



# Seasonal variation in soil CO<sub>2</sub> emission and leaf gas exchange of well-managed commercial *Citrus sinensis* (L.) orchards

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## Abstract

**Purpose** To investigate whether soil clay content, cultivar and seasonal variation have any effect on soil CO<sub>2</sub> emission rates and leaf CO<sub>2</sub> assimilation rates in a drip-irrigated commercial *Citrus sinensis* orchard.

**Methods** The study was carried out in the field as a randomised complete block design in a 2 × 2 factorial consisting of two soil types and two citrus cultivars on a drip-irrigated commercial *Citrus sinensis* orchards with 2-week interval measurements of soil CO<sub>2</sub> emission and leaf gas exchanges for a year.

**Results** Soil clay content did not influence plant CO<sub>2</sub> assimilation rates and soil CO<sub>2</sub> emission rates in irrigated citrus. However, seasonal variation significantly influenced both processes. Soil CO<sub>2</sub> emission rates were highest in summer and were more than double the rates observed in winter while leaf CO<sub>2</sub> assimilation rates

were highest in autumn and four times higher than the winter season rates. Mean seasonal soil CO<sub>2</sub> emission rates were strongly influenced by mean minimum seasonal temperatures while leaf CO<sub>2</sub> assimilation rates only showed a relatively weak relationship with mean maximum seasonal temperatures.

**Conclusions** Soil clay content did not influence soil CO<sub>2</sub> emission and assimilation rates in drip irrigated citrus suggesting a non-significant effect of clay content for soils subjected to similar management practices. Citrus CO<sub>2</sub> assimilation rate peaks in the autumn while soil CO<sub>2</sub> emission rates peak in summer. A snapshot analysis of CO<sub>2</sub> sequestration rates suggests that irrigated citrus orchards are net sinks of CO<sub>2</sub> in summer, autumn and winter season.

**Keywords** CO<sub>2</sub> assimilation · CO<sub>2</sub> emission · citrus · Seasonal variation · Leaf gas exchanges

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## Introduction

Soil CO<sub>2</sub> fluxes play a vital role in the terrestrial carbon cycle as they integrate the decomposition of organic matter and root respiration (Paudel et al. 2018; Wu 2020). It is believed that 25 to 60 % of CO<sub>2</sub> assimilated through photosynthesis is lost through respiration and that soil respiration alone contributes up to 88 % (Paudel et al. 2018). Due to climate change, soil respiration is anticipated to contribute even more CO<sub>2</sub> to the atmosphere due to its sensitivity to global warming (Davidson and Janssens 2006). However, the dynamics

of soil respiration are still not well understood due to the high measured variability in terrestrial ecosystems (Bond-Lamberty and Thomson 2010). The high measured variability in soil respiration and the need to accurately predict the response of soil respiration to climate change as well as its feedback to global warming, have promoted the urgent need to determine soil respiration at higher temporal and spatial scales.

In agricultural systems, it is even more crucial to understand this spatiotemporal variation in soil respiration in combination with CO<sub>2</sub> assimilation to better understand if systems are net sinks or net emitters of CO<sub>2</sub>. Soil CO<sub>2</sub> emission rates and leaf CO<sub>2</sub> assimilation rates respond strongly to environmental conditions such as temperature and water availability (Avola et al. 2008; Bond-Lamberty and Thomson 2010; Davidson and Janssens 2006; Qu et al. 2020; Tankari et al. 2019; Wu 2020). Some studies have found soil water content and temperature to have a confounding effect on soil respiration (Yuste et al. 2003; Wu 2020) while others such as Davidson et al. (1998), found the two to either act independently or together in controlling soil respiration. Nonetheless, there are still several studies that dispute the temperature dependence of organic matter decomposition (Fang et al. 2005; Giardina and Ryan 2000). Thus, there is no consensus on how global warming affects CO<sub>2</sub> fluxes. Soil texture is also another factor that can influence soil CO<sub>2</sub> fluxes as it influences gas movement in soils (Yang et al. 2018). Soils with high clay content present restrictions to gas movements due to the tortuosity of the micropores (Neira et al. 2015). In addition, soil with high clay content can physically protect organic carbon within aggregates from microbial decomposition thus also decreasing the amount of CO<sub>2</sub> lost through decomposition (Hassink et al. 1993; Razafimbelo et al. 2008).

The CO<sub>2</sub> from soil comes from the autotrophic respiration of plant roots and the decomposition of soil organic carbon by microbes (heterotrophic respiration). All the processes are regulated by soil organic carbon availability, root activity, microbes, soil and air temperature, and soil moisture content (Atarashi-Andoh et al. 2012; Wu 2020; Hu et al. 2018). Higher soil temperature and moisture content increase microbial activity (Qu et al. 2020) and thus higher CO<sub>2</sub> emission rates. However, the impact of soil microbial community and function on CO<sub>2</sub> emission still needs more research.

Similar to soil respiration, leaf CO<sub>2</sub> assimilation is also controlled by both ambient temperature and soil moisture. However, unlike soil respiration which is

predominantly affected by soil moisture and temperature, leaf CO<sub>2</sub> assimilation is also strongly influenced by other factors such as light, nutrient availability and atmospheric CO<sub>2</sub> concentration (Davidson and Janssens 2006). Several studies have shown that soil moisture controls CO<sub>2</sub> assimilation through its impact on stomatal conductance (Tankari et al. 2019; Munjonji et al. 2017; Zhang et al. 2013; Carvalho et al. 2019; Rivas et al. 2016). Under unlimited soil moisture, leaf CO<sub>2</sub> assimilation is high due to a higher stomatal conductance with the reverse being true for limited water supply. Likewise, temperature also controls CO<sub>2</sub> assimilation by increasing vapour pressure deficit and the subsequent effect on stomatal conductance. A high vapour pressure deficit leads to lower leaf CO<sub>2</sub> assimilation as the plant closes its stomata to limit water loss (Aliniaiefard et al. 2014).

Cultivar differences can also show differences in CO<sub>2</sub> assimilation. Lu et al. (2012) reported differences between five cultivars of mangos. In a similar study with litchis (another tropical fruit) phenological differences in CO<sub>2</sub> assimilation were reported whereby higher CO<sub>2</sub> assimilation in leaves at the fruiting stage were observed compared to the de-fruiting stage (Chang and Lin 2007). In apples as well, higher CO<sub>2</sub> assimilation rates were reported at fruiting compared to at the vegetative stage (Fujii and Kennedy 1985).

The main challenge of using leaf CO<sub>2</sub> assimilation rates to estimate carbon capture is that they are mostly instantaneous and represent individual leaves. Over the years models have been developed and used to upscale leaf measurements to canopy level using leaf area index (LAI) (Friend 2001; Gara et al. 2019; Sprintsin et al. 2012; Luo et al. 2018). The most common methods of upscaling are the Big-Leaf model, Two-Big-Leaf model and Two-leaf model which are all well described by Luo et al. (2018). The Big-Leaf model assumes that canopy carbon fluxes have the same relative responses to the environment as any single unshaded leaf on a canopy top (Sprintsin et al. 2012) while the other two stratify the canopy into sunlit and shaded leaves (Luo et al. 2018). The Big-Leaf model is believed to under-estimate CO<sub>2</sub> assimilation by approximately 20 % (Friend 2001) thus the Two-Big-Leaf model and the Two-leaf model are more accurate.

In many agroecosystems in semi-arid environments, soil water content appears to be the most studied due to it being the most limiting as well as the seasonality of crop production. Many annual crops are seasonal and

hence are produced when ambient temperatures are relatively similar. However, the dynamics may differ in perennial fruit trees. Deciduous fruit trees such as apples and peaches lose their leaves in winter while evergreen fruit trees such as citrus maintain them. A perennial evergreen crop such as citrus is subjected to large seasonal variation of environmental conditions throughout the annual cycle (Ribeiro and Machado 2007) hence their ecophysiology is unique and probably less understood. As leaves are the main photosynthetic organs in citrus trees (Iglesias et al. 2013), their annual CO<sub>2</sub> assimilation would be expected to be higher than for deciduous as reported in similar studies by Iglesias et al. (2013) and Luyssaert et al. (2007). However, soil respiration was found to vary similarly with the season between deciduous species and evergreen forest trees (Sun et al. 2020).

According to Paudel et al. (2018), carbon balance i.e. the net result of CO<sub>2</sub> assimilation (sequestration) and emission may vary with season, management practices, irrigation method and water quality. Thus, it is important to understand the variation and the factors that control CO<sub>2</sub> efflux and assimilation to accurately predict the impact of climate change and global warming on CO<sub>2</sub> assimilation and loss from agroecosystems. Currently, not much work has been done on the variation of CO<sub>2</sub> assimilation rates and emission rates in irrigated citrus orchards. The objectives of this current study were to investigate (1) whether soil clay content has any effect on soil CO<sub>2</sub> emission rates and leaf CO<sub>2</sub> assimilation rates in a drip-irrigated commercial *Citrus sinensis* orchard and (2) how soil CO<sub>2</sub> emission rates and leaf CO<sub>2</sub> assimilation rates vary with seasons in a drip-irrigated commercial *Citrus sinensis* orchard.

## Methodology

### Study site

The study was conducted at Mahela Group, a commercial citrus orchard, in Letsitele area, located about 100 km east of Polokwane in the Limpopo province of South Africa (Fig. 1) from May 2018 to May 2019. The coordinates of the location are 23°52'5.10" S and 30°23'28.65" E. The general climate of the area is warm-temperate, dry winter and hot summer (Cwa) (Kottek et al. 2006). The area receives unimodal rainfall, most of which falls between December and April. A

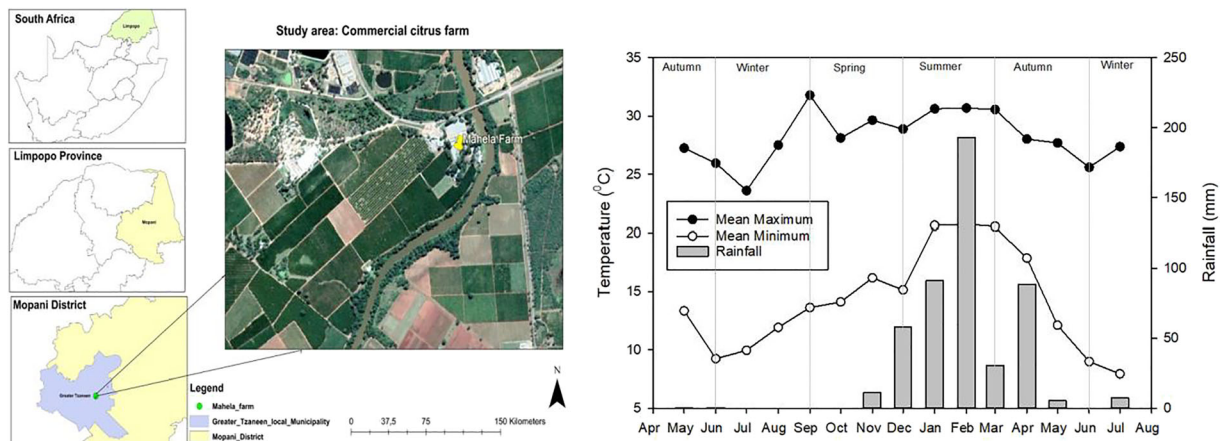
total of 485 mm of rainfall were received during the study period with the highest amount of 193 mm being received in February alone. The mean minimum temperatures ranged from 8 to 21 °C while mean maximum temperatures ranged from 24 to 32 °C. The weather data shown in Fig. 1 was obtained from an automatic weather station installed at the experimental site.

### Experimental design and management

This experiment was conducted on a commercial farm and thus the orchards were already established. The design of the experiment was done after a survey on the soil types and cultivars grown on the farm. The experiment was then laid out in a randomised complete block design in a 2 × 2 factorial arrangement consisting of two soil types and two citrus cultivars. The treatments were replicated three times. The two soil types were rich clay content soil (RC) with more than 20 % clay and moderate clay content soil (MC) with 10–20 % clay. The two citrus cultivars studied were Alpha Valencia and Valencia late. All cultivars were at the fruit-bearing stage and more than 10 years old. The trees were spaced at 7 × 3 m resulting in 476 trees per hectare. The irrigation was by drip and the schedule differed with the season, weather and soil type. Generally, irrigation was applied for two hours a day and three times a week in autumn and winter (March to August) and three hours a day, three days a week in spring and summer (September to February). Fertilisation is done following soil and foliar analysis. Foliar and soil samples are normally collected in March and sent for analysis. Depending on the deficient nutrient fertilizers are then applied through fertigation, foliar sprays or as granules.

### Installation of chambers and measurement of soil CO<sub>2</sub>

The CO<sub>2</sub> chambers were installed in May 2018 at a distance of 1 m from the main stem. Three chambers were installed in three adjacent rows at the centre of each orchard. A total of 12 chambers were installed i.e. 3 chambers × 4 treatments (n = 12). The CO<sub>2</sub> chambers were made and installed in the field according to the USDA-ARS GRACEnet Project Protocols (Parkin and Venterea 2010). The gas chambers were however modified and interfaced with an infrared CO<sub>2</sub> sensor, GMP343 CO<sub>2</sub> probe along with MI70 data logger (Vaisala, Vantaa, Finland) to allow for in-situ CO<sub>2</sub> measurements. The chambers consisted of two separate



**Fig. 1** Location map (left) and total monthly rainfall, mean minimum and mean maximum temperatures during the experimental period (right)

PVC rings: 1) a PVC ring/collar (0.20 m diameter and 0.15 m in height and 2) another PVC ring (0.20 m diameter and 0.10 m height) sealed on one side with a PVC circle to make a chamber lid. The chamber lid had a small gas ball valve on it to discourage pressure build up in the chambers during measurements. The chamber lid was also perforated on top to fix the mounting flange that holds the GMP343 CO<sub>2</sub> probe. The collars were hammered into the soil to a depth of 0.05 m leaving 0.10 m above the soil. These collars were left in the soil for a few days to settle before the measurements were taken (Fig. 2).

When taking measurements, the chamber lid with the fixed CO<sub>2</sub> probe on it was attached to the collar and secured with a tube strip to make it airtight (Fig. 2). The CO<sub>2</sub> probe GMP343 was set to record measurements every 30 s for 5 min. All measurements were taken between 10h00 and 14h00. CO<sub>2</sub> fluxes, which is the emission rate of CO<sub>2</sub>, were measured for 12 months starting from June 2018 to May 2019 at 2 weeks intervals.

The emission rates were then calculated as described in Munjonji et al. (2020).

#### Calculation of CO<sub>2</sub> fluxes

The CO<sub>2</sub> probe GMP343 gives measurements of CO<sub>2</sub> in parts per million (ppm). The measurements were first converted to mg m<sup>-3</sup> using the ideal gas law (Eq. 1):

$$PV = nRT \quad (1)$$

Where P = pressure, V = volume, n = moles of gas, R = gas law constant (8.3145 J mol<sup>-1</sup> K<sup>-1</sup>), and T =

temperature in Kelvin. The molar volume of an ideal gas at 1 atm pressure (101.325 kPa) and 25 °C is 22.4 L mol<sup>-1</sup>. Thus, at different pressures, the molar volume of the gas can be calculated as follows:

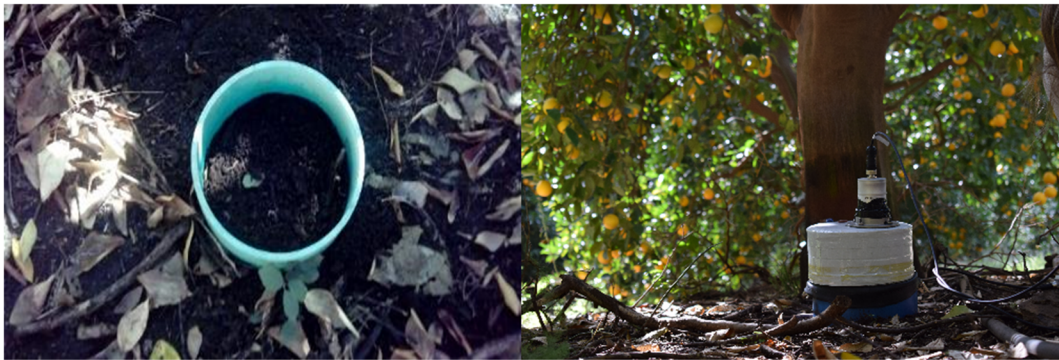
$$\text{Molar Volume} = \frac{RT}{P} \quad (2)$$

At different temperature and pressure the concentration of CO<sub>2</sub> in mg m<sup>-3</sup> was calculated as follows:

$$\begin{aligned} \text{CO}_2 (\text{mgm}^{-3}) &= \left( \frac{\text{CO}_2 \text{ppm} \times \text{Molar weight}(\text{CO}_2)}{22.4 \text{Lmol}^{-1}} \right) \\ &\times \left( \frac{273.15 \text{K}}{T(\text{K})} \right) \times \left( \frac{P(\text{kPa})}{101 \text{kPa}} \right) \end{aligned} \quad (3)$$

Where CO<sub>2</sub> ppm is the measured concentration of CO<sub>2</sub> at any given time, T is the chamber temperature (Temperature in °C + 273.15 K) and P is the ambient pressure.

The CO<sub>2</sub> concentration in mg m<sup>-3</sup> was then plotted against time (min) giving a slope in mg m<sup>-3</sup> min<sup>-1</sup>. The slope of the resulting regression lines was then determined for each installed chamber. The slope was then multiplied by the volume of the chamber and divided by the area covered by the chamber giving the resultant flux in mg m<sup>-2</sup> min<sup>-1</sup>, which describes the CO<sub>2</sub> flux out of the soil. Cumulative CO<sub>2</sub> was calculated by assuming that the rate of CO<sub>2</sub> release was constant between two measurement points.



**Fig. 2** Pictures of the installed collar (left) and the whole chamber (right) used to measure soil CO<sub>2</sub> emission rates

### Leaf gas exchange

Leaf gas exchanges were measured on the trees that were next to the CO<sub>2</sub> chambers. Leaf gas exchanges were measured using LCi-SD Ultra-Compact Photosynthesis System (BioScientific, UK). The measurements were taken between 10h00 and 14h00 on clear sunny days on fully grown illuminated leaves at a height of about 1.5 m. The leaves were located on the periphery of the crown. When conditions allowed, measurements were taken every 2 weeks. The measured parameters included CO<sub>2</sub> assimilation rate ( $A$ ), stomatal conductance ( $g_s$ ), transpiration rate ( $E$ ) and intercellular CO<sub>2</sub> concentration ( $C_i$ ). Leaf gas exchanges were upscale to canopy level using the Big Leaf Model (Luo et al. 2018). The upscaling was done using the formula:

$$A_c = A_0 \times \frac{1 - \exp(-k \times LAI_{tot})}{k} \quad (4)$$

Where  $A_c$  is the total canopy photosynthesis rate,  $A_0$  is the photosynthetic rate of the fully illuminated leaves on the canopy,  $k$  is the extinction coefficient and  $LAI_{tot}$  is the total leaf area index of the canopy.

Intrinsic and Instantaneous water use efficiencies were calculated from the gas exchange measurements using the following formulas:

$$\text{Intrinsic WUE} = \frac{A}{g_s} \quad (5)$$

$$\text{Instantaneous WUE} = \frac{A}{E} \quad (6)$$

### Determination of bulk density, infiltration rate and particle size

Bulk density was measured using the core ring method. Cores with a diameter of 5 cm and a height of 5 cm were

used to collect undisturbed soils cores in the top 5 cm of the soils. A total of 12 soil cores were collected following the design of  $2 \times 2 \times 3$  replications. The soils were then oven-dried at 105 °C for 24 h before being weighed. The infiltration rate was measured using mini-disk infiltrometers (Decagon Devices, USA). The infiltration measurements were taken once in each experimental plot ( $n=12$ ). Soil samples for particle size were also collected from each experimental plot ( $n=12$ ) and determined using the pipette method (Day 1965). All three parameters (bulk density, infiltration rate and particle size) were measured about 1 m from the tree trunk and close to the installed chambers.

### Soil chemical analyses

Soil samples were collected from two depths i.e. 0–15 cm and 15–30 cm using augers. Similar to the other parameters 12 soil auger samples were collected per depth (one composited sample per experimental plot). Three samples were collected in each experimental plot and composited to make one sample. The samples were then air-dried and sieved to pass through a 2 mm sieve. Soil pH was determined in both water and KCl. De-ionised water and 1 M KCl solution were used in a ratio of 1:2.5 and measured using a glass electrode. Calcium and Mg were determined by atomic absorption after being extracted using 1 M KCl, filtered and diluted with 20 ml of 0.0356 M SrCl<sub>2</sub>. Phosphorus, K, Zn, Cu, and Mn were extracted using Ambic-2 solution and determined using atomic absorption. Total C and N were analyzed by the Automated Dumas dry combustion method using a LECO CNS 2000 (Leco Corporation, Michigan).

## Determination of soil carbon stocks

Soil carbon stocks refer to the amount of carbon in a soil layer of known bulk density. Soil carbon stocks are normally expressed as weight/mass per unit area and are commonly limited to the soil fraction of less than 2 mm in size. Soil C stocks were determined by the following formula (Batjes 1996):

$$\text{Soil C stock} = C_{\text{tot}} \times BD \times d \quad (7)$$

Where Soil C stock is soil carbon stock ( $\text{kg C m}^{-2}$ ),  $C_{\text{tot}}$  is the total carbon content ( $\text{g C g}^{-1}$  soil),  $BD$  is bulk density ( $\text{kg m}^{-3}$ );  $d$  is soil depth (m). Carbon stocks were calculated from the top 5 cm since bulk density was only determined in that depth.

## Data analysis

A two-way ANOVA was run using SPSS 25 (SPSS, USA) to determine the effect of soil type, cultivar and their interaction on the measured parameters. A further ANOVA was carried out to determine the impact of season on the measured parameters. Where differences were significant, Tukey HSD was used to separate means. Paired T-tests were also carried out to compare leaf-level gas exchanges and canopy level gas exchanges (upscaled values). Regression analyses were run to compare minimum, maximum and mean seasonal temperatures with mean seasonal  $\text{CO}_2$  flux rates and mean seasonal photosynthesis rates. Where cultivar by soil type interaction was non-significant, the impact of soil type was compared across cultivars, whereas that of cultivar was made across soil types. When running ANOVA for seasonal variation, data of the two cultivars and the two soil types were combined.

## Results

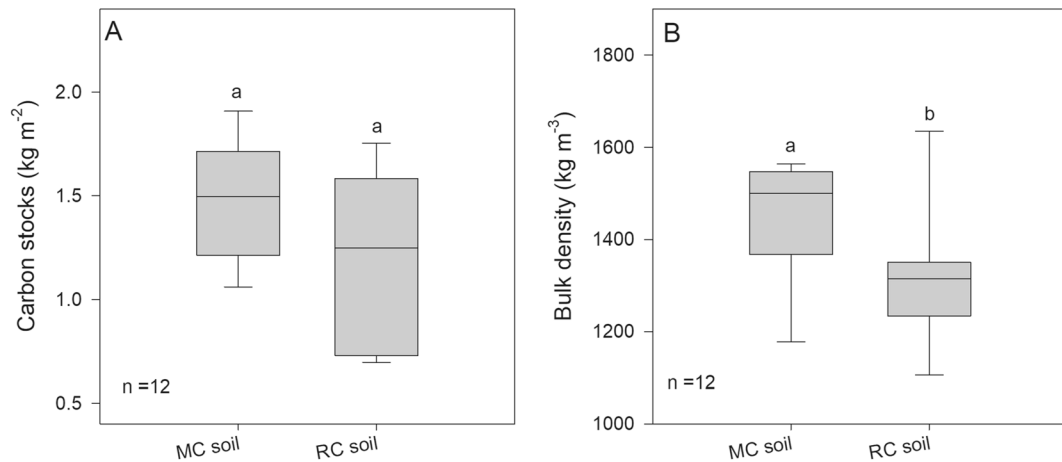
### Physical and chemical characteristics of the soils

The average clay content in the rich clay content (RC) soil was twice that of the moderate clay content (MC) soil (Table 1). A two-sample T-test showed that the potassium (K) was significantly higher in the RC soil compared to the MC soil ( $p = 0.004$ ). The results showed that the RC soil had 66.81 to 297.57  $\text{mg kg}^{-1}$  more K than in the MC soil. The other macronutrients

(Ca and Mg), did not differ between the two soils but tended to be higher in the RC soil compared to the MC soil. Phosphorus (P) on the other hand did not differ between the two soils but was relatively higher in the MC soil compared to the RC soil. The concentrations of micronutrients Mn and Zn in the RC soil were significantly higher compared to in the MC soil. The soil pH was 1 unit higher in MC soil but both soils were slightly acidic with pH values of 6.9 and 5.9 for MC and RC soil, respectively. The total carbon content was not different between the two soils only with only a 0.2 % difference between MC soils and the RC soil. Due to the 0.2 % difference observed between the two soils, carbon stocks were relatively higher in MC soil compared to the RC soil (Fig. 3a). Figure 3B also shows that bulk density was higher in MC soils when compared to RC soil. Moderate clay content soils had an average bulk density of about  $1450 \text{ kg m}^{-3}$  while the RC soil had an average bulk density of  $1310 \text{ kg m}^{-3}$ .

### $\text{CO}_2$ flux rates over the year and seasons

The  $\text{CO}_2$  flux rates fluctuated throughout the year as shown in Fig. 4a. Figure 4a shows averaged values for the two cultivars under each soil type. The  $\text{CO}_2$  flux rates did not significantly differ between the RC soil and the MC soil ( $p = 0.845$ ). However, the average  $\text{CO}_2$  flux rate for the MC soil was slightly higher ( $0.109 \pm 0.037 \text{ tons ha}^{-1} \text{ day}^{-1}$ ) as compared to  $0.107 \pm 0.036 \text{ tons ha}^{-1} \text{ day}^{-1}$  of the RC soil. Cumulative  $\text{CO}_2$  over the whole experimental period did not significantly differ between the two soils (Fig. 4b). However, at the end of the experimental period, an MC soil had cumulatively emitted 36.29  $\text{tons ha}^{-1}$  which was 7.56 % higher than that of the RC soil with 33.74  $\text{tons ha}^{-1}$ .  $\text{CO}_2$  flux rates differed in response to the season. The flux rates were lowest in the late autumn and winter with an average of  $0.065 \text{ tons ha}^{-1} \text{ day}^{-1}$  and highest in summer at  $0.136 \text{ tons ha}^{-1} \text{ day}^{-1}$  (Fig. 5a). Spring and autumn seasons did not differ in their  $\text{CO}_2$  flux rates. The results showed that  $\text{CO}_2$  flux rates in summer were more than double the rates observed in winter. Similarly, the cumulative  $\text{CO}_2$  emitted per season was also different (Fig. 5b). As observed with the flux rates, the winter season emitted the least amount of  $\text{CO}_2$  with an average cumulative amount of 3.16  $\text{tons ha}^{-1}$  which was more than three times lower than emitted in summer of 9.982  $\text{tons ha}^{-1}$ .



**Fig. 3** Carbon stocks and bulk density as influenced by soil clay content. A: effect of moderate clay content soil (MC soil) and rich clay content soil (RC soil) on carbon stocks; B: effect of MC and RC soils on bulk density

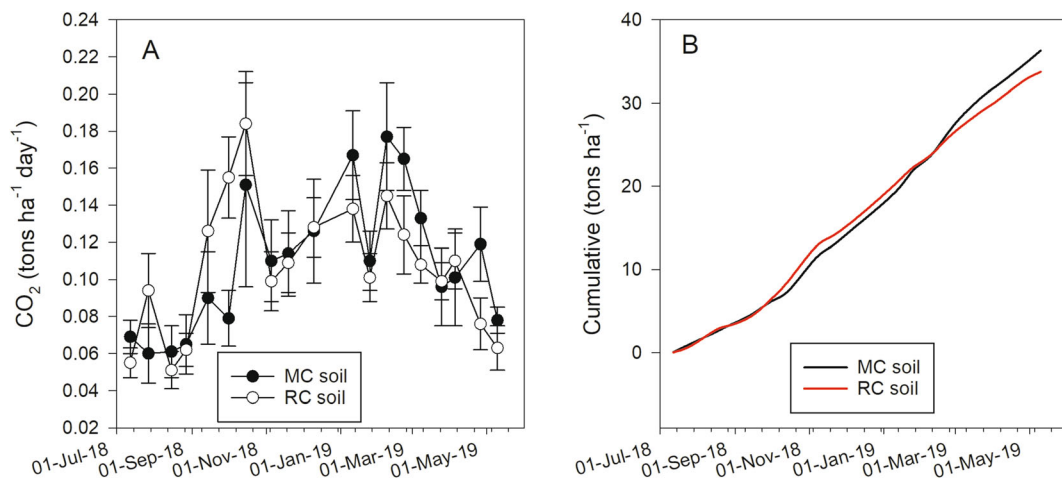
### Annual and seasonal leaf gas exchanges

Leaf gas exchanges of the two citrus cultivars were measured throughout the year. Stomatal conductance ( $g_s$ ), photosynthesis rate ( $A$ ), transpiration rate ( $E$ ) and intercellular  $\text{CO}_2$  concentration ( $C_i$ ) did not differ between the two cultivars (Fig. 6a-d). Both cultivars peaked in  $g_s$ ,  $A$  and  $E$  in March. On the other hand,  $C_i$  remained relatively constant throughout the year with values ranging from 200 to 400 ppm. A similar trend was also observed with the two soils (results not shown) and no differences were also observed. Similar to  $\text{CO}_2$  flux rates, only season had a significant influence on the

leaf gas exchanges (Fig. 7). Seasonal transpiration rate was highest in autumn ( $3.77 \text{ mmol m}^{-2} \text{ s}^{-1}$ ) followed by the summer season ( $2.68 \text{ mmol m}^{-2} \text{ s}^{-1}$ ) and then winter and spring (Fig. 7b). No differences in seasonal transpiration rate were observed between the winter and the spring season. Seasonal  $\text{CO}_2$  assimilation rates responded similarly to transpiration rates with the rates following the order of autumn ( $9.75 \mu\text{mol m}^{-2} \text{ s}^{-1}$ ) > summer ( $4.64 \mu\text{mol m}^{-2} \text{ s}^{-1}$ ) > winter ( $2.13 \mu\text{mol m}^{-2} \text{ s}^{-1}$ ) = spring ( $2.20 \mu\text{mol m}^{-2} \text{ s}^{-1}$ ) (Fig. 7d). Seasonal stomatal conductance was not different between the summer and autumn seasons but was higher than the winter and the spring seasons. As expected intercellular

**Table 1** Soil physical and chemical properties of the rich clay content and the moderate clay content soils average for the two depths

Soil parameter	Moderate clay content	Rich clay content	P value
P $\text{mg kg}^{-1}$	15.6±7.3	8.0±4.4	0.054
K $\text{mg kg}^{-1}$	130.3±26.4	312.5±192.8	0.004
Ca $\text{mg kg}^{-1}$	670.2±209.4	1306.9±234.4	0.907
Mg $\text{mg kg}^{-1}$	160.3±63.1	235.0±65.5	0.485
pH (KCl)	6.9±0.2	5.9±0.8	0.001
Zn $\text{mg kg}^{-1}$	13.5±17.8	9.8±6.2	0.001
Mn $\text{mg kg}^{-1}$	7.5±2.9	18.2±10.5	0.001
Cu $\text{mg kg}^{-1}$	2.9±1.8	5.8±1.5	0.488
Carbon (%)	2.0±0.3	1.8±0.6	0.360
Nitrogen (%)	0.08±0.07	0.11±0.09	0.045
Clay (%)	11±5.4	22±7.7	0.242
Silt (%)	8±1.7	9±2.4	0.003
Sand (%)	81±7.2	69±8.6	0.513
Textural Class	Loamy Sand	Sandy Clay Loam	



**Fig. 4** Annual variation of CO<sub>2</sub> flux rates and cumulative CO<sub>2</sub> at different dates. A: CO<sub>2</sub> flux rate as affected by moderate clay content soil (MC soil) and rich clay content soil (RC soil); B: cumulative CO<sub>2</sub> as affected by moderate clay content soil (MC soil) and rich clay content soil (RC soil)

CO<sub>2</sub> concentration did not vary over the seasons (Fig. 7a).

#### Leaf area index and canopy leaf gas exchanges

Leaf area index varied with the season (Fig. 8a). Leaf area index was higher in autumn compared to summer and winter. The LAI in spring did not differ from the other seasons. The average LAI in spring was 6.81, summer 5.27, winter 4.91 and spring 5.89. Leaf area index was used to upscale leaf gas exchange parameters such as  $g_s$ ,  $E$  and  $A$  to canopy level using Eq. 1. The results of the upscaling are presented in Fig. 8. Differences between seasons at canopy level gas exchanges were the same as those observed with leaf-level gas exchanges. The only difference was that canopy values were relatively higher than leaf-level gas exchanges. Paired samples tests showed significant differences between canopy and leaf-level for transpiration rate, stomatal conductivity and photosynthesis rate. The canopy level transpiration rate was 1.05 to 1.52 mmol m<sup>-2</sup> s<sup>-1</sup> higher than the leaf-level transpiration rate. Stomatal conductance at canopy level was 0.41 to 0.62 mol m<sup>-2</sup> s<sup>-1</sup> higher than leaf-level  $g_s$ . Likewise, the canopy photosynthesis rate was 2.06 to 3.26 μmol m<sup>-2</sup> s<sup>-1</sup> higher than leaf-level  $A$ . There were also differences in the upscaling factors for the different seasons. The highest percentage increase from leaf to canopy level of 79 % occurred in spring followed by summer 61 %, autumn 56 % and winter 26 %.

Intrinsic (IntrWUE) did not differ between autumn, winter and spring seasons. No differences in IntrWUE were also observed between summer, winter and spring.

IntrWUE was however significantly higher in autumn compared to summer (Fig. 9a). On the other hand, instantaneous (InstWUE) water use efficiency was higher in autumn compared to the other seasons (Fig. 9b). No variation in both IntrWUE and InstWUE were observed between summer, winter and the spring seasons. Also, due to similar scaling up factors, no differences were observed between the leaf level and canopy level. The values shown in Fig. 9 are therefore for both leaf level and canopy level.

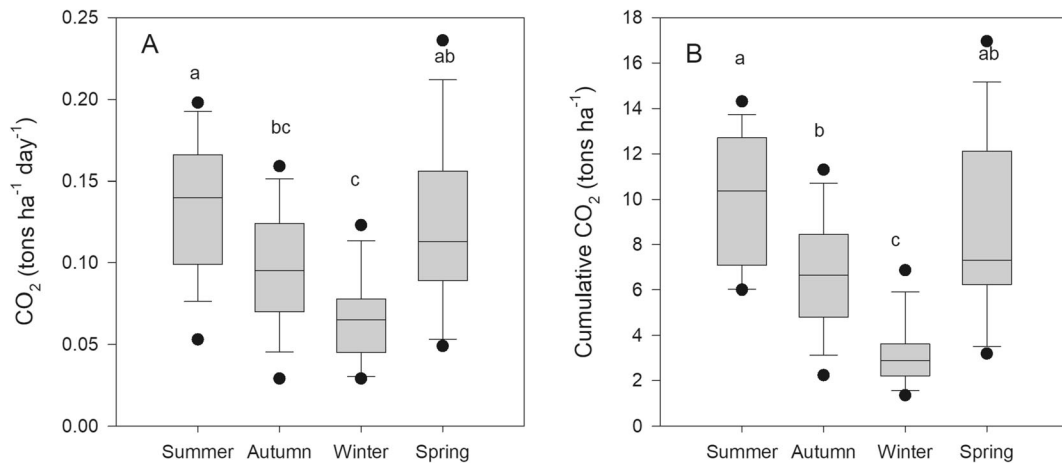
#### Relationships between temperature, CO<sub>2</sub> flux rates and CO<sub>2</sub> assimilation

A strong linear relationship ( $P < 0.05$ ,  $r^2 = 0.99$ ) between mean seasonal minimum temperatures and CO<sub>2</sub> flux rate was observed (Fig. 10a). The results showed that 99 % of the variation observed in CO<sub>2</sub> flux rates could be explained by mean seasonal minimum temperatures. Mean seasonal maximum temperatures did not show a significant relationship with CO<sub>2</sub> flux rate. CO<sub>2</sub> assimilation rate was also not related to either mean seasonal minimum or maximum temperatures during the measurement period (Fig. 10b).

#### Comparison between CO<sub>2</sub> assimilation and CO<sub>2</sub> emission rates

Canopy CO<sub>2</sub> assimilation rates and soil CO<sub>2</sub> emission rates were compared per season (Fig. 11). Significant differences in the rates were observed for the summer, autumn and winter seasons while the spring season





**Fig. 5** Average seasonal CO<sub>2</sub> flux rates (A) and cumulative CO<sub>2</sub> emitted per season (B)

showed no significant variation between the two. In the autumn season, the citrus trees assimilated CO<sub>2</sub> at rates (578.4 kg ha<sup>-1</sup> day<sup>-1</sup>) that were almost six times higher than the soil CO<sub>2</sub> emission rates (96.8 kg ha<sup>-1</sup> day<sup>-1</sup>). In the summer season, the assimilation rate was almost double the emission rate. Overall, canopy CO<sub>2</sub> assimilation rates were higher than soil CO<sub>2</sub> emission rates. There was a balance between CO<sub>2</sub> assimilation and CO<sub>2</sub> emission rates in the spring season.

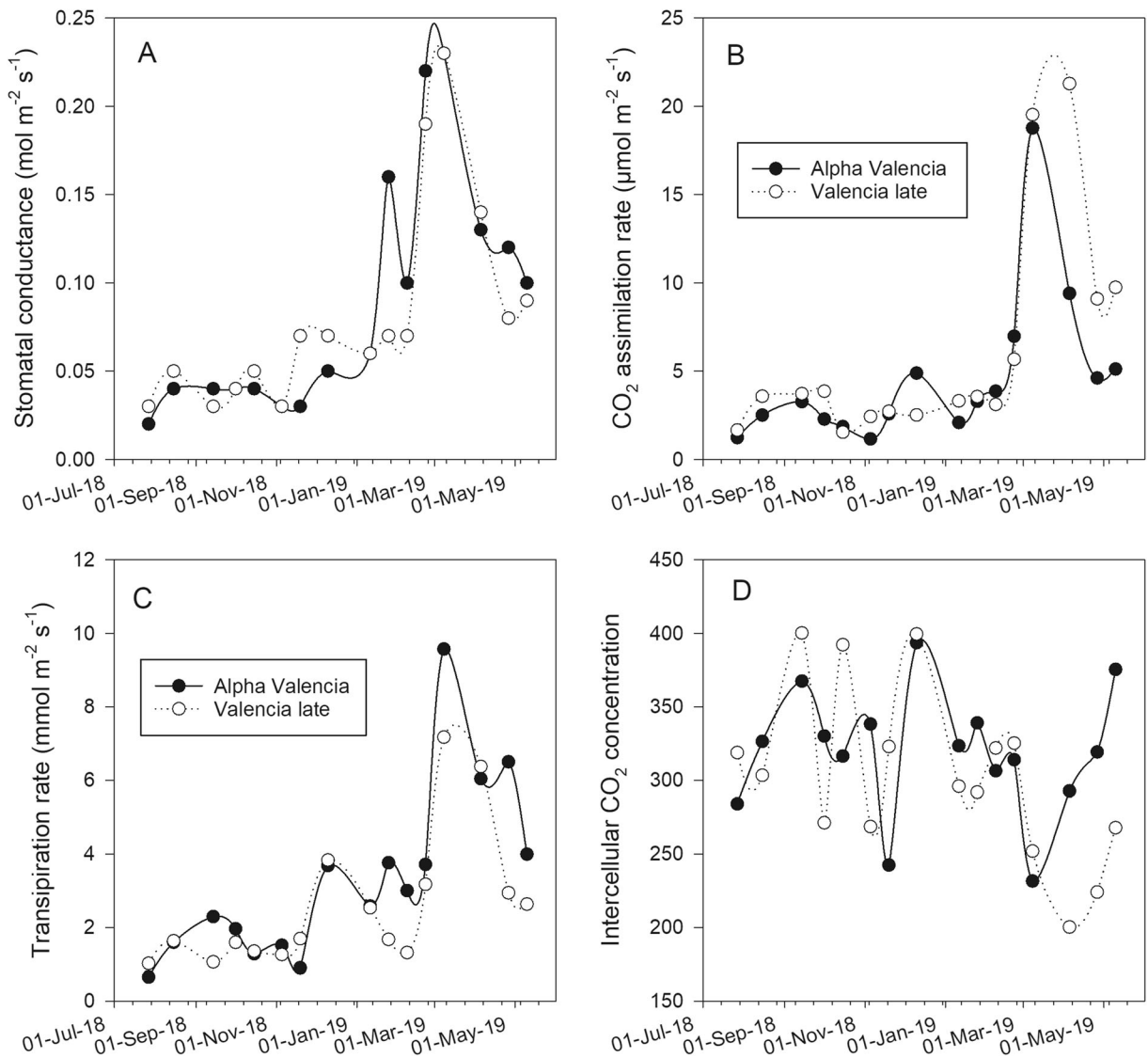
## Discussion

### Annual and seasonal soil CO<sub>2</sub> flux rates

Studies, such as that of Neira et al. (2015) and Yang et al. (2018) have shown that soil clay content influences the rate at which gases move in the soil through its influence on soil porosity and gaseous movement. Thus, soils with high clay content would be expected to restrict gas movements due to the tortuosity of the micropores (Neira et al. 2015). In this study, though not statistically significant, the moderate clay content (MC) soil cumulatively released about 7.56 % more CO<sub>2</sub> compared to the rich clay content (RC) soil. This variation could be attributed to the differences in clay content. The MC soil had an average of 11 % clay while the RC soil had 22 %. The difference might have also resulted from the differences in soil carbon stocks which were observed to be higher in MC soil (1.47 kg m<sup>-2</sup>) compared to RC soil (1.16 kg m<sup>-2</sup>).

Seasonal variations of soil CO<sub>2</sub> emission showed that both the rate and the cumulative amount were highest in the summer season and lowest in the winter season

(Fig. 5). The average soil CO<sub>2</sub> emission rate in the summer season was 0.136 tons ha<sup>-1</sup> day<sup>-1</sup> which was more than double the rate observed in the winter season (0.065 tons ha<sup>-1</sup> day<sup>-1</sup>). The differences were mainly due to the variation in temperatures between these two seasons as also observed by Yuste et al. (2003). The influence of temperature on soil respiration has also been reported in other studies (Burton and Pregitzer 2003; Davidson and Janssens 2006). Several studies have shown that soil moisture and temperature are the main drivers of soil CO<sub>2</sub> emission rates (Burton and Pregitzer 2003; Li et al. 2018; Wu 2020). However, in this study moisture was well controlled and kept at near-optimal thus only temperature influenced that variation in the CO<sub>2</sub> release. Due to the differences observed in the rates of soil CO<sub>2</sub> release, the cumulative amounts of CO<sub>2</sub> emitted per season also differed and was congruent to the emission rates. Thus, the summer season also cumulatively released more CO<sub>2</sub> to the atmosphere compared to the other seasons. In the summer season alone, the citrus orchard released 9.98 tons of CO<sub>2</sub> per hectare compared to the winter season where 3.16 tons ha<sup>-1</sup> were emitted. The high CO<sub>2</sub> released in summer could be attributed to an increase in both root and microbial respiration resulting from a temperature increase which promotes enzymatic and microbial activity (Li et al. 2021; Hu et al. 2018; Wu 2020). The significantly higher amounts of CO<sub>2</sub> emitted in warmer months of the year suggest future increases in CO<sub>2</sub> emission even in cooler months due to global warming. Climate change projections suggest that Southern Africa should expect temperature increases of up to 2 °C if society continues to use fossil fuels at a moderate growth rate, while drastic increases of up to

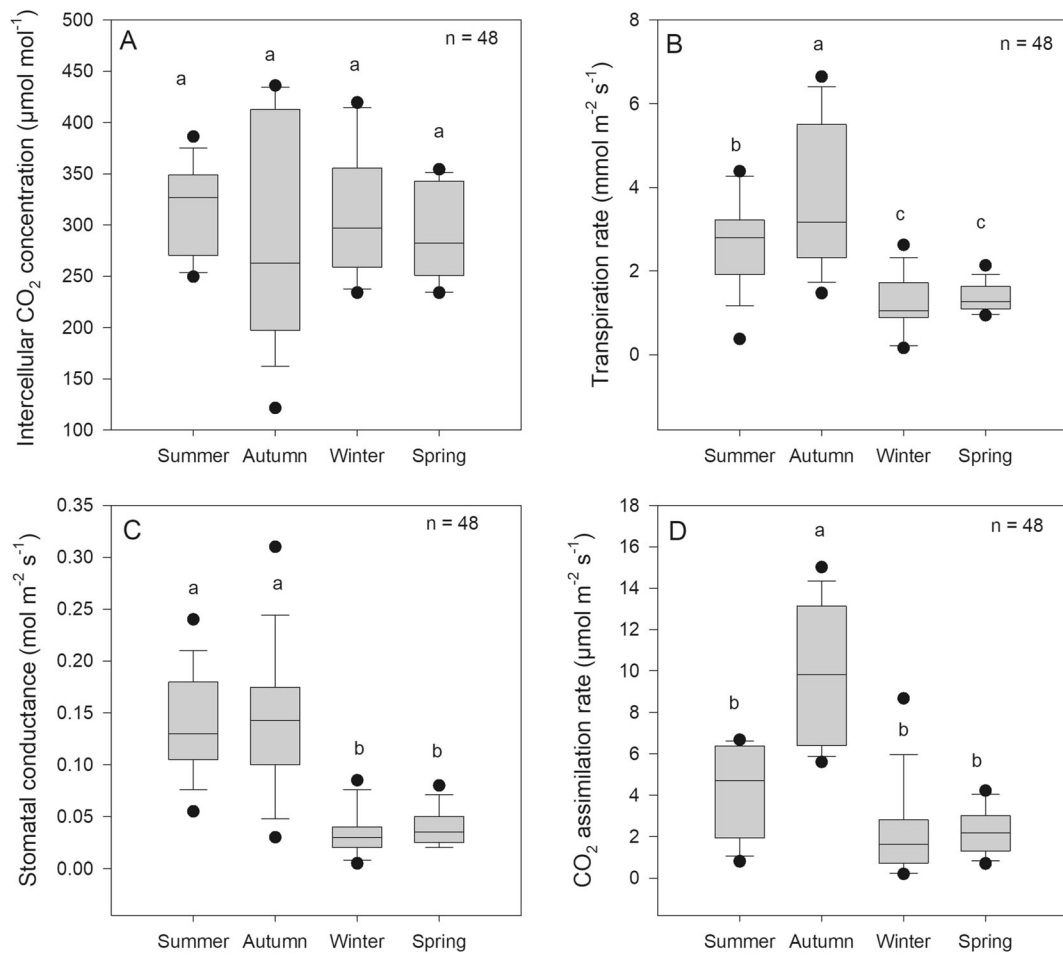


**Fig. 6** Variation in leaf gas exchanges of the two citrus cultivars (Alpha Valencia and Valencia late) throughout the year. A: Stomatal conductance, B: CO<sub>2</sub> assimilation rate, C: Transpiration rate, D: Intercellular CO<sub>2</sub> concentration

7°C are expected under high emission scenarios (Davis et al. 2017; DEA 2013).

It is interesting to note that Yuste et al. (2003) reported that in the absence of severe drought, soil temperature becomes a more reliable predictor of soil respiration. In this current study, the citrus orchards were well-watered throughout the year. Thus, the differences can therefore be attributed to the differences in mean seasonal temperatures as observed in Fig. 10. The results showed that 99 % of the variation observed in the soil CO<sub>2</sub> emission rate could be explained by the minimum ambient temperatures while maximum temperatures could only

explain 66 % of the variation. These results show that minimum ambient temperatures have a stronger influence on soil CO<sub>2</sub> emission rates compared to maximum temperatures. Mean maximum seasonal temperatures were less influential on soil CO<sub>2</sub> emission rates probably because the temperatures are close to optimal. Though variable, depending on substrate and moisture content, the optimal temperature for soil respiration is believed to be around 35 °C (Richardson et al. 2012). Temperature sensitivity of respiration is also reported to decrease as temperature increases (Yuste et al. 2003). Even though no actual soil temperature measurements were



**Fig. 7** Effect of season on leaf gas exchanges of the two citrus cultivars. A: Intercellular CO<sub>2</sub> concentration, B: Transpiration rate, C: Stomatal conductance, D: CO<sub>2</sub> assimilation rate

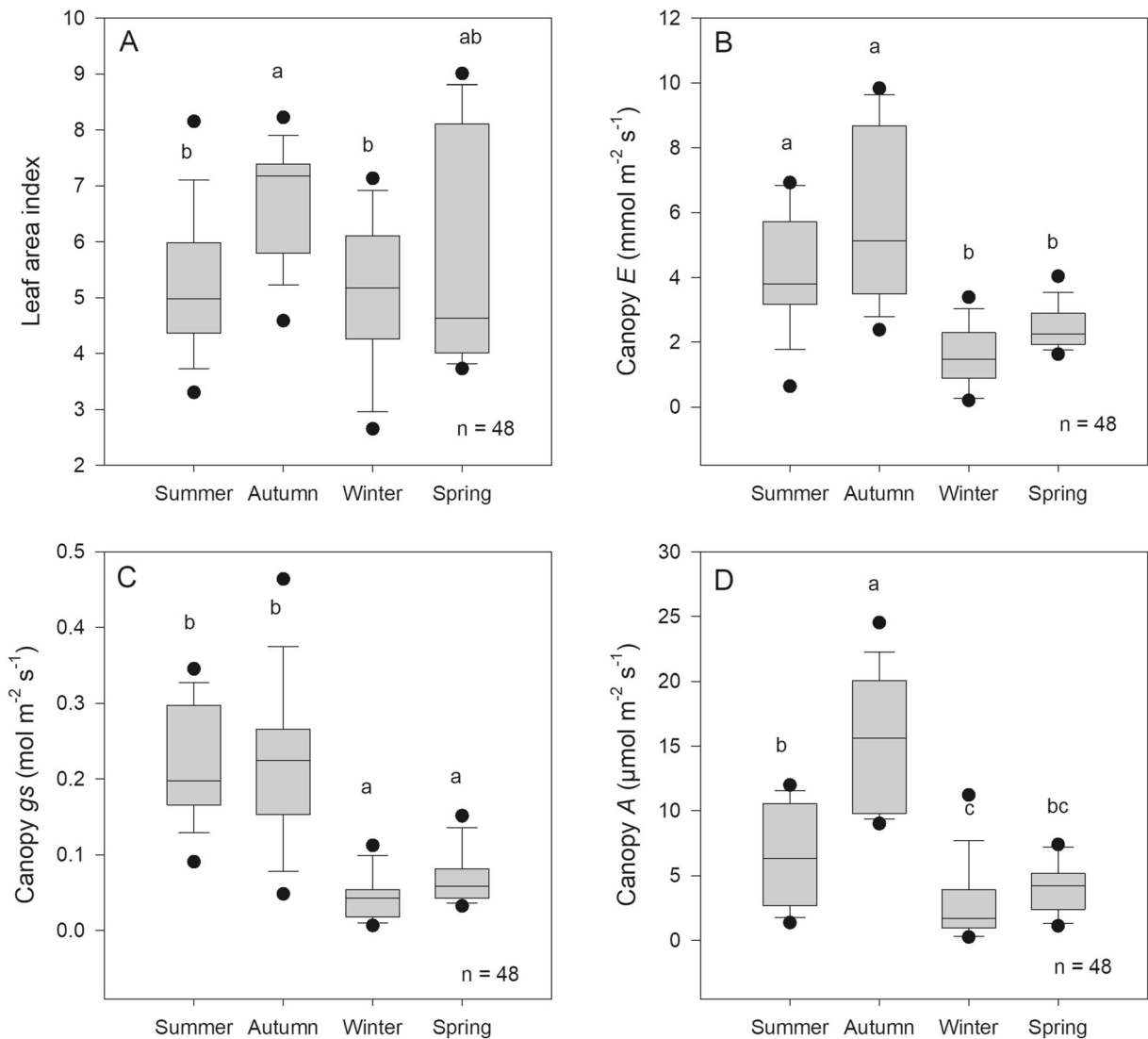
conducted in this study, Islam et al. (2015) reported a strong relationship between atmospheric and soil temperature thus the recorded ambient temperatures could be indicative of the soil temperatures. Others studies such as Brown et al. (2000) and Zheng et al. (1993) have also shown positive relationships between soil and air temperature and that soil temperature can be predicted from air temperature. Yilmaz (2012) found both soil and air temperature to be significant and positively related to CO<sub>2</sub> emission rates.

The findings of this study suggest that if temperatures get warmer as predicted by the IPCC (2014), more CO<sub>2</sub> would be released in the citrus orchards in the winter and spring seasons. The reason being that increasing global temperatures could potentially cause large increases in root and associated soil respiration (Burton and Pregitzer 2003). The increase in CO<sub>2</sub>

emission could result in potentially strong feedback to global warming. However, according to Burton and Pregitzer (2003), if root respiration acclimates to higher temperatures, increases in CO<sub>2</sub> emission could be minimal.

#### Annual and seasonal leaf gas exchanges

As observed with soil type, citrus cultivars did not vary in the CO<sub>2</sub> assimilation rates and other leaf gas exchange parameters such as *g<sub>s</sub>*, *E* and *C<sub>i</sub>* but fluctuated throughout the experimental period. Seasonal variation had a strong influence on leaf gas exchanges. The highest rates of CO<sub>2</sub> assimilation were observed in autumn as compared to the other seasons for CO<sub>2</sub> emission rates. These findings are similar to those reported by Doyis et al. (2014) from a greenhouse

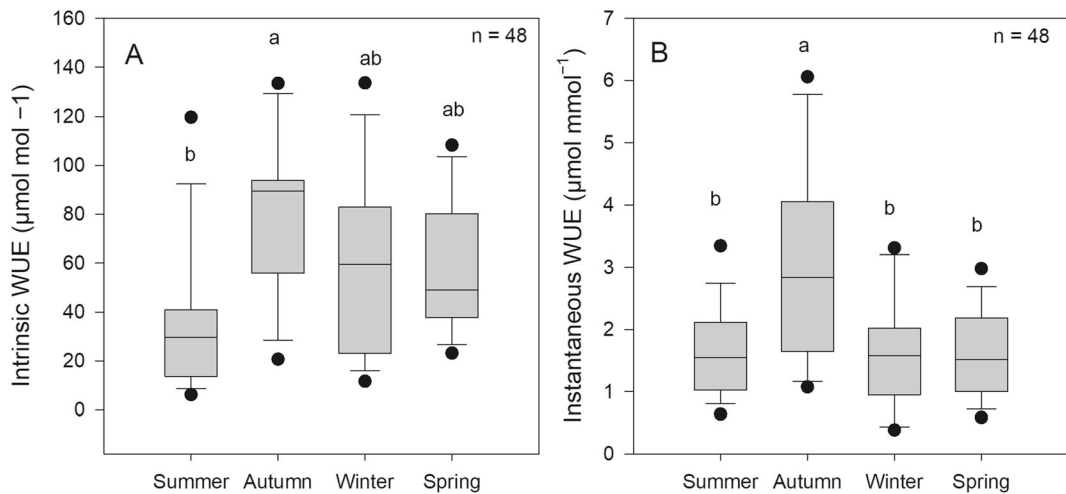


**Fig. 8** Effect of season on leaf area index and canopy level gas exchanges of two citrus cultivars. A: Leaf area index, B: canopy transpiration rate, C: canopy stomatal conductance, D: Canopy CO<sub>2</sub> assimilation rate

experiment carried out in Brazil but are contrary to the review findings of Ribeiro and Machado (2007) who reported higher CO<sub>2</sub> assimilation rates in spring followed by summer and lowest in winter. However, all studies report the lowest rates of CO<sub>2</sub> assimilation rates in winter.

In this study, CO<sub>2</sub> assimilation rates in the winter season were four times lower than those reported in the autumn season. Ribeiro et al. (2009) who reported similar findings attributed the differences to decreased root permeability and plant hydraulic conductance due to low temperatures. Poor root permeability is thought to result from increased viscosity of water which then

affects water supply to the leaves (Angelocci et al. 2004). The low plant hydraulic conductivity due to poor root permeability results in lower stomatal conductance leading to lower CO<sub>2</sub> assimilation rates (Ribeiro and Machado 2007; Ribeiro et al. 2009). Accordingly, *g<sub>s</sub>* in winter was about 75 % lower when compared to mean *g<sub>s</sub>* in autumn. In a lime orchard, Angelocci et al. (2004) found *g<sub>s</sub>* to decrease with lower temperatures and vapour pressure deficit. Lower CO<sub>2</sub> assimilation rates in winter could also be attributed to the reduction in the activity of ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) an enzyme that catalyses the fixation of CO<sub>2</sub> in C3 plants (Hendrickson et al. 2004; Sage

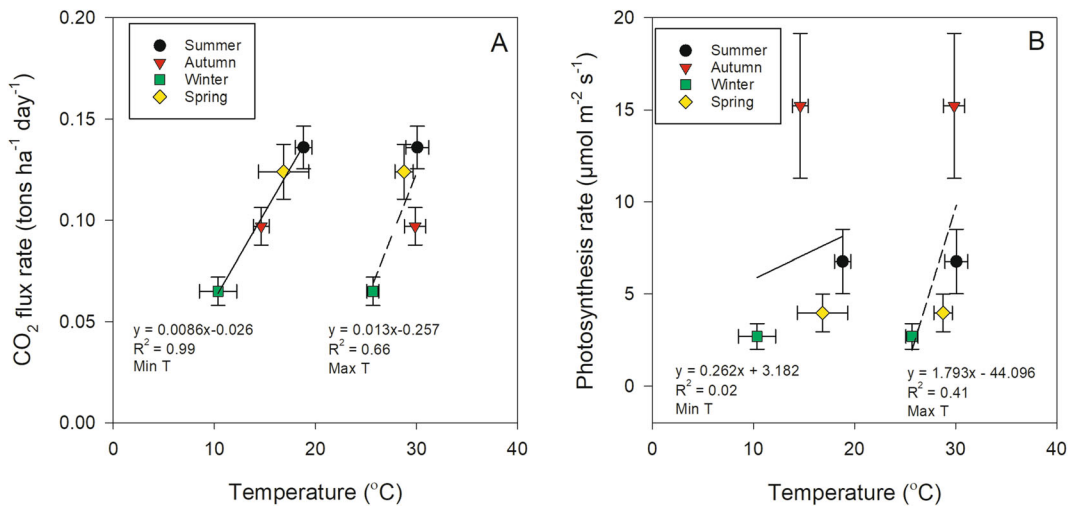


**Fig. 9** Intrinsic and instantaneous water use efficiency as influenced by season. The values are for both canopy and leaf level. A: Intrinsic Water Use Efficiency (WUE), B: Instantaneous Water Use Efficiency

2002). Also, according to Ribeiro et al. (2018), citrus plants have a low-temperature threshold of around 13 °C. Thus citrus plant metabolism is severely reduced at lower temperatures.

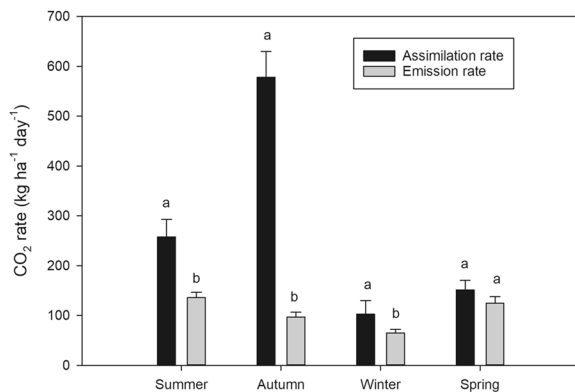
Intercellular CO<sub>2</sub> concentration (*C<sub>i</sub>*) is one other parameter that is reported to influence CO<sub>2</sub> assimilation in plants. In this current study, *C<sub>i</sub>* did not vary with season and hence could not have affected CO<sub>2</sub> assimilation. In other studies with other evergreen tree crops such as macadamia, CO<sub>2</sub> assimilation rate responded to *C<sub>i</sub>* where higher *C<sub>i</sub>* resulted in increased CO<sub>2</sub>

assimilation (Smit et al. 2020). However, CO<sub>2</sub> assimilation rates were as expected strongly related to *E* and *g<sub>s</sub>* (results not shown). However, mean minimum seasonal temperatures did not show any significant relationship with CO<sub>2</sub> assimilation rate despite the obvious influence of temperature on CO<sub>2</sub> assimilation rates. Mean maximum seasonal temperatures had a modest positive relationship (*r*<sup>2</sup> = 0.41; Fig. 10b) with CO<sub>2</sub> assimilation. The observed weak relationship between CO<sub>2</sub> assimilation and temperature could have been due to the influence of temperature on the O<sub>2</sub>/CO<sub>2</sub> ratio and consequently



**Fig. 10** Relationship between soil CO<sub>2</sub> flux rate and CO<sub>2</sub> assimilation rate to mean seasonal minimum and maximum temperatures. A: mean seasonal CO<sub>2</sub> flux rate against mean seasonal

minimum and maximum temperatures. B: mean seasonal CO<sub>2</sub> assimilation rate against mean seasonal minimum and maximum temperatures



**Fig. 11** Comparison between CO<sub>2</sub> assimilation rate and CO<sub>2</sub> emission rate in a citrus orchard. Small letters on bar graphs shows differences between CO<sub>2</sub> assimilation rate and CO<sub>2</sub> emission rate per season

photorespiration. Studies have shown that as temperature increases the O<sub>2</sub>/CO<sub>2</sub> ratio increases leading to higher photorespiration and lower net photosynthesis rate (Ku and Edwards 1978; Brooks and Farquhar 1985). This could also be the reason why CO<sub>2</sub> assimilation rates were lower in summer compared to autumn. Another plausible reason for the poor temperature and CO<sub>2</sub> relationship could be that other plant intrinsic factors are contributing to that.

In many seasonal crops, the CO<sub>2</sub> assimilation rate normally peaks just before the flowering and fruiting stages probably due to higher sink activity (Lewis et al. 2002). And indeed some studies have suggested an association between sink demand and photosynthesis rate (Dovis et al. 2014; Nebauer et al. 2013; Ribeiro et al. 2012). As evergreen species, citrus trees assimilate and consume carbon throughout the year (Dovis et al. 2014). Citrus flowers in the spring but their CO<sub>2</sub> assimilation rates were not highest in spring and this could be because the flowering was driven by stored assimilates. Dovis et al. (2014) showed that reserve assimilate consumption from the roots was high during citrus flowering.

#### Canopy CO<sub>2</sub> assimilation vs. soil CO<sub>2</sub> emission rate

Due to the limitation of studies on the role of orchards in sequestering atmospheric CO<sub>2</sub> this study attempted to provide a snapshot of whether a citrus orchard is a net sink or emitter of CO<sub>2</sub>. As such seasonal canopy CO<sub>2</sub> assimilation rates were compared to seasonal soil CO<sub>2</sub> emission rate (Fig. 11). The results showed that in most seasons (summer, autumn and winter) CO<sub>2</sub> assimilation rates were

significantly higher than CO<sub>2</sub> emission rates suggesting that citrus orchard could be net sinks of CO<sub>2</sub>. Even though this snapshot method applied in this study is not as accurate and common as the eddy covariance methods (Aubinet et al. 2012), it is however very applicable and acceptable in that it provides a relatively high spatial and temporal capture of the influence of management practices that are known to strongly influence both plant physiology and soil condition which consequently affect carbon exchange (Nardino et al. 2013). One drawback of this snapshot is that it does not capture CO<sub>2</sub> losses from plant respiration (Huntingford et al. 2017) but it is known that plant assimilates more CO<sub>2</sub> than they emit. Other studies use carbon stocks methods to estimate CO<sub>2</sub> sequestration in tree-based systems (Dube et al. 2018; Ryan et al. 2011).

It was also observed that while leaf and canopy CO<sub>2</sub> assimilation rates peaked in autumn, soil CO<sub>2</sub> emission rates peaked in the summer season. These differences could just be attributed to the mechanisms and the optimal operational conditions for each of the process. As discussed earlier, soil respiration rates increase with temperature (Burton and Pregitzer 2003) and since soil CO<sub>2</sub> emission rates were measured under a tree canopy, it is possible that maximum warming of the soil occurred in summer when temperatures were higher (Fig. 1). On the other hand, CO<sub>2</sub> assimilation rates might have peaked in autumn due to a combination of factors that include optimal environmental conditions and an increase in assimilate demand by the plant. Interestingly, no significant difference in canopy CO<sub>2</sub> assimilation and soil emission rates were observed in the spring season.

## Conclusions

This study is one of the few studies to present empirically measured CO<sub>2</sub> flux rates and CO<sub>2</sub> assimilation rates in a commercial drip-irrigated citrus orchard. This information is important in designing policies to mitigate CO<sub>2</sub> emission in agroecosystem thus help meet sustainable development goal 13 (SDG13) on climate action. The amount of CO<sub>2</sub> emitted in summer, the warmest season, was three times higher than in winter, which is an indication of the potential CO<sub>2</sub> that could be emitted from the soil in cooler seasons should temperature continue to increase due to global warming. The

study showed that under near-optimal growth conditions, soil clay content did not influence the rate at which CO<sub>2</sub> was released in the soil neither did it have any effect on the rate at which the citrus assimilated atmospheric CO<sub>2</sub>. These findings suggest that under similar management practices, the clay content of the soil does not affect the CO<sub>2</sub> emission rate. Despite the near-optimal growth conditions, both soil CO<sub>2</sub> emission rates and leaf CO<sub>2</sub> assimilates rates responded strongly to seasonal variations confirming the influence of environmental conditions particularly of temperature on the release and capture of carbon in agroecosystems. The findings showed that the citrus CO<sub>2</sub> assimilation rate peaked in the autumn and was six times higher than the CO<sub>2</sub> emission rates but the two rates balanced up in the spring season. A snapshot analysis of the CO<sub>2</sub> sequestration rates suggests that citrus orchards are net sinks of CO<sub>2</sub> in summer, autumn and winter season.

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**Data availability** Some data can be made available through request.

**Code availability** No custom codes were used.

## Declarations

**Conflicts of interest/Competing interests** The authors declare no conflict of interests.

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