interest to citrus producers were measured during CCs lifespan, which were affected by the irrigation level imposed. Plant height was measured manually with a ruler from the soil level of each pot to the most fully developed and expanded leaf. Chlorophyll index was measured by deliberately selecting a healthy leaf in the middle section of each plant that allowed us to clip the sensor. These measurements were recorded nine times each repetition, with an average interval of eight days between measurements. Data were recorded between 10:00 a.m. and 1:00 p.m. using a self-calibrating chlorophyll meter [Soil and Plant Analytical Development (SPAD), Model 502, Konica Minolta Optics, Tokyo, Japan] because the plants were well-lighted and fully active during this time of the day. Plants were harvested when visual symptoms of water deficit were severe, and aboveground tissue did not respond to irrigation for two consecutive days. These data were recorded periodically to quantify individuals’ mortality through time. Pots were transported to the laboratory, the shoot was cut off manually using scissors, and cutting at the soil base. Subsequently, a hole was dug carefully to extract intact roots followed by separation of soil and roots using a 1.0 mm sieve. Shoots were stored in paper

bags, labeled, and put in the dryer at 65 °C for a minimum of 72 h or when dry matter data were consistent, indicating no additional moisture loss. Roots were carefully placed in Kim wipes (Kimberly-Clark, Roswell, GA, USA), stored in plastic bags, and placed in a fridge at 4 °C until subsequent analysis. Roots were removed from the fridge, allowed to reach room temperature, and carefully placed in plastic trays with enough water to cover them. Afterwards, roots were manually distributed in the tray using plastic tweezers to avoid minimum overlapping. The tray was carefully placed on a digital scanner (Epson Perfection V700, Los Alamitos, CA, USA) paired with a commercial software package WinRhizo 2016 (Regent Instruments Inc., Quebec City, QC, Canada), which quantifies root length (cm), surface area (cm²), and diameter (mm).

2.3. Statistical Analysis

PROC UNIVARIATE of SAS software version 9.4 [19] was used to assess the normality of data distribution and homoscedasticity. Similarly, PROC ANOVA was used to evaluate analysis of variance among treatments. Cover crop, irrigation treatment, and soil type were considered fixed effects. Replicates, repetitions, and their interactions were considered random effects. Means were separated using Tukey–Kramer honest significant difference at the 0.05 level. When effects of repetition were not significant ($p > 0.05$), data for that specific variable from both repetitions were combined, analyzed together, and results were presented and discussed accordingly.

3. Results

3.1. Growing Conditions

Minimum air temperature was 8.5 and 21.5 °C in repetition 1 (2022) and repetition 2 (2023), respectively (Figure 1). Maximum air temperature was 39.8 and 47.0 °C in 2022 and 2023, respectively. Relativity humidity (RH) values ranged from 22.8 to 94.0% and 19.3 to 80.5% in 2022 and 2023, respectively. Photosynthetically active radiation was on average 100 and 320 $\mu\text{mol m}^{-2} \text{s}^{-1}$ during 2022 and 2023, respectively. Not surprisingly, given differences in planting date, environmental conditions, and staggered harvesting of plants of the two replications (i.e., 2022 and 2023), the replication effect was significant for every plant trait examined, except root length (Table 2).

Table 2. Summary of analysis of variance (ANOVA) for cover crops emergence, plant height, SPAD, above and belowground dry matter accumulation, and root traits: length, surface area, diameter, and calculated root–shoot (R–S) affected by treatments evaluated.

Main Effect	d.f.	Dry Matter Accumulation					Root Traits ^b			
		Emergence	Plant Height	SPAD ^a	Aboveground	Belowground	Length	Surface Area	Diameter	R–S ^c
Cover crop (C)	2	<0.0001	0.0015	<0.0001	0.0017	0.0046	<0.0001	<0.0001	0.0104	0.0002
Irrigation level (I)	3	0.0699	<0.0001	0.0215	<0.0001	<0.0001	<0.0001	<0.0001	0.0487	0.0023
Soil type (S)	1	0.1624	0.0037	0.0030	0.0059	0.8100	0.1499	0.1874	0.2413	0.7159
Repetition (R)	1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.5109	0.0488	0.0004	<0.0001
C × I	6	0.4550	0.0005	0.4842	0.0819	0.0112	<0.0001	<0.0001	0.6517	0.0101
C × S	2	0.07003	0.0129	0.3687	0.0739	0.8435	0.1187	0.0581	0.1832	0.6679
I × S	3	0.0940	0.1470	0.0092	0.0493	0.2583	0.0601	0.0721	0.6105	0.6852
C × I × S	6	0.8771	0.1665	0.0011	0.3751	0.5787	0.6854	0.4089	0.0062	0.5715

^a SPAD: soil plant analysis development. A unitless measurement of chlorophyll concentration in leaves. ^b Root traits: length, surface area, and diameter output by WinRhizo software. ^c Root–shoot: calculated root (mg) to shoot (mg) ratio. Indicator of resource use optimization [20]. Results of ANOVA test indicate significant effects on plant traits due to single treatment or treatments interaction when p -value was <0.05.

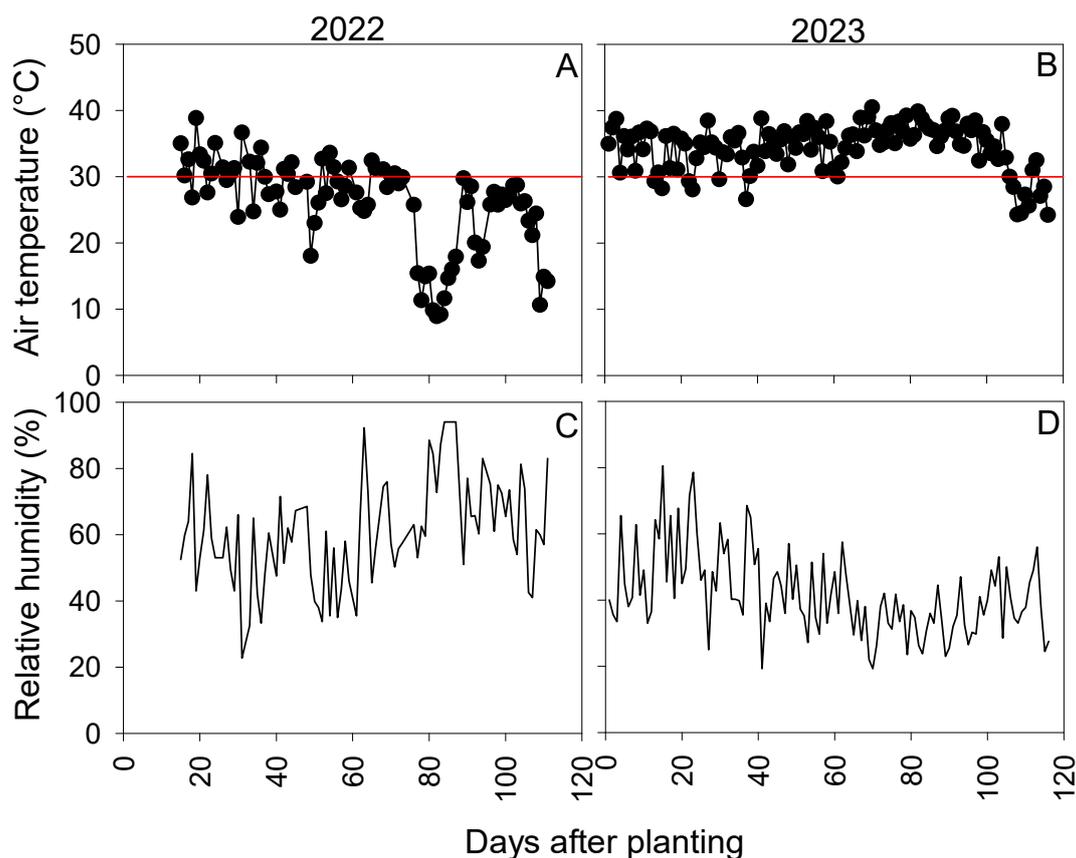


Figure 1. (A,B) Daily average mean air temperature, and (C,D) relative humidity inside the shade house in 2022 (A,C) and 2023 (B,D). Red lines in panels (A,B) indicate an air temperature threshold of 30 °C.

3.2. Aboveground Plant Traits

3.2.1. Emergence and Mortality

Sunn hemp consistently emerged promptly after planting (Figure 2). It took an average of two and five DAPs for this cover crop to emerge in repetition 1 and 2, respectively. Additionally, sunflower emerged the last, which was six and 12 DAPs in repetition 1 and 2, respectively. Buckwheat emerged four and 12 DAPs in repetition 1 and 2, respectively. In terms of mortality, there was no difference among CCs at 30, 31–60, and >60 DAPs (Figure 2). Plants receiving 25 and 50% ET irrigation treatments exhibited the highest mortality within 60 DAPs. Environmental conditions produced significant effects in each replication, especially due to the vulnerability to heat stress early during plant establishment in both years.

3.2.2. Aboveground Biomass

Sunflower and sunn hemp exhibited the highest shoot dry matter accumulation in repetitions 1 and 2, respectively (Figure 3). In repetition 1, sunflower produced 79.6 g of shoot, followed by sunn hemp with 27.0 g. Additionally, sunflower consistently produced greater aboveground biomass in all irrigation treatments compared to the other two CCs. In repetition 2, sunn hemp produced 327.7 g whereas sunflower produced 273.9 g. There were no significant differences between sunflower and sunn hemp aboveground biomass when irrigated across all ET replenishment levels. Conversely, buckwheat consistently produced the lowest aboveground biomass in both repetitions: 19.6 and 61.1 g in repetitions 1 and 2, respectively. On average, aboveground biomass was five-fold greater in repetition 2 compared with repetition 1. Additionally, there was an interaction between soil type and

irrigation level on aboveground dry matter ($p = 0.04$, Table 2). Plants produced on average 121% more aboveground biomass in the SRF soil compared with the Citrus Center soil. In both soils, there was an increasing trend of aboveground biomass production associated with water availability $25 < 50 < 75 < 100\%$ ET.

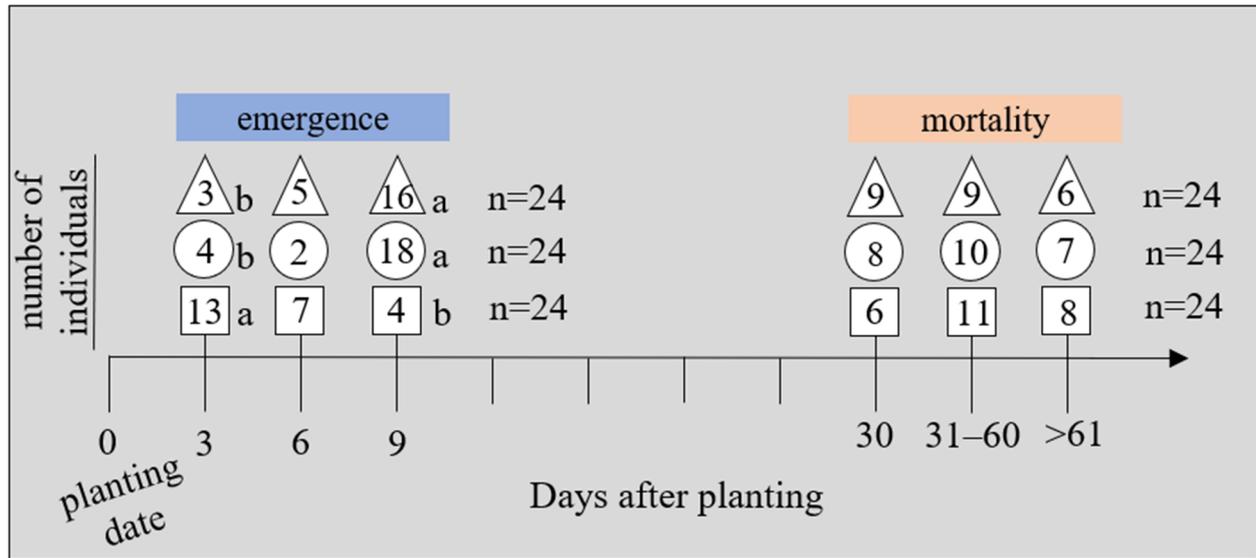


Figure 2. Illustration of cover crops (CCs) emergence (left side) at 3, 6, and 9 days after planting (DAPs); and mortality at 30, 31–60, and >61 DAPs (right side). Buckwheat (▲, $n = 24$), sunflower (●, $n = 24$), and sunn hemp (■, $n = 24$) were planted in pots in controlled conditions in the Texas A&M University–Kingsville (TAMUK)–Citrus Center located in Weslaco, TX, USA. When present, values followed by lowercase letter within DAPs indicate significant difference among CCs. No differences were detected for CC mortality. Data presented are the average of repetitions 1 (2022) and 2 (2023).

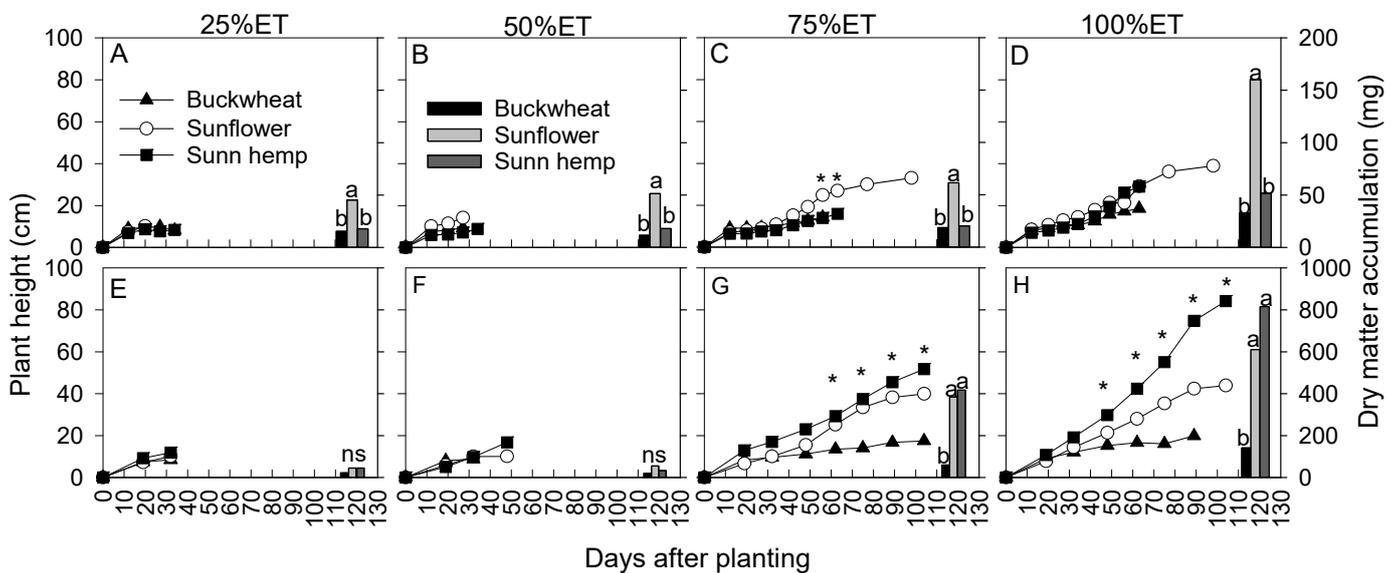


Figure 3. Plant height (lines), and dry matter accumulation (bars) of summer cover crops: buckwheat, sunflower, and sunn hemp receiving 25 (A,E), 50 (B,F), 75 (C,G), and 100% (D,H) irrigation level based on daily evapotranspiration (ET) grown in controlled conditions at the TAMUK–Citrus Center in Weslaco, TX, USA. Height values with a star (*) indicate difference among CC heights within that sampling date. Bars with different lowercase letter within irrigation treatment are different; ns indicates not significant differences. Repetition 1 (2022) and 2 are panels (A–D), and (E–H), respectively.

3.2.3. Plant Height

Cover crop species and irrigation level produced a significant effect on plant height ($p = 0.0005$, Table 2). Similarly, CCs and soil type produced an interactive effect on plant height ($p = 0.01$). Repetition produced a significant effect ($p < 0.0001$). In repetition 1, sunflower irrigated at 75 and 100% ET produced the tallest plants, which were on average 18.2 cm tall, and sunn hemp irrigated at 50% ET produced the smallest plant with 6.2 cm height (Figure 3). No differences were measured among CCs heights when irrigated either at 25 or 50% ET. In repetition 2, sunn hemp irrigated at 100% ET was on average the tallest plant with 38.9 cm, and buckwheat irrigated at 25% ET was on average the shortest plant with 7.9 cm height (Figure 3). On average, plants grew taller in the soil collected from SRF soil compared with the soil from the Citrus Center.

3.3. SPAD

There was a triple interaction among CCs, irrigation level, and soil type ($p = 0.0011$, Table 2) on SPAD, which is an indicator of leaf chlorophyll concentration. Additionally, SPAD was affected by repetition ($p < 0.001$). On average, sunn hemp irrigated at 75% ET grown in the Citrus Center soil had the highest SPAD value of 42.5 whereas sunflower irrigated at 100% ET had the lowest SPAD value of 27.9. In the soil collected from the SRF, buckwheat irrigated at 75% ET had the highest SPAD value of 40.9. Conversely, sunflower had the lowest value, equal to 30.3 when irrigated at 100% ET. In repetition 2, when CCs were grown in the Citrus Center soil, sunflower receiving 100% ET irrigation had the lowest SPAD value of 21.9, whereas buckwheat had the highest SPAD (34.6) at the same irrigation treatment. In the case of CCs growing in the SRF, sunn hemp had the highest SPAD value and sunflower the lowest.

3.4. Root Traits

There was an interaction between CCs and irrigation level ($p = 0.01$, Table 2) on root dry matter. In repetition 1 (2022), sunflower and sunn hemp irrigated at 100% ET produced 219 and 200 mg of root dry matter, respectively (Figure 4). Similarly, these two CCs produced comparable root dry matter values of 57 mg on average when irrigated at 75% ET. There was no difference between these two CCs at any irrigation level during this repetition (Figure 4). In repetition 2 (2023), sunn hemp showed a consistent trend for superior root dry matter production when irrigated at 75 and 100% ET levels (Figure 4). Sunn hemp produced on average 35.2 mg of root dry matter either with 75 or 100% ET irrigation treatments. This result was on average 25- and 2-fold greater than the root dry matter of buckwheat (1.67 mg) and sunflower (18.5 mg), respectively, irrigated at 75% ET, and 10-fold greater than buckwheat root dry matter (3.5 mg) receiving 100% ET irrigation. Conversely, buckwheat produced the lowest root dry matter in both repetitions (Figure 4). Buckwheat produced on average 7.8 and 0.87 mg of root dry matter when irrigated at 50 and 25% ET in repetition 1 and 2 of the trial, respectively.

Root length was affected by CC and irrigation level ($p < 0.0001$, Table 2). Sunn hemp irrigated at 100% ET produced the largest root length, which was on average 457% greater than the rest of CCs across all irrigation level treatments (Table 3). There was a significant interaction between cover crop and irrigation level on root surface area ($p < 0.0001$, Table 2). Similarly, root surface area was affected by experiment repetitions ($p = 0.04$, Table 2). In repetition 1, roots of sunflower and sunn hemp exhibited the highest surface area, which was on average 311% greater than buckwheat root's surface area (Table 3). Root surface area values were 2.3, 3.0, 4.2, and 11.0 cm² for irrigation levels 25, 50, 75, and 100% ET. In repetition 2, the root surface area of CCs was on average 81% greater in the SRF soil compared with the soil from the Citrus Center.

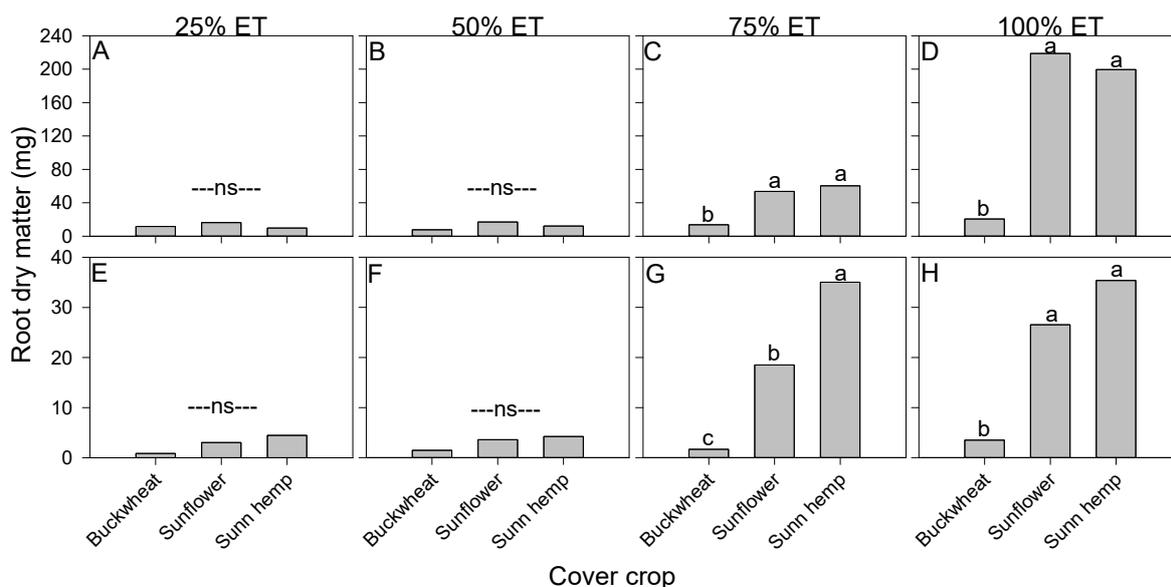


Figure 4. Root dry matter of summer cover crops buckwheat, sunflower, and sunn hemp receiving 25 (A,E), 50 (B,F), 75 (C,G), and 100% (D,H) irrigation level based on daily evapotranspiration (ET) grown in controlled conditions at the TAMUK-Citrus Center in Weslaco, TX, USA. Bars with different lowercase letters within irrigation level are statistically significant. ns indicates not significant differences.

Table 3. Root length (cm), root surface area (cm²), and diameter (mm) of three summer cover crops: buckwheat (BW), sunflower (SF), and sunn hemp (SH) affected by irrigation treatments (25, 50, 75, and 100% ET) and soil type (SRF: South Research Farm or Citrus Center soil). The experiment was repeated twice [repetition 1 and 2: 2022 and 2023, respectively] under controlled conditions in Weslaco, TX, USA.

Repetition	Main Effect	Root Length (cm)			Surface Area (cm ²)			Root Diameter (mm)		
		BW	SF	SH	BW	SF	SH	BW	SF	SH
1	Irrigation									
	25	20.38 a ^a	42.99 b	19.04 c	1.34 b	3.76 b	1.89 b	0.21 a	0.28 b	0.32 a
	50	19.16 a	61.32 b	31.21 c	1.34 b	4.54 b	3.20 b	0.27 a	0.24 b	0.34 a
	75	27.85 a	45.70 b	83.19 b	1.91 a	3.98 b	6.79 b	0.23 a	0.34 b	0.31 a
	100	35.84 a	127.58 a	209.09 a	2.11 a	15.49 a	15.26 a	0.21 a	0.51 a	0.25 a
	Soil type									
	SRF	27.61 a	70.02 a	78.09 b	1.80 a	5.77 a	6.11 a	0.25 a	0.29 a	0.28 a
	Citrus Center	24.00 a	68.78 a	93.18 a	1.54 a	8.12 a	7.47 a	0.21 a	0.40 a	0.33 a
2	Irrigation									
	25	6.49 b	28.99 c	29.20 c	0.69 c	3.06 b	3.11 c	0.34 a	0.37 a	0.35 b
	50	12.61 a	24.95 c	36.19 c	1.21 b	3.18 b	3.79 c	0.33 a	0.40 a	0.33 b
	75	19.86 a	59.51 b	159.45 b	1.92 b	7.46 b	17.84 b	0.32 a	0.39 a	0.40 b
	100	24.56 a	94.42 a	298.28 a	2.49 a	12.29 a	30.32 a	0.36 a	0.42 a	0.70 a
	Soil type									
	SRF	14.46 a	51.36 a	185.10 a	1.47 a	6.82 a	19.85 a	0.35 a	0.41 a	0.57 a
	Citrus Center	17.29 a	52.57 a	76.46 b	1.69 a	6.17 a	7.69 b	0.35 a	0.37 a	0.33 a

^a Values followed by different lowercase letters within repetition, and main effects of irrigation and soil type, are different at $p = 0.05$ level of significance using Tukey-Kramer honest significant difference.

Root diameter of CCs was affected by a triple interaction among cover crop species \times irrigation level \times soil type ($p < 0.0001$, Table 2). In repetition 1, sunflower growing in Citrus Center soil irrigated at 100% ET had an average root diameter of 0.70 mm, which was 154% greater than the other CCs cultivated in any of the combinations between the experimental soils and irrigation levels (Table 3). In repetition 2, sunn hemp growing in the SRF soil at 100% ET exhibited the highest average root diameter of 1.09 mm, which was

202% greater than the average root diameter of all other CCs across soil types and irrigation levels. Similarly, sunn hemp growing in the SRF soil at 75% ET exhibited 52% greater root diameter than buckwheat growing in any of the two experimental soils irrigated at 50, 75, and 100% ET irrigation levels.

The calculated root to shoot ratio (R–S), which is an indicator of resource use optimization [20], was affected by an interaction between CCs and irrigation level ($p = 0.01$, Table 2). Similar trends were observed for sunn hemp irrigated at 50, 75, or 100% ET in repetitions 1 and 2. Sunn hemp had on average a 52, 188, and 207% greater R–S, respectively, compared to the other two CCs. Conversely, when CCs were irrigated at the 25% ET irrigation treatment, buckwheat exhibited on average 118 and 28% greater R–S than sunflower and sunn hemp, respectively. R–S values were on average 33 times greater in repetition 1 compared with repetition 2, indicating that plants growing in repetition 1 (2022) allocated more carbon to belowground than aboveground biomass.

3.5. Water Dynamics

Crop establishment was characterized by application of similar irrigation volume to all treatments. This period lasted 13 and 35 days in 2022 and 2023, respectively (Figure 5). Following this period, irrigation treatments were initiated. The volume of irrigation increased in the order of 25 < 50 < 75 < 100% ET treatments. In repetition 1 (2022), the corresponding average irrigation for 25, 50, 75, and 100% ET treatments was 0.5, 1.5, 26.9, and 57.3 mm, across all CC and soil type treatments. In repetition 2 (2023), the corresponding average irrigation for 25, 50, 75, and 100% ET treatments was 1, 23, 145, and 223 mm across all CC and soil type treatments. Neither 25 or 50% ET irrigation treatments appeared to suffice any of these CC water demands.

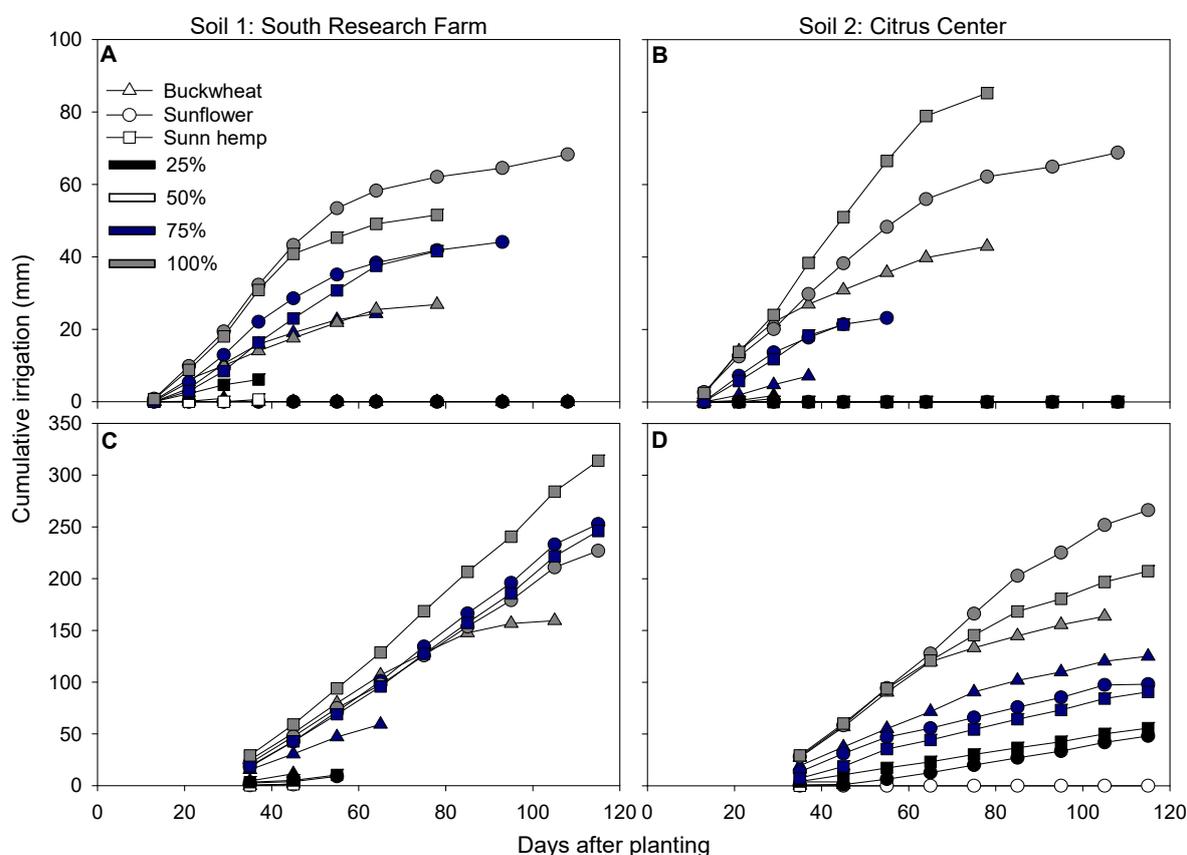


Figure 5. Cumulative irrigation of summer cover crops after initial plant establishment. Buckwheat (\blacktriangle), sunflower (\bullet), and sunn hemp (\blacksquare) received either 25% (black-filled symbols), 50% (white-filled

symbols), 75% (blue-filled symbols), or 100% (gray-filled symbols) water to replenish losses calculated gravimetrically, which were determined to represent crop evapotranspiration (ET) during 2022 (A,B) and 2023 (C,D) growing seasons. Plants received similar irrigation volumes during establishment, which was 16 and 25 days after planting in 2022 and 2023, respectively.

4. Discussion

The present study investigated the above and belowground growth dynamics of three summer cover crops (CCs): buckwheat, sunflower, and sunn hemp cultivated on two representative soils of the Texas citrus region without the addition of mineral fertilizers, and irrigated with one of the following levels: 25, 50, 75, and 100% evapotranspiration (ET) based on the soil field capacity (g g^{-1}) replenishment of periodic water losses. One objective of this research was to determine the fitness of these summer CCs to the harsh environmental conditions common in southern Texas. Furthermore, CC above and belowground biomass production with minimum management must be adequate to elicit positive results on soil indicators of health (e.g., organic matter) and the potential incorporation to current citrus production systems in subtropical regions [7,21]. Sunn hemp and sunflower produced the highest aboveground biomass, which responded positively to increments in water (i.e., irrigation) availability. All CC species were able to establish in both soil types, but only sunflower and sunn hemp grew to an average of 116 DAPs without fertilization.

Sunn hemp's ability to survive and produce high aboveground biomass under high ($>30\text{ }^{\circ}\text{C}$) air temperature during the growing season was consistent with previous experiments [22]. Sunn hemp's ability to grow in soils with poor to moderate fertility (Table 1) was primarily due to its strong tap root and robust radicular system. Additionally, the distinctive trait of nitrogen (N) fixation helps to explain its rapid growth compared to the other two CCs [23]. The use of N-fixing species as CCs is an attractive practice to reduce the reliance on mineral fertilizers and nitrous oxides emissions from citriculture [24]. Therefore, there is a need to estimate the N supplying capacity of sunn hemp to the soil on an annual basis. Sunn hemp produced long roots and when irrigated, $> 75\%$ ET also produced roots with high surface area and diameter values, which suggest an adequate allocation of resources to support the construction costs of belowground biomass.

Previous studies indicated that sunflower has intermediate water use, and is well adapted to many regions of the U.S. [25]. In our study, sunflower was observed to tolerate dry conditions and its phenotypical traits (e.g., height, SPAD, biomass production) were similar to the top-performing sunn hemp. Moreover, sunflower performed satisfactorily in both experimental soils, but providing adequate soil moisture at planting is critical for sunflower germination and establishment. Sunflower invested in root length and surface area construction costs, which may have improved plant performance. Plants' resource allocation to root construction costs was primarily driven by water availability and not soil type.

Buckwheat was the inferior performing cover crop. Aboveground vegetative growth was severely impaired by deficit irrigation treatments (i.e., 25, 50, and 75% ET), and hot ($>30\text{ }^{\circ}\text{C}$) air temperatures prevalent in both repetitions. Our results differ from those reported by Martinez-Goni et al. [26]. They grew buckwheat in controlled conditions of $24.6/21\text{ }^{\circ}\text{C}$, and RH of 68/77% for day/night periods, respectively, and found that buckwheat was capable of maintaining adequate photosynthetic capacity under the imposed severe drought treatments. Conversely, we observed similar responses of buckwheat to water stress as those reported by Aubert et al. [27]. These authors reported that buckwheat decreased leaf area and gas exchange when irrigated at 20% of soil field capacity in comparison with the control at 45% field capacity. In addition to water stress, we suspect that environmental conditions in our experiments with predominant air temperature $> 30\text{ }^{\circ}\text{C}$

and RH exceeding 80% severely impaired buckwheat performance. Hunt et al. [28] reported that buckwheat is well adapted to temperate zones, but also capable of thriving in mild to moderate environments (air temperature = 24.6/21 °C, and RH of 68/77% for day/night periods, respectively) like those imposed in Martinez-Goni et al.'s [26] experiment. Of the three CCs investigated in this research, buckwheat exhibited on average low root length and surface area across all irrigation levels (Table 3) in comparison with the other CCs. This result indicated buckwheat's low drought tolerance, which comes at the expense of plant growth, and the need for refinement strategies to deploy this cover crop in field settings. Despite these shortcomings, there is scientific interest in further exploring and optimizing buckwheat use as a cover crop in subtropical regions with alkaline soils due to its ability to solubilize calcium-bound phosphorus in the soil, which could facilitate the bioavailability and uptake of this essential nutrient for the concurrently growing cash crop, although buckwheat may not reach full vegetative growth.

Several factors determine CC success. In southern Texas conditions, the ability to germinate promptly, establish and thrive with minimum inputs, and reach a modest plant height (<1 m tall) are plant phenotypical traits that could benefit perennial citrus (e.g., grapefruit or oranges) production. These are the top considerations of citrus producers to support the adoption of CCs in their operations. Our experimental approach facilitated adequate soil moisture to ensure CCs germination and emergence, which in practice could be achieved by planting CCs after an irrigation or rainfall event. This timely planting is critical to obtain uniform establishment, which will directly influence the magnitude of CCs ecosystem services. Citrus production in southern Texas is primarily rainfed, and the crop is irrigated at key phenological stages or when municipal watering restrictions allow irrigation, which primarily is completed during periods of high evaporative demand (May–September), and prior to fruit expansion. Therefore, caution is warranted to avoid thirsty CC species that may compete for water with the cash crop, and ensure those selected are capable of thriving and surviving under water deficit conditions.

We did not fertilize the soil. This decision allowed us to mimic the potential management strategy a citrus producer could pursue in their operation when planting CCs. All CCs were able to establish in both soil types regardless of differences in physical and chemical properties (Table 1). This is an important result, which suggests that there is opportunity to accommodate these summer CCs to present fertility levels of soils where citrus is produced in Texas. Moreover, we did not observe any visual sign of nutrient deficiency that limited plant growth, and newly produced roots of these CCs can forage existing soil resources and recycle these nutrients through their biomass and subsequent addition of organic matter at termination [9]. Cover crops' performance without fertilization could be interpreted as a positive outcome, because it shows their potential to adapt to current macronutrient fertilization strategies for orchards, but caution is warranted for possible micronutrient deficiency since most micronutrients are foliar-applied to trees, which will lead to CCs depleting the existing soil reserves of these essential nutrients.

Summer CCs must exhibit strong resilience to adverse, and sometimes extreme, environmental conditions. Changing regional climatic conditions are creating unfavorable growing conditions such as hot (>30 °C) air temperatures, and limited water supply, that lie outside the range of past historic weather patterns [29]. In southern Texas, heat waves and short- and medium-term droughts are increasing in frequency and intensity. The average air temperature has increased by up to 1.7 °C in the last decades [30,31] compared to the 30-year norm, with warm daily extremes occurring more frequently in a changing climate, and is expected to continue to increase in the future [32,33]. Therefore, summer CCs must tolerate and successfully acclimate to the disadvantageous environmental conditions of this agricultural area with minimum irrigation. Plant species have different responses to

variation in warming and water stress [34]. For instance, Kumar et al. [35] reported that plants adapt to heat and drought stress by adjusting their developmental reprogramming, through shedding leaves or early flowering, which was observed in our study for sunflower and sunn hemp. These leaves represent nutrient-rich biomass that recycles nutrients into the soil [36,37]. In contrast, buckwheat exhibited limited ability to abscise leaves, which diminished its survival in both repetitions of the study. Plants prematurely dropping leaves affects plant height, since there is a diminished leaf area fixating carbon. Plant height plays a key role in determining resource capture and productivity. Moreover, it is important to avoid the potential aggressive “weedy” behavior of CCs in the field; thereby, height is a trait that can inform producers about the timely termination of CCs species in the field [38]. Tall plants growing near citrus trees are undesirable in the field because they hinder regular orchard management practices. Additionally, water stress has different effects on SPAD (i.e., leaf chlorophyll content). Some researchers report an increase [39,40] while others report a decrease [41], and still, others observe no change [42] in the chlorophyll levels under water stress. The triple interaction of the treatments evaluated on SPAD suggests the high variability of this plant trait with the legume (sunn hemp) trending above the other two CCs studied.

The incorporation of summer CCs to citrus orchards in southern Texas and other subtropical regions will primarily depend on the producer’s goal for their farm, but it has clear benefits such as a reduction in topsoil erosion during rainfall [9] and high-speed wind events [36,43]. Achieving and replicating success when summer CCs are incorporated in citrus production may not be straightforward. However, multiple efforts to reduce external inputs and create intermediate-input citrus production intercropped with CCs might balance economic and environmental performance by tailoring inputs to the system needs [44,45]. Advancing the successful adoption of CCs in citrus orchards requires reliable data about the provision of ecosystem services these crop species might accomplish as well as their responses to environmental change and management factors. Overall, our evidence suggests that benefits associated with CCs on agroecosystem services were heavily influenced by crop species, water availability, and climatic conditions during the duration of each repetition.

5. Conclusions

The proper selection of cover crop (CC) species is a crucial decision that determines their adaptability and potential to provide ecosystem services. This study showed that sunn hemp and sunflower irrigated with a minimum replenishment of 75% evapotranspiration losses (ET) during their growing season exhibited adaptability (i.e., limited biomass production) and potential to withstand harsh environmental conditions typical of southern Texas. Similarly, both CCs successfully germinated, emerged, and established for a minimum of 60 days after planting, relying exclusively on soil’s native fertility without additional fertilizer application. Buckwheat performed poorly under the drought treatments and environmental conditions of this study, which indicated minimum potential for subsequent field evaluation. There are challenges to the successful implementation of CCs in field settings not evaluated in this study under controlled conditions. However, this study is a valuable first step in the identification of summer CC species that could be advantageous to citrus production with the aim to offer guidance to producers on optimizing species selection and management. The next step is expanding this experimental design to field conditions.

Author Contributions: Conceptualization, J.R.-C.; Methodology, D.K.A. and J.R.-C.; Formal analysis, D.K.A. and J.R.-C.; Investigation, D.K.A. and J.R.-C.; Resources, J.R.-C.; Data curation, J.R.-C.; Writing—original draft, D.K.A. and J.R.-C.; Writing—review & editing, V.A., M.S., C.D., S.D.N. and

J.R.-C.; Supervision, J.R.-C.; Project administration, J.R.-C.; Funding acquisition, C.D., S.D.N. and J.R.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This project was partially supported by the National Science Foundation Centers of Research Excellence in Science and Technology (NSF-CREST)—Sustainable Water Use (SWU project) NSF CREST Award No. 1914745, and Texas Citrus Producers board award no. 571257.

Data Availability Statement: Data is contained within the article.

Acknowledgments: The authors thank former members of the Cabrera lab that helped with the experiment setup, sampling, and data collection. Special thanks to Jorge L. Jimenez for his contribution to experiment organization and management.

Conflicts of Interest: The authors declare no conflict of interest.

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