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Enhanced Nutrition Programs to Rehabilitate Freeze-stressed Citrus Trees in Subtropical Regions

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Abstract. Citrus **spp. trees are not fully dormant during the winter months in the northern hemisphere; therefore, they are susceptible to sporadic freeze events of various magnitudes that could decline tree productivity or be lethal. In Feb 2021, winter storm Uri produced freezing air temperatures for nearly 72 hours, which created several degrees of injuries to citrus orchards in southern Texas. Producers in the area implemented combinations of multiple horticultural practices aimed at remediating injuries from the cold spell to stimulate root and tree recovery. However, there is a gap in our understanding of how practices such as compost application (CA) combined with varying rates of nitrogen (N) might facilitate tree recovery. Therefore, we conducted a 2-year field experiment using two CAs as soil amendments in combination with three N rates (112, 168, and 224 kg·ha^{-1} N) to evaluate fruit yield and internal quality, root growth, and recovery of 'Rio Red' grapefruits (*Citrus ×paradisi* Macf.) and 'Marrs' sweet oranges (*Citrus sinensis*). The yields of both crops exhibited modest improvement with CA in 2022; however, it was nonsignificant. Moreover, CA elicited more beneficial effects than N rates alone when rehabilitating trees and improving fruit internal quality after freezing events. Grapefruit brix was 4% higher in fruits harvested from trees treated with compost, and grapefruit roots exhibited a two-fold dry weight increment with CA. Sweet oranges from trees in the CA treatment had 22% lower acidity compared with that of untreated trees. Overall, our results indicate that citrus producers in southern Texas and other subtropical citrus-producing regions might facilitate the rehabilitation of tree injuries attributed to mild to moderate freeze events with moderate financial gains with the timely application of compost, which enhanced tree fitness and ameliorated fruit productivity declines during subsequent harvests.**

Citrus spp. is a highly valued horticultural commodity. Texas is the third largest citrus-producing state in the United States, and with 7300 ha bearing fruit in the Lower Rio Grande Valley (LRGV), it accounts for 2% of the total US citrus production and represents an estimated crop value of $37 million (NASS 2022). The subtropical and semi-arid climate in the southern plain regions of Texas is suitable for the production of several citrus crops, but producers have historically favored grapefruits (*Citrus ×paradisi* Macfad. var. Rio Red) and oranges (*Citrus sinensis*) because of their profitable market value, adaptability to local soil conditions, and moderate horticultural care practices (Nelson et al. 2011, 2013). Environmental conditions in southern Texas are increasingly different from the recorded historic patterns. The rainfall variability, cold spells, large number of days exceeding 37.8 °C, and high wind speed during sensitive citrus trees phenological stages such as flowering, fruit setting, and fruit maturation are common (Nielsen-Gammon 2011; Runkle et al. 2022). Moreover, severe cold weather is a continuous threat to citrus trees during the winter months (December–March) in these subtropical areas of the United States, and the high susceptibility of fruit to low air temperatures in the late maturing stages is also a threat. However, if the duration of the low temperatures is short (i.e., less than 24 h), then trees will not suffer extended damage and could recover with a combination of horticultural practices that rehabilitate trees and stimulate productivity (Zekri et al. 2016). Conversely, if air temperatures below −2.2 °C exceed more than 24 h, and if low temperatures at night <0 °C are present, then vascular tissue damage and tree mortality could occur (Inch et al. 2014). The citrus region in Texas has mild to moderate winters and air temperatures that range from 7 to 29 °C; however, the aforementioned changing climatic conditions have increased the likelihood and duration of cold spells. Most commercial grapefruit and orange cultivars are susceptible to prolonged low air and soil temperatures, and tree resilience to freezing temperatures depends on the cultivar grown, ecoregion, duration of exposure to freezing temperatures, wind speed, and rate of temperature changes before and after the freeze (Inch et al. 2014).

In the United States, other citrus-producing regions have experienced sub-zero air temperatures, and the results of their experiences demonstrated the importance of adequate plant nutrition and irrigation practices to facilitate aboveground and belowground recovery of tree functions (Obreza et al. 2020). For example, the Florida citrus region has experienced several freeze events since the 1980s that reduced their citrus acreage (Inch et al. 2014; Louzada and Ramadugu 2021) and provided an opportunity to evaluate several horticultural practices to protect trees from freeze damage. For instance, microsprinkler irrigation is a viable strategy of protecting young trees, especially the graft union of rootstock and scions (Paramasivam et al. 2001). Moreover, research conducted recently by Makam et al. (2023) illustrated the value of enhanced nutrition programs (ENPs), which are defined as the implementation of refined macronutrient and micronutrient fertility recommendations to ameliorate the effects of biotic and abiotic stressors of citrus trees in a particular growing region (Stansly et al. 2014). Timely execution of ENPs offers producers options to minimize the negative impact of freeze damage in citrus orchards while simultaneously increasing nutrient use efficiency (Obreza and Morgan 2020). Similarly, compost applications (CAs) to amend the soil have been reported to stimulate tree root growth by increasing soil organic matter that could expedite tree recovery when freeze damage was moderate (Lecompte et al. 2005; Navarro et al. 2020; Nelson et al. 2008; Uckoo et al. 2009).

The Texas citrus region experiences sporadic cold events ranging from moderate to severe. For instance, in mid-Feb 2021, citrus orchards in the LRGV suffered from prolonged freezing temperatures for approximately 48 h as a result of winter storm Uri, and some of the orchards experienced temperatures as low as –7.2 °C (Glazer et al. 2021; Louzada and Ramadugu 2021). The timing of the storm caused immediate crop loss of a majority of fruits remaining on the trees in 2021, and it also led to young fruit drop and loss of fruit bud development for much of the following year's harvest in 2022 (Schattenberg 2021).

Because commercial cultivation of citrus crops migrates northward to regions with temperate-like climates free of the devastating huanglongbing disease, there is growing interest among citrus stakeholders to gain a better understanding of horticultural practices that increase citrus resilience to freezing temperatures. Our limited knowledge of managing and responding to severe weather or climate change-related events that affect perennial crops such as citrus (Williams et al. 2008) indicates that on-farm investigations of ENPs and CA may provide producers with more tools to prepare for episodes of prolonged winter freezes in citrus orchards as well as facilitate tree recovery from the detrimental effects of freeze damage. Citrus producers at the border between subtropical and temperate regions with an emergent citrus industry could benefit from information regarding nutrient management strategies that mitigate cold stress on trees. Therefore, the objectives of this study were to assess the effects of ENPs on freeze-affected citrus fruit yield and quality, determine whether CA is a potential post-freeze field management strategy that can facilitate tree recovery, and estimate the economic impact that a winter storm has on fresh fruit. We hypothesized that CA will increase the yield of freeze-stressed citrus trees 2 years after the freeze event. Our goal was to assist citrus producers in subtropical ecoregions with in-field management strategies by characterizing citrus trees responses to ENPs and CA after cold stress.

Materials and Methods

Study site and experimental design. A field study was conducted during two years (2021 and 2022) in two 2.8-ha plots of 'Rio Red' grapefruit (*Citrus ×paradisi* Macfad. var. Rio Red) trees and 'Marrs' sweet orange (*Citrus sinensis*) trees grafted on sour orange (*Citrus ×aurantium*) rootstocks. The crops were located at the Texas A&M University–Kingsville Citrus Center in Weslaco, TX (26°09′51″ N, 97°57′23″ W), and both orchards were planted in 1991 on sandy clay loam (fine-loamy, mixed, active, hyperthermic Typic Calciustolls). However, the grapefruit orchard was planted in a 7- × 5-m grid (280 trees/ha), whereas the sweet orange orchard was planted in a 7- × 4-m grid (350 trees/ha). Each orchard was divided into three blocks of equal size (1.01 ha for sweet orange and 0.79 ha for grapefruit) and within blocks, we selected the three center rows to apply treatments, which left buffer rows between treatments to minimize confounding effects (Fig. 1). In-field horticultural practices such as micronutrients fertilization and tree care (i.e., crop protection, hedging, pruning) followed conventional practices by producers in the area. The climate of the area is characterized as subtropical, with an annual cumulative precipitation of 685 mm and mean temperature of 30 °C.

The trial was arranged in a randomized complete block design. The ENP consisted of refined N rates. Accordingly, main plots received one of three doses of granular N rates per hectare [112 kg·ha^{-1} N (T1 = 1×), 168 kg·ha^{-1} N (T2 = 1.5×), and 224 kg·ha^{-1} N (T3 = 2×)], and sub-plots consisted of a single annual rate (11 Mg·ha^{-1} = 5 tons/acre) of CA. The T1 without CA was considered the control treatment because it was identical to the N rate used by citrus producers in the area. There was a maximum of 48 and 60 trees per experimental plot for grapefruit and sweet orange crops, respectively. Fertilizer blends primarily consisted of urea (46–0–0), monoammonium phosphate (10–50–0), and potassium sulfate (0–0–50). Two main fertilization events occurred during 3 Aug 2021 [162 d after storm (DAS)] and 18 Mar 2022 (389 DAS). Compost was obtained from an organic citrus farm located in Mission, TX, USA (54 km away from the research site). A compost subsample was collected, oven-dried at 65 °C, and analyzed to determine the chemical composition. Results of this analysis are presented in Table 1. The CA was mechanically broadcasted to the grapefruit and orange orchards on 9 Aug 2021 (168 DAS), similar to local citrus producers' practices. During the second CA, we used approximately 30 kg compost/tree, which was manually distributed underneath the canopy of 36 trees in a radius 0.3 m away from the tree trunk on 24 Mar 2022 (395 DAS). The difference in the delivery method between years was attributable to malfunctioning of the spreader and the need for a timely CA (i.e., treatment imposition). All plots received 25.4 mm of water through flooding after fertilizer applications and CAs to minimize wind erosion of the material and facilitate infiltration.

Soil and root analyses. The initial composite soil samples were manually collected

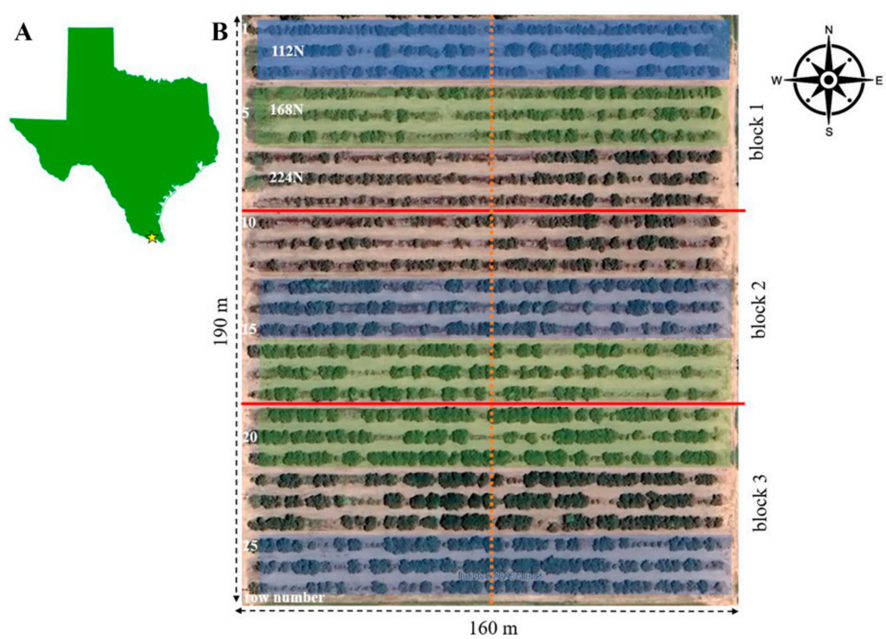

Fig. 1. (A) Yellow star indicates orchards located at the TAMUK Citrus Center in southern Texas. (B) Map of the 'Marrs' sweet orange experiment indicating enhanced nutrition programs: 112 (blue rectangle), 168 (green rectangle), and 224 (clay rectangle) kg·ha^{-1} N applied. Red horizontal lines indicate block boundaries. Each block had a total of nine rows. The orange vertical dotted line indicates the east-west boundary, which was used for broadcast compost applications (CAs) on the east sides of blocks 1 and 3 and west side of block 2 in Aug 2021 and Mar 2022.

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Table 1. Chemical analysis of compost used in the field study[i].

Parameter	Unit	Value
Nitrogen	$g \cdot kg^{-1}$	15.9
Phosphorus	$g \cdot kg^{-1}$	9.2
Potassium	$g \cdot kg^{-1}$	16.7
Calcium	$g \cdot kg^{-1}$	53.1
Magnesium	$g \cdot kg^{-1}$	8.7
Sulfur	$g \cdot kg^{-1}$	6.8
Iron	$g \cdot kg^{-1}$	5.1
Sodium	$g \cdot kg^{-1}$	9.0
Zinc	$mg \cdot kg^{-1}$	396.1
Copper	$mg \cdot kg^{-1}$	76.2
Manganese	$mg \cdot kg^{-1}$	372.6
Boron	$mg \cdot kg^{-1}$	68.8
pH		8.1

[i]The compost mineral content was determined by a laboratory analysis. The same compost was used during both years.

using a soil auger and probe at a depth of 0.17 m from 18 random locations in grapefruit and sweet orange orchards on 5 Jul 2021 (133 DAS) to quantify baseline soil fertility before treatment applications (Table 2). To assess the effects of ENPs and CAs on soil properties, soil samples were taken from a location near (0.5 m apart) the initial cores 18 months after treatment applications (Table 2). Soil cores were mixed to create a composite pool, homogenized, sieved to pass a 2-mm screen, and analyzed to determine N using the combustion method. To determine the soil pH and EC, samples were air-dried and ground to pass through a 2-mm sieve. Soil pH was measured using 1:1 wt/wt soil:water slurry (Schofield and Taylor 1955). Plant-available phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), boron (B), zinc (Zn), manganese (Mn), and copper (Cu) were extracted using the Mehlich-3 procedure (Mehlich 1953); iron (Fe) and sulfur were extracted with dilute acid. The total carbon and total N levels were measured using the combustion method.

On 1 Mar 2023 (737 DAS), one tree per treatment in the center row was randomly selected to evaluate root growth and distribution in experimental areas that only received ENPs and areas that received ENPs and both variations of CAs. Eighteen root samples were taken from all treatment areas in the grapefruit orchard. These samples were used to compare the effects of fertilizer and compost trials on root density in the grapefruit orchard. Root samples were manually collected using a 100.2-mm internal diameter soil auger at a 0.17-m depth to assess secondary (>2.0 mm) and tertiary (<2.0 mm) roots. Zobel (2005) considered roots smaller than 0.6 mm as a separate tertiary level; however, for the ease of manually separating soil and roots, we deliberately defined tertiary roots as those passing through a 2.0-mm sieve. Roots entangled in soil aggregates were manually separated, sieved through a 2.0-mm sieve, and carefully extracted with forceps. Fresh roots (secondary and tertiary) were weighed independently to quantify the roots present in each sample. Additionally, the total weight was recorded to compare the effectiveness of the experimental treatment on increasing citrus tree root growth.

Yield and internal fruit quality. Two representative trees per treatment were manually harvested in each season on 15 Dec 2021 (296 DAS) and 13 Dec 2022 (659 DAS) for 'Rio Red' grapefruits and 'Marrs' sweet oranges. Fruits were transported to the Citrus Center warehouse to be mechanically sorted by cultivar and size classes for each fruit type and stored in paper bags until juice quality was ready to be evaluated. Ten randomly selected fruits were taken from each treatment, cut transversally, and squeezed using an electric juicer. Juice was manually mixed in a container until it was homogenous. Subsequently, a 100-mL sample was collected from the solution to measure the brix and acid percentage using the digital Atago PAL-1 brix acidity refractometer (Atago Co., Saitama, Japan). After the brix result was obtained, 1 mL of citrus juice was pipetted into a separate beaker and then diluted with 49 mL of distilled water for a 50:1 dilution ratio. The diluted juice was titrated against a standard 0.1 mol/L NaOH solution to determine the acid percentage. The juice sugar:acid ratio was calculated using this data (El-Zeftawi et al. 1982).

Table 2. Soil chemical properties at baseline before treatment (5 Jul 2021) and 18 months after the treatment application (1 Mar 2023) averaged using a per-treatment basis (n = 3).

Property	Unit	Before treatment	After treatment
pH		8.2 a	7.9 b
EC[i]	dS/m	0.2 a	0.1 b
OM	%	2.2 a	2.2 a
N	%	2.5 a	2.1 a
P	$mg \cdot kg^{-1}$	42.3 b	141.5 a
K	$mg \cdot kg^{-1}$	420.3 b	489.7 a
Ca	$mg \cdot kg^{-1}$	4,047.7 b	6,388.6 a
Mg	$mg \cdot kg^{-1}$	536.7 b	615.4 a
S	$mg \cdot kg^{-1}$	74.1 a	78.1 a
Na	$mg \cdot kg^{-1}$	127 b	178.6 a
Zn	$mg \cdot kg^{-1}$	1.7 a	2.6 a
Fe	$mg \cdot kg^{-1}$	10.4 a	5.7 b
Cu	$mg \cdot kg^{-1}$	8.1 a	5.0 b
Mn	$mg \cdot kg^{-1}$	3.6 a	3.4 a
B	$mg \cdot kg^{-1}$	1.0 a	0.9 a

[i]EC = electrical conductivity; OM = organic matter.
Values within a row followed by a different lowercase letter are significant according to the Tukey-Kramer test ($\alpha = 0.05$).

The size classification varied by citrus cultivar, and it was an extension of the tentative fruit market on an annual basis. A set of organized numbers or standard size classes represented the number of fruits that can fit in an 18.15-kg carton after the harvest of tree fruit. For 'Rio Red' grapefruit, size classes ranged from the smallest fruit size (size class 56 or smaller) to the largest fruit size (size 27 or larger). Similarly, for 'Marrs' sweet oranges, size classes ranged from the smallest (size class 80 or smaller) to the largest fruit size (size 40 or larger). The complete size distributions used for this research were 56, 48, 40, 36, and 27 for grapefruit and 80, 64, 56, 48, and 40 for sweet oranges. Therefore, fruit size was inversely proportional to the numerical value of the standard fruit size classification. In other words, small numbers indicated large fruit size, and vice versa.

Economic assessment. Refining fertilization rates (i.e., ENP) is perceived as a risk-decreasing strategy by producers to enhance marketable yield (Paulson and Babcock 2010). Similarly, CA is an additional production cost that may or may not produce an immediate return on investment (Ozores-Hampton et al. 2015). Therefore, we used a simplified simulation (Microsoft Excel; Microsoft, Redmond, WA, USA) to explore the net return distribution of citrus fruits when ENPs combined with CAs are implemented. This approach allowed us to account for production risks related to the yield and size distribution variability of citrus fruits as well as N fertilizer prices at the time of the experiment. Grapefruit and sweet orange net returns were estimated on a per-hectare basis as the difference between total revenues and costs using the following equation:

$$R(N) = Y_j(N, \varepsilon) * 0 + Y_l(N, \eta) * P_l + Y_s(N, \delta) * P_j - N * C_N - n(N) * C_M - C_f \pm CA(0, 1).$$

where R is returns and N ($kg \cdot ha^{-1}$) was used because the N application rate influences the fruit size of both crops (Wiedenfeld et al. 2009). Additionally, Y_j, Y_l, and Y_s refer to jumbo, large, and small size yields, respectively, for each crop species. Revenues are directly influenced by the size classes and final market goal (i.e., fresh vs processed) of fruits. The citrus yield depends on the N rate and random variables (ε, η, and δ) that account for the influence of soil properties, weather, and other factors on marketable yield, respectively (He et al. 2022). These random variables are equitably distributed because they were components of the same total yield. Additionally, P_l and P_j are the prices of large and jumbo fruits (\$/kg), respectively, and are modeled as random variables. The C_N denotes the N fertilizer price (urea, \$/kg), which is considered a random variable. Furthermore, n (N) is the number of fertilization events annually, C_M is the cost of each N application (excluding the cost of N fertilizer = C_N), C_f denotes other operation costs (\$/ha) assumed to be fixed, and CA can be present or absent. Our methodology did not account for producers' preferences among alternative fertilizer rates (1×, 1.5×, 2×). Fruit yield and size class distribution data were the results of the experiment conducted during the 2021–22 and 2022–23 production seasons at the Citrus Center in Weslaco, TX, USA. Production costs were based on the 2023 Texas valley citrus committee utilization report developed for the LRGV (Joyner 2023). Weekly prices for large and jumbo fruits (USDA-ERS 2023) were analyzed and calculated. Typically, harvesting season in southern Texas spans from late September to March; therefore, we selected weekly prices for the period close to the fruit harvest in the experiment. These data were analyzed independently for each citrus fruit, yield per hectare, prices for each size class, and N fertilizer and compost prices.

Statistical analysis. Data were analyzed using PROC GLIMMIX of SAS 9.4 (SAS Institute Inc., Cary, NC, USA) to determine treatment differences in parameters evaluated. An analysis of variance was used to determine the effects of ENPs and CAs and their interaction on fruit yield, weight, and size distribution. Whenever significant differences were obtained, treatment means were separated using the Student-Newman-Keuls test. Fruit size class distributions affected by treatments were analyzed using a log-likelihood ratio test (χ^2 test). Significant differences were determined by the least significant means procedure and adjusted using the Tukey-Kramer post hoc honest significant difference at $P < 0.05$.

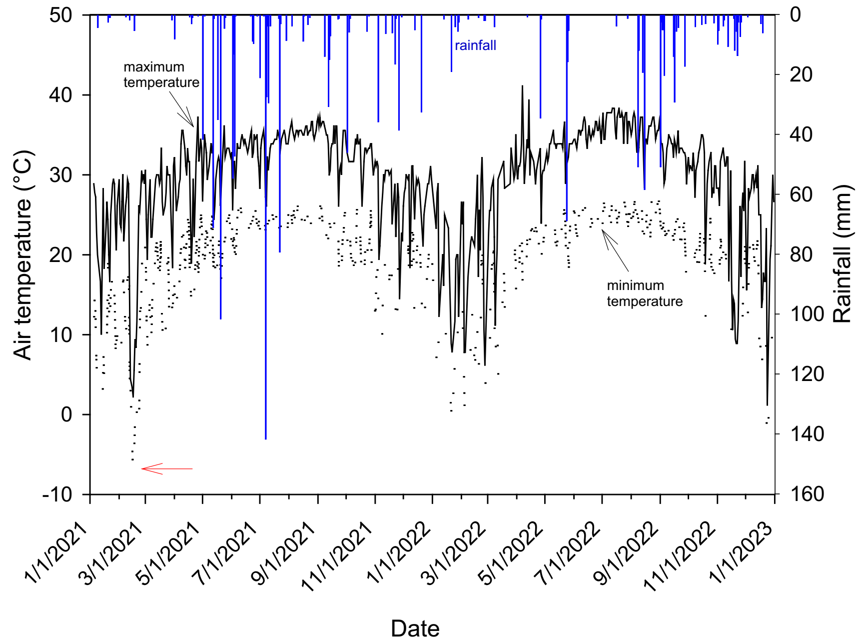

Fig. 2. Minimum and maximum daily air temperatures (°C) at 2 m, and rainfall (mm) from 1 Jan 2021 until 31 Dec 2023 at the research site in Weslaco, TX, USA. Red arrow indicates the minimum air temperature (−7 °C) produced by winter storm Uri in mid-Feb 2021.

Results

Environmental conditions

The total annual precipitations in Hidalgo County were approximately 890 mm in 2021 and 480 mm in 2022, with an average temperature of 24.1 °C (Fig. 2) (NOAA 2023). Therefore, irrigation was deemed necessary to supplement trees water loss, especially during 2022. There were four flood irrigation events in 2021 (4 Mar, 19 Apr, 6 Sep, and 3 Nov) and eight irrigation events in 2022 (14 Jan, 22 Mar, 11 May, 14 Jun, 7 Jul, 9 Aug, 26 Sep, and 20 Oct). Each irrigation event added 100 mm of supplemental water. The mean air temperature in both years was 24.2 ± 0.01 °C.

Fruit yield

Grapefruit. The treatments evaluated (i.e., ENPs and CAs) did not elicit statistical differences in grapefruit yield (Table 3). However, there were arithmetic differences measured that indicated a modest and positive effect of CA on grapefruit yield (Fig. 3) after two consecutive years. In 2021, the highest grapefruit yield (22.3 kg fruit/tree) was observed for the T2 (168 kg·ha^{-1} N) treatment without CA, which represented a 1.5-fold increase compared with the lowest yield (14.7 kg fruit/tree) observed for the T1 treatment with CA. In 2022, the T3 (224 kg·ha^{-1} N) The ENP treatment exhibited the highest yield (24.5 kg fruit/tree), which was, on average, 1.1-times greater than the fruit yield measured for the T1 (112 kg·ha^{-1} N) and T2 ENP treatments. The CA produced a moderate increase in fruit yield during year 2 (i.e., 2022) of the study. The yield was, on average, 26% higher in the plots that received CA compared to those that were left untreated (Fig. 3). The grapefruit yield was 11% greater in 2022 than it was in 2021.

Sweet orange. Enhanced nutrition programs through refined N rates did not produce differences in sweet orange yield ($P = 0.21$). In 2021, the sweet orange yield was 11.5 kg fruit/tree for all N rate treatments. In 2022, the T1 treatment produced 16.1 kg fruit/tree, which was 20% and 56% higher than the yields produced by trees with T2 and T3 treatments, respectively (Fig. 4). The CA had a more pronounced effect in 2022, when trees produced, on average, 10% more fruits than did the untreated control. Sweet orange yield in 2022 was 15% higher compared with that in 2021.

Fruit size distribution

Grapefruit. No significant differences were observed in fruit size distribution with ENP or CA treatments ($P > 0.05$) (Table 3) after two sequential harvests. During both years, 2021 and 2022, the fruit size of grapefruit did not exhibit differences associated with the CA treatment. The average percentages of fruits were 30%, 28%, 12%, 10%, 7%, and 14% for size classes 56, 48, 40, 36, 32, and 27, respectively (Fig. 5). The large size number indicates the small fruit size (i.e., class size 56 is a smaller fruit than class size 27). In 2021, T2 and T3 ENPs with CAs exhibited a slightly larger proportion of fruit with the 32 size and 27 size grapefruit classes (Fig. 5). In 2022, the average percentages of fruits were 37%, 46%, 10%, 5%, 15%, and 0% for size classes 56, 48, 40, 36, 32, and 27, respectively. We further analyzed the variability in fruit size classes from year 1 to year 2 of CA imposition, and we found that trees that received consecutive CAs exhibited a lower decline in their percentages of fruit sizes in the 27, 48, and 56 size classes. Trees with the CA treatment had 8.5, 15.3, and 5.4 reductions in the percentages of fruits classified as the 27, 48, and 56 size classes from the 2021 to 2022 harvest seasons. Conversely, trees that were not treated with compost had 14.4, 18.8, and 7.0 reductions in the percentages of fruits classified as the 27, 48, and 56 size classes. No differences in the 32, 36, and 40 size classes between years were observed.

Sweet orange. Although large increases in size classes 64 and 80 were measured, the data were variable and many of the changes elicited by CAs or ENPs were not significant in any year. The fruit size class distribution of 'Marrs' sweet orange exhibited similar trends for all the ENP treatments with or without CAs (Fig. 6). The T1 treatment produced the highest proportion (80%) of sweet oranges in the smaller size class categories of 100 through 163 (Fig. 6).

Fruit internal quality

Grapefruit. The ENP and CA treatments had an important effect on the fruit juice analysis [soluble solids content (reported as brix degrees) and acidity] ($P = 0.001$ and $P < 0.001$, respectively) (Table 3). In 2022, 'Rio Red' grapefruit that received the T1 treatment had a 3% higher brix level than Rio Red' grapefruit that received the T2 and T3 treatments across all the analyzed fruit size classes 36, 32, and 27 (Table 4). Similarly, the brix level was 5% higher for those fruits harvested from trees that received CA in comparison with trees without compost. Additionally,

Table 3. Results of an analysis of variance of all studied variables, degrees of freedom (df), and associated probabilities of main effects and their interactions.

Main effect	df	Yield	Size distribution	Fruit quantity	Fruit mass	Soluble solids content	Acidity	Root dry wt[ii]
Grapefruit								
ENP[i] (N)	2	0.63	0.57	0.78	0.49	0.001	0.85	0.16
Compost (C)	1	0.66	0.22	0.75	0.65	<0.001	0.97	0.03
Year (Y)	1	0.54	<0.001	0.20	0.39	na	na	na[iii]
N × C	2	0.86	0.90	0.86	0.77	0.59	0.74	0.13
N × Y	2	0.92	0.85	0.92	0.89	na	na	na
C × Y	1	0.31	0.74	0.57	0.44	na	na	na
N × C × Y	2	0.86	0.95	0.94	0.63	na	na	na
Sweet orange								
ENP (N)	2	0.21	0.60	0.16	0.43	0.09	0.32	na
Compost (C)	1	0.86	0.59	0.96	0.95	0.30	0.01	na
Year (Y)	1	0.33	<0.001	0.10	0.10	na	na	na
N × C	2	0.41	0.38	0.10	0.60	0.26	0.83	na
N × Y	2	0.66	0.43	0.47	0.93	na	na	na
C × Y	1	0.61	0.57	0.53	0.69	na	na	na
N × C × Y	2	0.74	0.70	0.96	0.77	na	na	na

[i] ENP = enhanced nutrition program.

[ii] Root dry weight was only collected in 2022 from the 'Rio Red' grapefruit orchard. Data were further analyzed by diameter (secondary, >2.0 mm; tertiary, <2.0 mm).

[iii] na = not applicable. Data were collected only during year 2.

the CA did not elicit changes in the grapefruit acid content because the value remained the same for composted trees and noncomposted trees (Table 4).

Sweet orange. No significant differences in brix levels of sweet oranges was observed after treatment applications (Table 3). On average, the brix level was 13.2 for the ENP treatments evaluated. Similarly, fruits harvested from trees with and without CA had, on average, the same 13.2 brix level. On the contrary, CA decreased the juice acidity level by 15% compared with that of the untreated control (Table 4).

Root dry weight

Significant differences in the root dry weight were quantified in plots that received CA compared to those without CA (Table 3). On average, the root weights were 4.7 g in trees treated with compost and 2.4 g in the control trees without CA. We further analyzed these differences by comparing the root diameter size (i.e., secondary and tertiary) and found nine-times greater secondary root dry weights in the T2 composted areas compared with those in T1 composted trees (Fig. 7). The root dry weight ranged from 1.2 to 4.5 g among the ENP treatments; however, it was nonsignificant. Similarly, no significant differences were observed among treatments for tertiary root dry weights ($\bar{X}$ = 2.5 g).

Soil fertility

The CA produced significant changes in several soil chemical properties measured during our study (Table 2). The soil pH decreased 0.3 units in comparison with the baseline pH level before treatments were imposed. Similarly, soil electrical conductivity decreased 0.1 $dS{\cdot}m^{-1}$. Soil macronutrient levels of P, K, Ca, and Mg increased 235%, 17%, 58%, and 15%, respectively, compared with the initial soil fertility baseline data. The level of the beneficial nutrient Na after CA was also 41% higher compared with that at the baseline sampling date. Conversely, the micronutrient levels of Fe and Cu were 45% and 38% lower compared with the pretreatment levels, indicating a reduction of availability when CA was incorporated in the soil.

Economic assessment

Summary statistics for citrus net returns are shown in Table 5. Citrus profitability was determined based on yield per hectare, input costs, and sale prices using data from this 2-year citrus production experiment in southern Texas. The market for citrus fruits is primarily governed by the size class of the fruit, as well as desirable internal quality parameters such as double-digit brix values and low acidity. Winter storm Uri in Feb 2021 decreased the appearance and quality of the fruit remaining on the trees that would typically be targeted for the fresh market. Moreover, the cold stress decreased citrus production by reducing the average percent distribution of optimum fruit sizes for the fresh market. Refined nutrient management practices such as ENPs are important, but the CA treatment was the most significant factor in this study relative to economic gains.

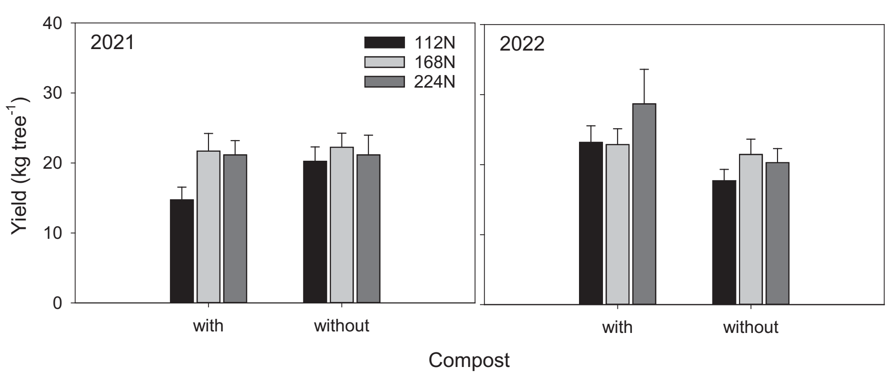

Fig. 3. 'Rio Red' grapefruit yield at 6 (2021) and 18 (2022) months after winter storm Uri. Trees received one of the enhanced nutrition programs (112, 168, or 222 $kg{\cdot}ha^{-1}$ N) with or without compost applications. The yield (kg) is the average weight of all harvested fruits per tree (n = 3). Error bars represent standard error of the mean.

Discussion

This study investigated the rehabilitating effects of CAs and refined N fertilizer rates (ENPs) to stimulate recovery and prevent further productive decline of freeze-stressed citrus trees. Mature 'Rio Red' grapefruit and 'Marrs' sweet orange orchards that exhibited mild to moderate damage after winter storm Uri in Feb 2021 received annual soil-surface applications of 11 Mg compost/ha with one of the following synthetic N fertilizer at 112, 168, or 224 $kg{\cdot}ha^{-1}$, which corresponds to 1×, 1.5×, and 2× of the traditional (112 $kg{\cdot}ha^{-1}$ N) annual N fertilization for citrus production in the LRGV of southern Texas. These combination of CAs with ENPs aimed to improve soil fertility characteristics and modify physical properties of the surface soil layer (Stansly et al. 2014).

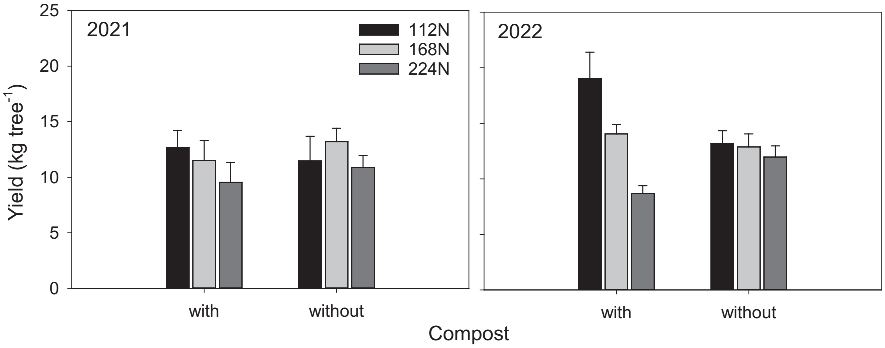

Fig. 4. Interactive effects of treatments evaluated: compost applications (CAs) and enhanced nutrition program (ENPs) (112, 168, and 222 kg·ha^{-1} N) on 'Marrs' sweet orange yield at 6 (2021) and 18 (2022) months after winter storm Uri. Yield (kg) is the average weight of all harvested fruits per tree (n = 3). Error bars represent standard error of the mean.

Despite freeze protection strategies to prevent damage to trees and fruits annually, the duration and magnitude of these weather events can produce a wide spectrum of distress to citrus orchards, especially during the fruit development and expansion stages. Winter storm Uri produced several degrees of damage to a large area of the citrus belt in southern Texas. Although some citrus orchards were located in the southernmost portion of the state (lat. 26.09, long. 97.57) and did not experience the totality of the storm, orchards were still impacted, and trees exhibited diverse levels of freeze damage. This natural phenomenon presented a valuable opportunity to conduct experiments to rehabilitate citrus trees and ameliorate the stress on field conditions.

The ENP treatments aimed to stimulate root growth and avoid subsequent tree productivity decline of these mature orchards (>30 years), which are representative of commercial orchards located in southern Texas. The nutrition programs for citrus production in the LRGV are based on the cultivar grown and are dependent on the expected productivity and age of an orchard (Wiedenfeld and Sauls 2008). However, soil applications of macronutrients (i.e., N, P, and K) have remained relatively unchanged for the past 30 years, when a basic approach to citrus fertilization was adopted at 80 to 112 kg·ha^{-1} N on an annual basis and nutrient deficiencies were corrected (Wiedenfeld et al. 2009). Despite increasing this baseline N rate by adding an extra 0.5× and 1.0× to the 168 and 224 kg·ha^{-1} N, respectively, the yield remained similar among treatments with different amounts of N fertilizer. Soil surface applications of high fertilization rates were expected to increase N availability for tree uptake and to be conducive to improved yield and distribution of fruits. However, a modest arithmetic gain in yield was measured only in 2022 for grapefruit when 224 kg·ha^{-1} N was combined with CA. Similarly, sweet orange yield exhibited a modest increment in yield when trees received a combination of 112 kg·ha^{-1} N with CA. Overall, these results suggest that the 112 kg·ha^{-1} N standard N application rate was sufficient during the growing season to support yield despite the effects of cold stress 24 months after the storm ended, and the presence of compost facilitated more fruit production but did not necessarily promote changes in fruit size distribution favoring large class sizes (i.e., small size numbers). Fertilization treatment rates that exceeded the basal 112 kg·ha^{-1} N rate effectively promoted short-term vegetative growth and increased the leaf nutrient concentration of citrus trees (Wiedenfeld and Sauls 2008), but they may not be cost-effective after 1 year after freezing because of the unresponsive yield and unmodified size class distribution. Furthermore, these high N inputs increase the risk of nutrient losses to surface and groundwater; therefore, caution must be exercised when exceeding 112 kg·ha^{-1} N annually, and mitigation strategies, such as CA, cover crops (Linares et al. 2008), nutrient mass balances (Paramasivam et al. 2001), and selection of environmental conditions conducive to minimum fertilizer escape, are deemed necessary. Composted materials tend to store soil organic N, which could be mineralized in subsequent vegetative flushes and reproductive phases of flowering and fruit development (Diacono and Montemurro 2010).

The CA maintained 'Rio Red' grapefruit and 'Marrs' sweet orange yields during the two years of this field experiment. In agreement with results of this study, Li et al. (2019) reported no decline in the fruit yield of Murcott mandarin [*Citrus reticulata* (L.) Blanco] and Midsweet orange [*Citrus sinensis* (L.) Osbeck] when compost was broadcast to the field in combination with their specific ENP. We failed to reject our hypothesis that CA would increase fruit yield because CA maintained 'Rio Red' grapefruit yield, increased the dry weight of secondary roots, and enhanced the internal fruit quality of 'Marrs' sweet orange. Compost is normally perceived as a low-risk practice that can return nutrients to the field that usually enhance yield in the mid-term to long-term (Goyal et al. 2005). Moreover, CA increased the soil water-holding capacity, which could be advantageous in semi-arid citrus-producing regions where evaporative water loss is superior to annual precipitation (Fares et al. 2017). However, the effects of CA on horticultural parameters of interest such as yield and large fruit size classes are more evident with increased compost mineralization in the field (i.e., longevity). For instance, neither CA nor varying N rates modified fruit size class distributions in the two annual harvests of this study. However, a detailed examination of these data indicated that CA +224 kg·ha^{-1} N produced 1% grapefruit fruits in size class 27 in year 2, whereas all

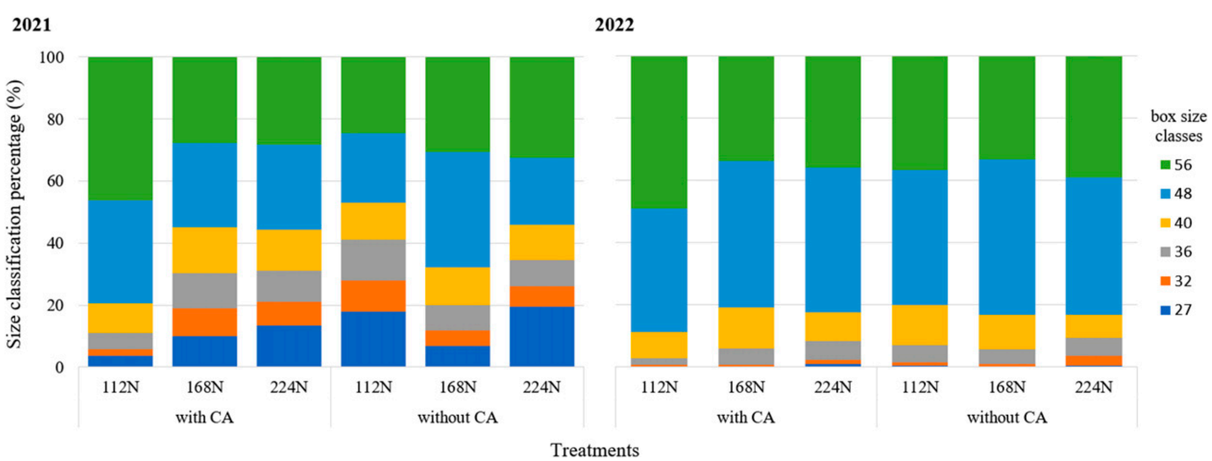

Fig. 5. 'Rio Red' grapefruit percent distribution in relation to the fruit box size classifications following harvests in Dec 2021 and Dec 2022. Three enhanced nutrition programs (112, 168, and 224 kg·ha^{-1} N) with and without compost applications (CAs) were used to rehabilitate trees after winter storm Uri passed in Feb 2021.

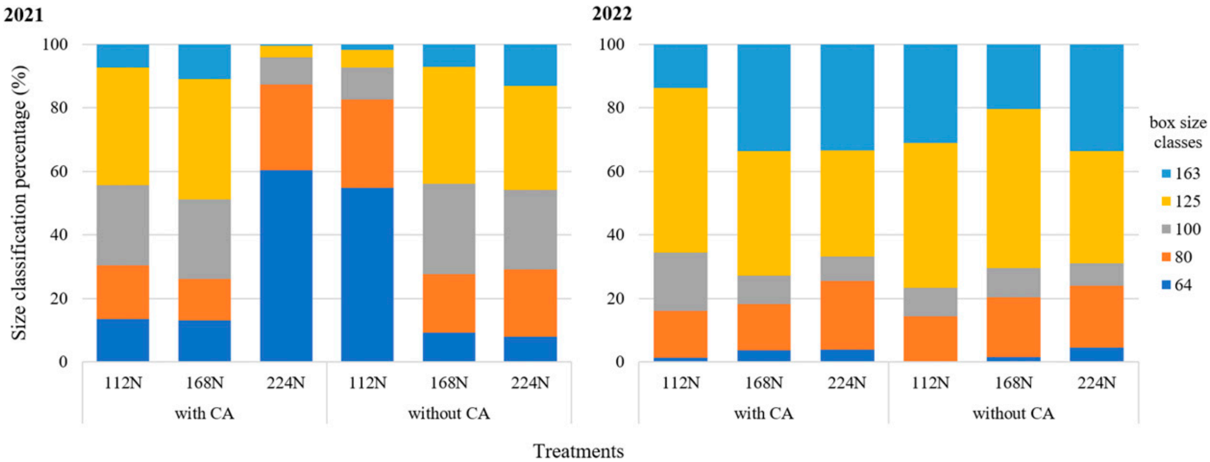

Fig. 6. 'Marrs' sweet orange percent distribution in relation to the fruit box size classifications following harvest in 2022. Three fertilizers ENP rates (112, 168, and 224 kg·ha^{-1} N) with and without compost application (CA) were used to rehabilitate sweet orange trees after winter storm Uri passed in Feb 2021.

other treatment combinations had zero fruit in this category, which is the most economically profitable for producers. Similarly, CA reduced the percentage of grapefruit fruits in the 48 and 56 categories compared with treatments with only the varying N rates. This incipient trend could indicate the beginning of more carbohydrates allocated to fruits.

Regarding 'Marrs' sweet oranges, the high percentage of small fruits classified in the high size categories (e.g., 125 and 163) was most likely attributable to the freeze event that impacted not only the 2021 yield but also citrus trees in the mid-Feb 2021 freeze, which had terminal buds and fruits on them during the following 2022 growing season. Thus, the effects of the freeze event impacted both 2021 and 2022 harvests. Regardless of this result, if all size classes of sweet oranges were directed to juicing, then the size class may not make a difference; however, a large fruit size necessitates a high fresh market sale price. Although these differences among treatments were not statistically significant, there were interesting relationships that may warrant additional years of CA and ENP treatments to understand whether notable changes regarding marketable fruit size occur over time.

Fruit internal quality

In addition to the optimum size class, the fresh citrus market is driven by fruit with high brix values (>10.0) or sweetness and low acidity content (Singh et al. 2021). Sweet grapefruit is beneficial for producers because their highest financial gains derive from the fresh market sales. High-degree brix values were observed for the standard T1 fertilizer application rate for 'Rio Red' grapefruit when compared with that of the other ENP treatments, suggesting the standard T1 rate promoted a high concentration of sugars in the fruits. Moreover, CA was conducive to higher sugar contents in the fruits harvested from trees that received CA compared with those of untreated trees. Although the gain was only equivalent to 0.42 brix units, this higher value compared with that of the control is well-regarded and well-remunerated in markets, and consumers are willing to pay for fresh fruits with high brix (although this was not statistically different in our experiment). In the case of 'Marrs' sweet oranges, low juice acidity was measured in fruits harvested from all areas that received CA. Orange production in Texas is intended for the juice market, and an acidity level lower than 2.0 is a positive fruit quality. This improvement in fruit internal quality might be attributed to the surplus of soil nutrients present in the compost (Table 1) in contrast with those of the untreated trees.

Roots

Citrus crops are generally shallow-rooted, and a large percentage of roots is present in the 0- to 0.4-m soil depth (Morgan et al. 2007). Grapefruit orchards that received CA as a groundcover were correlated with increased growth of the secondary root category (Fig. 7). This was a positive effect of CA, which, in the endemic conditions of the debilitating huanglongbing disease, might slow root loss and promote water and nutrient uptake. A previous study by Johnson and Graham (2015) demonstrated that modification of the soil environment improved the root density of huanglongbing disease-affected trees. Positive correlations between CAs and the increased quantity of roots in the grapefruit orchard could potentially influence harvest and overall citrus yield in subsequent seasons. The effects of T2 and T3 ENP treatments combined with CA demonstrated more secondary root growth in the grapefruit orchard with the 0.2-m soil depth compared with that of other trees. Results of previous studies supported these findings because the CA was shown to increase the quantity of secondary (0.09–0.52 mm) and tertiary (0.06–0.27 mm) roots in tree root zones, and other benefits such as increased soil microbial communities and alleviation of nutrient deficiencies in loamy soils (Lecompte et al. 2005; Navarro et al. 2020). Significantly fewer secondary roots were observed in plots that did not receive CA (Fig. 7), which may be attributed to lower soil water retention caused by higher evaporative water loss at the soil surface. Previous studies reported that CA in citrus orchards significantly increased the soil water-holding capacity at different depths (Abobatta and El-Azazy 2020). Improvements in the soil water-holding capacity and the presence of nutrients are critical advantages of compost in semi-arid regions such as southern Texas (Diacono and Montemurro 2010). Simpson et al. (2020, 2023) found that citrus trees with groundcover had improved water retention and significantly higher root growth compared with those of trees without groundcover. Although Simpson et al. (2020, 2023) studies involved groundcover made of synthetic materials, results from these field studies found that organic groundcover like compost can exhibit similar advantages that enhance root growth near the soil surface as long as the cost associated with CA is not prohibitive.

Table 4. Internal juice quality (brix and acidity) of 'Rio Red' grapefruit and 'Marrs' sweet orange. Fruits harvested from trees that received annual applications of three nitrogen (N) rates (112, 168, and 224 kg·ha^{-1}) as enhanced nutrition programs (ENPs) and annual compost applications of 11 Mg·ha^{-1} after winter storm Uri impacted southern Texas in Feb 2021.

	'Rio Red' grapefruit		'Marrs' sweet orange	
Treatment	Soluble solids content	Acidity	Soluble solids content	Acidity
ENP (kg·ha^{-1} N)				
112	9.81 a	1.10 a	12.83 a	0.90 a
168	9.40 b	1.11 a	13.45 a	0.76 a
224	9.56 ab	1.08 a	13.19 a	0.80 a
Compost application (11 Mg·ha^{-1})				
With	9.80 a	1.09 a	13.04 a	0.72 b
Without	9.38 b	1.09 a	13.28 a	0.92 a

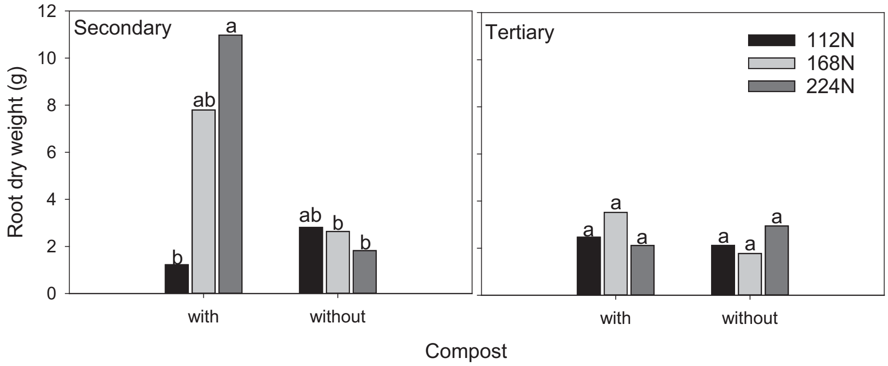

Fig. 7. 'Rio Red' root weight underneath tree canopies. Three enhanced nutrition program (ENP) rates (112, 168, and 224 kg·ha^{-1} N) with and without compost applications (CA) were used to rehabilitate grapefruit trees after winter storm Uri passed in Feb 2021. Bars with different letters indicate significant differences among treatments at a statistical significance level of $\alpha = 0.05$.

Amending soil with compost generally improved soil health indicators of intensive horticultural systems (Ozores-Hampton et al. 2015), with concomitant benefits on yield and plant fitness. However, there are potential drawbacks of returning compost to the soil. For example, nutrient immobilization was reported for perennial cropping systems, which alters N pools and cycling in the soil (Ginting et al. 2003). Additionally, we quantified decreases in the soil levels of Fe and Cu (Table 2), and although they did not lead to micronutrient deficiencies in citrus plants during the study, could be problematic for adequate supply of crop nutrient demands. Several different factors that we did not quantify during this study could explain this result, such as plant uptake, binding to macronutrients, or microbial immobilization. Regardless of the unaccounted fate of nutrients, our dataset indicated that during the two years of our experiment, trees benefited from the advantageous conditions that CA combined with a low N rate produced.

Conversely, we measured increments of the following nutrients: P, K, Ca, and Mg (Table 2). This short-term increase in the soil nutrient content was modest, the relationship between exposure to soil amendments such as CA and the continuous slow release of nutrients warrant further examination to determine whether this trend continues in the long-term. Furthermore, the presence of a compost layer with a minimum thickness of 5 cm protects the soil from evaporation and changes in seasonal conditions could be advantageous during the hot and dry months of summer. These results support CA under tree canopies as a potential soil amendment strategy to improve soil conditions conducive to tree rehabilitation after cold spells, which can also be beneficial during periods of increased air temperatures and drought, which were present throughout the 2022 growing season. Recycling these organic waste products is a step toward increasing the soil organic matter that will produce a cascade of desirable effects on the long-term cultivation of these citrus species.

Economics

Farm profitability is the strongest incentive to adopt an ENP or CA as a complement to the traditional practices. Our results indicated that surface broadcast of 112 kg·ha^{-1}·year^{-1} N with CA promoted superior mean net returns. The standard N rate of 112 kg·ha^{-1} N appears to be the most efficient in both short-term and mid-term scenarios for maintaining the marketable yield of large and jumbo fruit size classes of both crop species. Unfortunately, the short-term duration of the study limits our inferences; therefore, we consider that incentives from savings attributable to fewer fertilizer inputs (i.e., extra 56 or 112 kg·ha^{-1} N) could also be perceived by producers as a way to save capital or as an incentive to invest in CA, which improves synthetic fertilizer uptake and effectiveness when rehabilitating freeze-damaged citrus trees in contrast to increasing N fertilizer rates. Furthermore, high rates of N fertilization increase the likelihood of negative environmental externalities (Paramasivam et al. 2001) and increase the likelihood of misshapen fruits, thus decreasing the economic value of the fruit (Wiedenfeld et al. 2009). Despite the intricate economics of amending soil with compost in the mid-term and long-term, several short-term outcomes such as mitigation of tree decline, improvement of soil health indicators, and continuous productivity of mature orchards (>30 years) are desirable to producers. Each producer has a unique perception of risky situations, and the personal risk aversion level will drive the selection and application of a particular N rate or CA (Kingwell 2011; Menapace et al. 2013). Therefore, ENPs must represent minimal or null negative impacts on producers' economic profitability to avoid any disincentive for the adoption of these horticultural practices. Although we made several arbitrary assumptions of the economic assessment, our approach was based on cost-benefits in terms of the potential of these ENPs to mitigate the continuous decline of commercial orchards after freeze stress. Agricultural financial scenarios tend to be uncertain, but the adoption of ENPs and CAs could be seen as strategies that prevent the continued decline of revenue if alleviating management practices were not implemented.

Table 5. Summary of net returns when enhanced nutrition programs (ENPs) and compost applications (CAs) were added to the field on an annual basis.

Compost application	N rate	Estimated mean net return[i]	
		Grapefruit	Sweet orange
	kg·ha^{-1}	$/ha	
With	112	6,407.9	5,221.8
	168	7,070.5	4,075.2
	224	8,234.4	2,774.5
Without	112	5,836.5	3,894.5
	168	6,832.4	4,009.8
	224	6,475.3	3,581.4

[i]Calculations were performed using the 2021–22 average price per carton for each commodity (i.e., grapefruit and sweet orange).

Conclusion

This field study evaluated the responses of 'Rio Red' grapefruit and 'Marrs' sweet orange freeze-stressed mature trees to ENPs consisting of varying rates of synthetic N fertilization with or without CAs. The CA on the soil surface increased the root dry weight only in grapefruit trees. 'Rio Red' fruits exhibited higher soluble solids contents when trees were treated with CA compared with that of fruits not treated with it. Because winter storm Uri reduced the total amount of citrus trees in productive hectares in southern Texas, where the majority of citrus comprises red grapefruit cultivars, the results of this study indicated that a basal N fertilization combined with CA is a short-term measure that can maintain 'Rio Red' grapefruit tree health and productivity following mild to moderate freeze events. Conversely, there were limited positive and negative effects on parameters measured in 'Marrs' sweet oranges. Overall, our results indicated the modest benefits of CA with a baseline N rate for grapefruit and sweet orange mature trees after freeze stress. Additional studies should investigate the long-term (>2 years) benefits of CAs and ENPs for the rehabilitation of citrus orchards affected by mild, short-term freeze events, and these studies should emphasize measuring tree N uptake and resource allocation to fruits.

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