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Effects of sugarcane harvest method on microclimate in Florida and Costa Rica☆

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ABSTRACT

Sugarcane (a complex hybrid of *Saccharum* spp.) harvesting methods include both green and burnt cane harvest. Air and soil temperatures are microclimatic factors which control sugarcane emergence and growth and may be significantly affected by harvest method. A series of studies were conducted in Florida and Costa Rica during 2005–2011, on three soil types to determine the effects of harvest method on microclimate. Green cane harvest produced 11.4–17.3 t/ha (average for three cropping years) of crop residues across locations. At 2-cm soil depth, increases in soil temperature during burning were 2.1–2.5 °C in muck soil, 4.6–5.8 °C in clay soil, and 6.0–7.5 °C in sandy soil. At 10-cm depth, soil temperatures during burning increased by <0.5 °C in muck soil, 0.7–0.9 °C in clay soil, and 1.9–2.2 °C in sandy soil. During cold nights when air temperatures were near or below freezing, minimum air temperatures near the soil surface were lower for green cane compared to burnt cane harvest methods. The average temperature difference across these near-freeze events was 1.38 °C (1.20 °C for muck and 1.56 °C for sand). There was greater variation in the diurnal range of soil temperature following burnt cane harvest at each location. Soil temperature differences were greater at early growth stages (April) than late growth stages (August). Across soil types, reductions in soil temperature following green cane harvest were greater in sand and clay followed by muck soil. Our results indicate that young shoots emerged from green cane harvested fields may suffer frost damage and delayed growth when air temperatures are near or below freezing. In addition, transient increases in soil temperatures following burning were smaller than normal seasonal variations in soil temperature, suggesting that burning has minimal impact on soil microflora and fauna within the 2- to 10-cm soil profile range.

1. Introduction

Sugarcane (a complex hybrid of *Saccharum* spp.) production systems include either green cane or burnt cane harvesting. In burnt cane harvesting, leafy material is burned in situ before harvesting to reduce transportation costs to the mill and to increase harvesting efficiencies (Meyer et al., 2005). In green cane harvesting, sugarcane is harvested without burning and a thick leafy harvest residue mulch layer remains on the soil surface. Green cane and burnt cane are analogous to mulched and non-mulched fields. Harvest residues have both negative and positive effects on the emergence and growth of the next sugarcane crop (ratoon crop). Common negative effects of harvest residue are lower soil temperatures (Thompson, 1966; Oliveira et al., 2001), which delays regrowth of ratoon cane, and interference with tillage operations and fertilizer applications. In contrast, positive effects of mulches formed by unburned residues include

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increased soil carbon (C) and nutrient conservation, reduced weed growth (Samuels and Lopes, 1952), and soil water conservation (Juo and Lal, 1977; Derpsch et al., 1985; Ball-Coelho et al., 1993).

Choice of sugarcane harvest method varies with location because of differences in soil type and environmental conditions. Burnt cane harvesting is the traditional harvesting method in sugarcane. However, green cane harvest is becoming more popular in many of the sugarcane producing countries because of increased interest in green cane harvest residue for energy production and environmental concerns. Effects of green cane harvest on sugarcane yields vary among different locations. In Puerto Rico, Samuels and Lopes (1952) found no difference in yield between burnt and green cane harvesting until the 5th and 6th ratoons, at which point they found some positive effects of green cane harvest. Green cane harvesting resulted in increases in sugarcane yield in Brazil (Ball-Coelho et al., 1993) and South Africa (Van Antwerpen et al., 2001). In Louisiana, residues left on the soil surface did not effect sugarcane yield, but its incorporation into the soil increased the yield over burnt cane harvesting (Kennedy and Arceneaux, 2006). Viator and Wang (2011) reported that pre-harvest burning resulted in 7.4 t/ha greater cane yield than green-cane harvest in Louisiana. In Texas, compared to burnt cane harvesting, partial incorporation of residue left by green cane harvesting did not effect the yield of first and third ratoon, but there was 20% yield reduction in second ratoon (Wiedenfeld, 2009). In Florida and Costa Rica, we have reported that three-year average cane yield was greater following burnt-cane than green cane harvest by 7.8, 3.9, and 1.7 t/ha at El-Viejo, EREC, and Hilliards, respectively (Sandhu et al., in press).

Air and soil temperatures are microclimatic factors, which control sugarcane emergence and growth (Oliveira et al., 2001). Young sugarcane plants can be very susceptible to freezes which highlight the importance of air temperature near the soil surface. It has been previously reported that soil capacity to absorb heat during daylight hours and then transfer this heat back to the air near the soil surface at night was greater in bare soil than for soils covered with mulch or crop residue (Gradwell, 1963; Cochran et al., 1967; Fritton et al., 1976). Beater and Maud (1962) observed that frost damage to sugarcane occurs far less frequently on bare soil compared to soils covered with harvest residue. However, quantitative information on air temperature in different soil types was not reported in these experiments. Sugarcane crop residues left on the soil surface during green cane harvesting can affect microclimate through modifications in soil thermal conductivities and reflection coefficients, which consequently influence air temperatures close to the soil surface (Pezzopane et al., 1996).

Oliveira et al. (2001) reported significant soil temperature differences between mulched and non-mulched treatments at 3, 6, and 9-cm soil depths in Rhodic Kandiudox soils (25 kg m^{-3} of organic matter) in Brazil. At early growth stages when canopy coverage was less than 10% of the soil surface, soil temperatures were significantly different between green and burnt cane treatments. The temperature difference between mulched and non-mulched treatments ranged from 7 °C in November to near zero in February for the average of the three depths. Decrease in soil temperature with harvest residues in sugarcane was also reported by Moody et al. (1963), Thompson (1966), Page et al. (1986), Morandini et al. (2005) and Viator et al. (2005), but there are no reports for similar studies on muck soil and comparisons between different soil types is lacking. Sugarcane apical meristem tissue remains below-ground early in the growing season, thus soil temperatures are an important driver of early season growth and sugarcane harvesting method can appreciably affect sugarcane emergence and development.

Changes in soil temperature with choice of harvest method can also alter the pool size of C respired by soil microbes and the composition of microbial communities (Zogg et al., 1997). Increase in soil temperature from 5 °C to 25 °C resulted in apparent increase in the pool of C respired by soil microbes with little or no effect on the first-order rate constant. Also, the total phospholipid fatty acid (PLFA) content which reflects active microbial biomass declined with increase in temperature from 5 °C to 25 °C. Similarly, Peterson and Klug (1994) reported that increase in soil temperature from 4.5 °C to 25 °C results in metabolic stress and death of microbes, because biosynthesis of new lipids is energetically expensive at higher temperatures.

The fraction of incoming solar radiation that is reflected by the bare ground soil surface depends on the soil type, moisture level, and soil color (Jury et al., 1991). Heat flux in the soil also depends on the heat capacity and thermal conductivity of soils, which is largely dictated by soil structure, bulk density and water content (Hillel, 1998). Therefore, seasonal and diurnal changes in soil temperatures and the effect of burning on soil temperatures will differ across different soil types.

Due to growing worldwide interest in improving air quality, the practice of pre-harvest burning of sugarcane has become regulated in many sugarcane-growing countries. Previous reports (Beater and Maud, 1962; Thompson, 1966) provided speculation supporting an increased occurrence of frost when harvest residues were present. However, quantitative measurements of air temperature changes caused by sugarcane harvest systems have not been published to our knowledge. Also, there is a lack of information on change in soil temperatures at the time of pre-harvest burning and its potential effect on soil flora and fauna in comparison to the seasonal variations in soil temperatures in different soil types. Therefore, it was important to determine the effect of sugarcane harvesting methods on microclimate. Our objectives were:

(1) To compare soil temperatures during sugarcane burning in different soil types.
(2) To determine the effect of harvest residue on air temperatures during freeze events.
(3) To determine the effect of harvest residue on diurnal and seasonal soil temperatures in different soil types.

2. Materials and methods

A series of studies were conducted in 2005–2011 to determine the effects of sugarcane harvest method (green vs. burnt cane harvesting) on microclimate within the surface soil profile and immediately above the soil surface. Initially, the experiment was started at Everglades Research and Education Center (EREC) (26°39′ N, 80°38′ W) in Belle Glade, Florida in 2005, which was later expanded to Hilliards (26°42′ N, 81°00′ W) in Clewiston, Florida in 2006 and Azucarera El Viejo (10°25′ N, 85°25′ W) in Guanacaste, Costa Rica in 2008. The three soil types in this study included an organic Histosol at EREC (*Euic, hyperthermic lithic haplosaprist*), a sandy soil at Hilliards (*siliceous, hyperthermicmollicpsammaquents*), and a clay loam at El Viejo (*Fluventicustropept*). Soil bulk densities at EREC, Hilliards, and El-Viejo were 0.2–0.5, 1.2–1.6, and 1.25 g cm^{-3}, respectively. The soil at EREC contained 85–90% of organic matter. At Hilliards, sand, silt, and clay content were 90–98, 1–5, and 1–5%, respectively. At El-Viejo, sand, silt and clay content were 20–33, 41–42, and 26–38%, respectively. Approximate elevations for the El-Viejo and Florida sites were 10 and 3–4 meters above sea level, respectively. Sugarcane varieties grown at EREC, Hilliards and El Viejo were CP80-1743 (Deren et al., 1991), CP 78–1628 (Tai et al., 1991),

Table 1
Annual average weather data from the three experimental locations.

Year	EREC				Hilliards				El-Viejo			
	Temp. (°C)	RH (%)	Wind speed (m/s)	Rainfall (cm)	Temp. (°C)	RH (%)	Wind speed (m/s)	Rainfall (cm)	Temp. (°C)	RH (%)	Wind speed (m/s)	Rainfall (cm)
2005	21.9	80.6	3.4	159.1	–	–	–	–	–	–	–	–
2006	21.8	78.2	3.0	84.7	–	–	–	–	27.5	71.5	2.6	141.2
2007	22.2	79.2	3.2	95.0	–	–	–	–	27.0	71.9	1.9	263.2
2008	21.8	79.0	3.3	148.4	22.9	74.7	3.6	142.7	26.7	77.3	1.8	268.9
2009	22.0	77.6	3.1	135.5	22.7	77.9	3.3	142.6	27.3	74.9	1.9	166.9
2010	21.0	75.9	3.5	121.1	21.5	79.3	3.5	97.1	27.8	76.5	1.7	275.2
2011	22.2	77.5	2.8	119.5	22.8	81.2	3.3	134.0	26.4	75.0	3.7	225.2

–, Indicates missing values.

and B 80–689, respectively. Due to the different start dates of this experiment at three locations, measurement dates varied across locations. Diurnal and seasonal soil temperatures at EREC, Hilliards, and El-Viejo were recorded in 2005, 2006 and 2008, respectively. Air temperatures at EREC and Hilliards were recorded in 2006, and soil temperatures during burning were recorded in 2010 and 2011 at all three locations. Weather data on average temperature, humidity, wind speed, and rainfall are provided in Table 1 for the three experimental locations.

2.1. Experimental design and implementation

Each experiment included two harvest treatments (burnt and green cane harvest), with three to six replications arranged as a randomized complete block design. Sugarcane was grown for approximately 12 months with one harvest per year at all locations. Plot sizes at all locations were at least 12 m wide × 300 m long to allow for adequate burning, efficient commercial-scale mechanical harvest operations, and uniform trash deposition in the green cane treatments. Plots were burned prior to harvesting in the burnt cane harvest treatments and were not burned in the green cane harvest treatments. Due to different burn regulations between countries, the burnt treatment was implemented during daylight hours at EREC and Hilliards, whereas burns were conducted at night at El Viejo. Immediately after harvest, the harvest residue ‘trash’ was collected and weighed from a 3 m × 3 m subsample area at 2 locations separated by 190 m in each plot. The elapsed time between burning and harvesting also differed across locations. Thus ‘time after burning’ was used in soil temperature graphs (Figs. 1 and 2) to indicate the time period during which the data were recorded.

2.2. Soil temperature during burning

Soil temperatures were recorded before, during and after burn events prior to harvesting in 2010 and 2011. At all three sites, temperature sensors (HOBO Water Temperature Pro v2 Data Logger-U22-001, Onset HOBO Data Loggers, Bourne, MA) were installed four to five hours before burning and removed just before mechanical harvesting to avoid destruction of the sensors. Time between burning and commercial harvest differed among sites from two to eight hours. The temperature sensors were programmed for 15-s measurement intervals and are manufactured with a sealed waterproof durable case. Temperature sensors were installed at 2 cm and 10 cm soil depths in the center two rows with two sensors at each depth in each plot (a total four sensors in each plot). To install these sensors, the soil was carefully displaced with a small shovel; the sensor was placed at the appropriate depth and then covered back with soil. The soil was gently tamped down and any crop residue on the soil surface was returned back to its original location. The sensors were removed before harvesting, and the data were extracted by connecting them to a computer using HOBO software. Temperature data were recorded at 15-s intervals and then averaged over 15-min interval for graphical presentation purposes.

2.3. Diurnal soil and air temperatures

Soil temperatures at EREC, Hilliards, and El-Viejo were recorded in 2005, 2006, and 2007 sugarcane growing seasons, respectively. Air temperatures were recorded during the winter months at EREC and Hilliards in 2005–2006 and 2006–2007, respectively. Soil temperatures were recorded with HOBO Water Temperature Pro v2 Data Logger-U22-001 (Onset HOBO Data Loggers, Bourne, MA). Temperatures were recorded at 15-min intervals at 15 cm soil depth within the sugarcane row throughout the growing season. Air temperatures (TL-G Thermologger, Thermodata Corporation, Erie, PA) were recorded at 15-min intervals at a 10 cm height above the soil surface from January–May at the two Florida locations. Air temperatures were not recorded at the Costa Rica location since this tropical environment lacks freeze events.

2.4. Data analysis

Analysis of variance using Proc GLM in SAS (SAS Institute, 2008) were performed to determine the treatment effects on minimum air temperature, minimum and maximum soil temperature, and soil temperature during burning. Means were separated using LSD methods and significant differences were determined at $P < 0.05$ unless otherwise noted.

Table 2
Mean harvest residue fresh weights for green and burnt cane treatments.

Location	Crop	Harvest residue (t/ha)	
		Green	Burnt
EREC	Plant cane	23.3Aa	1.2Bb
	1st ratoon	17.1Ba	0.9Bb
	2nd ratoon	11.6Ca	3.8Ab
Hilliards	Plant cane	20.8Aa	4.7Ab
	1st ratoon	14.5Ba	3.0Bb
	2nd ratoon	13.2Ca	2.6Bb
El Viejo	Plant cane	12.9Aa	3.2Ab
	1st ratoon	7.6Ba	1.5Bb
	2nd ratoon	13.6Aa	2.8Ab

Standard error of the mean = 1.24 t/ha (EREC and Hilliards) and 1.07 t/ha (El Viejo). Different uppercase letters indicate significant differences among crops at each site, and different lowercase letters indicate significant differences between treatments in each crop at each location.

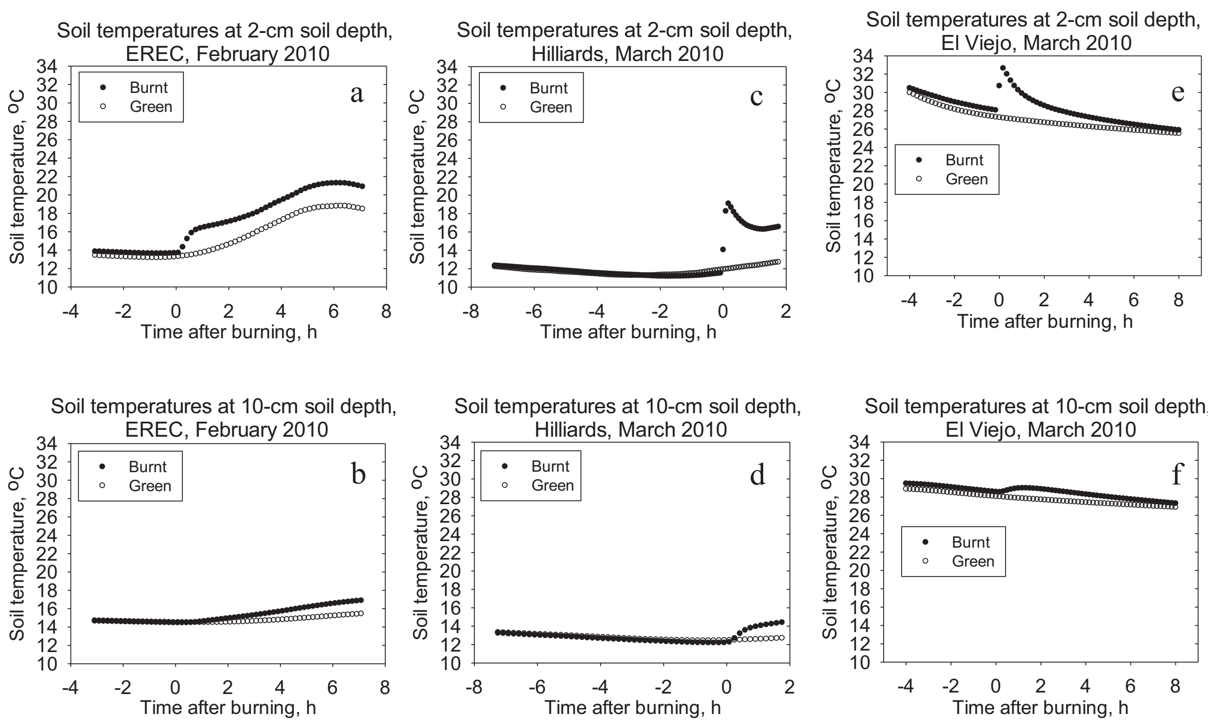

Fig. 1. Mean soil temperatures during burning in burnt cane harvested plots, and comparison with concurrently recorded soil temperatures in green cane harvested plots, at 2 and 10 cm soil depths at EREC, Hilliards and El Viejo in 2010.

3. Results

3.1. Harvest residue

The amount of harvest residue, or "trash", declined during the multi-year crop cycle, whereby plant cane had the greatest trash followed by progressively less trash for the first ratoon and second ratoon crops (Table 2). One exception occurred at El-Viejo, which had lower first ratoon trash levels relative to second ratoon because of low cane yield due to drought in first ratoon in 2009 (Table 1). As expected, green cane harvesting produced significantly greater harvest residue than burnt cane harvesting. Location had a

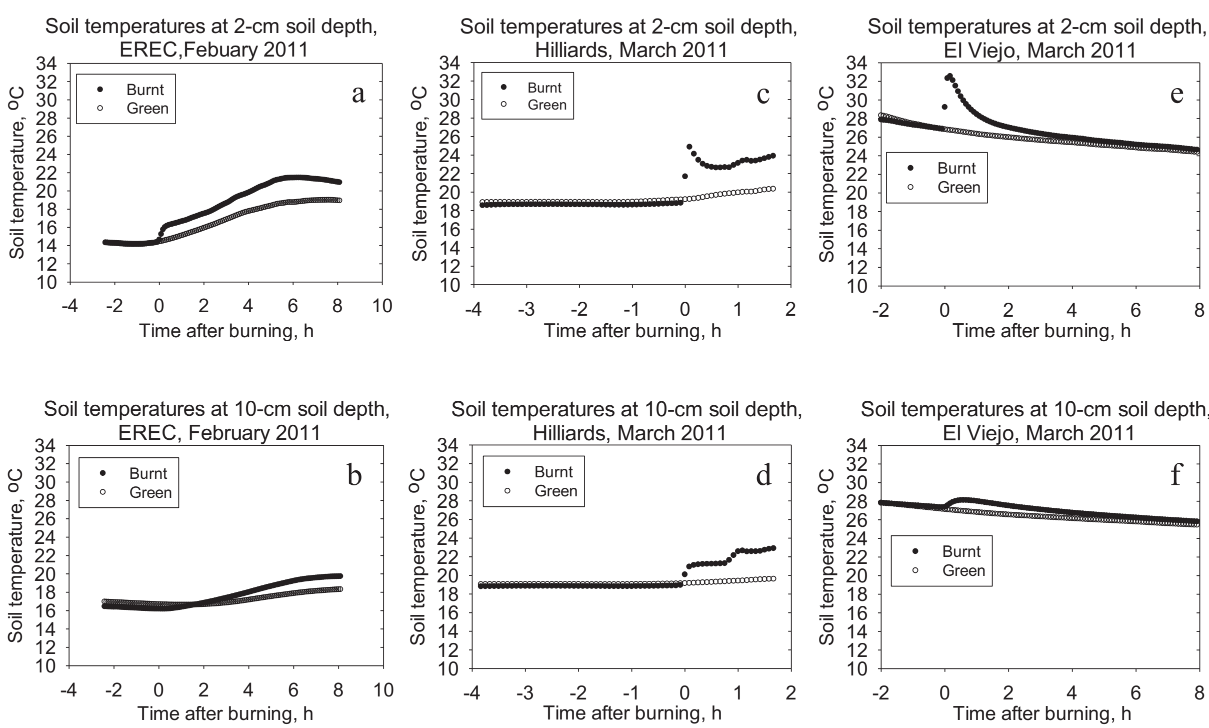

Fig. 2. Mean soil temperatures during burning in burnt cane harvested plots, and comparison with concurrently recorded soil temperatures in green cane harvested plots, at 2 and 10 cm soil depths at EREC, Hilliards and El Viejo in 2011.

significant effect on green cane harvest residues with the greatest three year average harvest residue at EREC (17.3 t/ha) followed by Hilliards (16.2 t/ha) and El Viejo (11.4 t/ha) and this was a consequence of sugarcane biomass accumulation trends (Sandhu et al., in press) and varietal differences among locations. Burning prior to harvest did not completely remove all crop residues, however residue quantity was low at EREC (three year average of 2.0 t/ha), Hilliards (3.4 t/ha) and El Viejo (2.5 t/ha). These results indicate that green cane harvesting leaves significantly greater amounts of crop residue compared to burnt cane harvesting and this amount also varies with location.

3.2. Soil temperature during pre-harvest burning

Increases in soil temperature during pre-harvest burning varied with soil depth and soil type. Soil temperature fluctuations during burning declined as soil depth increased from 2-cm to 10-cm (Figs. 1 and 2) in all soil types. Also, transient soil temperature increases during burning were greatest in sand soils (Hilliards) followed by clay (El Viejo) and then muck (EREC). The results were similar for both years of the study. At the 2-cm soil depth, the two year combined range of increases in soil temperature at burning in 2010 and 2011 was 2.1–2.5 °C in muck soil (EREC, Figs. 1a and 2a), 4.6–5.8 °C in clay soil (El-Viejo, Figs. 1e and 2e), and 6.0–7.5 °C in sandy soil (Hilliards, Figs. 1c and 2c). At the 10-cm soil depth, soil temperatures increased by <0.5 °C in muck (Figs. 1b and 2b), 0.7–0.9 °C in clay (Figs. 1f and 2f), and 1.9–2.2 °C in sandy soil (Figs. 1d and 2d). Temperature increases dissipated much faster (in approximately four hours) in clay soil (Fig. 1e) than muck soil (>8 h after burning, Fig. 1a). We could not record temperature dissipation in sandy soil (Hilliards) because sugarcane harvest occurred immediately after burning. Our results indicate that the transient increase in soil temperature during burning at 2-cm is lower in muck soils (EREC) than clay (El Viejo) or sand (Hilliards), but at 10-cm this increase was very similar in muck and clay which was lower than sand.

3.3. Air temperature

Air temperatures were recorded at EREC and Hilliards to determine if harvest residues had an effect on air temperature at a height (10-cm) similar to young emerging sugarcane plant canopies during freezing or near-freezing temperatures. For cold nights where air temperatures were near or below freezing, minimum air temperatures were always lower in green cane than burnt cane plots (Table 3). Across these cold nights, the average temperature difference between burnt and green cane harvest treatments were 1.20 °C for muck (EREC) and 1.56 °C for sand (Hilliards). A total of 17 freeze events were recorded at EREC and Hilliards during the study period. The temperature differences in green cane and burnt cane harvested plots were significant for five out of 17 freeze events ($P < 0.05$) or 11 out of 17 events ($P < 0.10$), indicating that the presence of thick residues layers with green cane harvest results in colder, and potentially frost-damaging, air temperatures surrounding young sugarcane canopies.

Temporal trends in air temperature for representative freeze events in green and burnt cane are presented in Fig. 3a–d. Length of freeze events ranged from as short as one hour to as long as eight hours. Air temperatures at a 10-cm height in green and burnt cane were similar when ambient temperatures were above 4 °C, but diverged as ambient temperatures dropped below 2 °C. This pattern was consistent across multiple freeze events and soil types, suggesting that the effect of crop residue on canopy air temperatures is noticeable only when ambient air temperatures are close (<2 °C) to freezing.

Table 3
Minimum air temperatures (°C) 10 cm above the soil surface in green cane and burnt cane during freeze or near-freeze events, and the difference between these minimum air temperatures (burnt-green), at EREC and Hilliards[a].

Date	Minimum air temperature (°C)			P
	Green	Burnt	Burnt-green	
EREC				
1/25/2005	−0.67	0.50	1.17	0.002
2/13/2005	−0.67	0.00	0.67	0.016
12/28/2005	−1.17	0.17	1.34	0.094
1/7/2006	−0.25	0.67	0.92	0.295
2/9/2006	−0.00	1.50	1.50	0.122
2/10/2006	−1.67	−0.17	1.50	0.035
2/13/2006	−0.33	0.33	0.66	0.057
2/14/2006	−5.33	−3.50	1.83	0.008
Mean	−1.26	−0.06	1.20	0.158
Hilliards				
1/8/2006	−2.33	−1.67	0.66	0.270
1/16/2006	0.67	1.17	0.50	0.225
2/9/2006	−1.17	1.00	2.17	0.096
2/10/2006	0.50	1.50	1.00	0.147
2/12/2006	0.00	2.17	2.17	0.133
2/13/2006	−0.33	1.33	1.66	0.063
2/14/2006	−5.00	−2.17	2.83	0.042
1/29/2007	0.00	1.67	1.67	0.084
1/30/2007	−1.33	0.00	1.33	0.091
Mean	−1.00	0.56	1.56	0.064

[a] El Viejo is not represented since freezing and near-freezing events did not occur in this tropical environment.

3.4. Diurnal soil temperature

During early-season sugarcane growth (April), there was greater diurnal variation in soil temperature (15-cm depth) at all three sites (EREC, Fig. 4a; Hilliards, Fig. 4c; El Viejo, Fig. 4e) following burnt cane harvest. Maximum daily soil temperatures were considerably lower for green cane harvest treatments. However, minimum daily soil temperature differences between green cane and burnt cane treatments were small. These diurnal temperature trends were still evident during late-growth season (August), but differences between burnt and green cane treatments for diurnal maximum and minimum soil temperatures were appreciably attenuated for all soil types, particularly for the muck soil at EREC (EREC, Fig. 4b; Hilliards, Fig. 4d; El Viejo, Fig. 4f). The insulating effects of crop residues observed during early season growth were likely minimized during late-season growth due to soil shading effects by the larger crop canopy.

Differences between green and burnt cane maximum and minimum soil temperatures throughout the sugarcane growing season (15-cm depth) are shown in Fig. 5. Maximum soil temperatures were higher in burnt cane systems, particularly at early growth stages, whereas minimum temperatures were similar in burnt and green cane systems. Reduced maximum soil temperatures in green cane treatments were greater in sand (Hilliards, Fig. 5b) and clay (El Viejo, Fig. 5c) and less dramatic for muck soils (EREC, Fig. 5a). In April, the greatest difference between harvest treatments for maximum soil temperature was 7–8 °C in sand and clay, and 3–4 °C in muck soil. By August, these differences had declined to <2 °C in sand and clay, and there was almost no difference in muck soil. These soil temperature trends, particularly those recorded during the early growing season, clearly illustrate the insulating effect by sugarcane harvest residues, which serve to reduce the amount of heat entering and/or leaving the soil. Our data also indicate that the trash layer mainly affects the maximum soil temperature early in the growing season and the effect is greater in clay (El-Viejo) and sand (Hilliards) compared to muck (EREC). Fig. 5a–c also highlight the gradual decline in crop residue insulation effects as crop canopies expanded and soil shading increased.

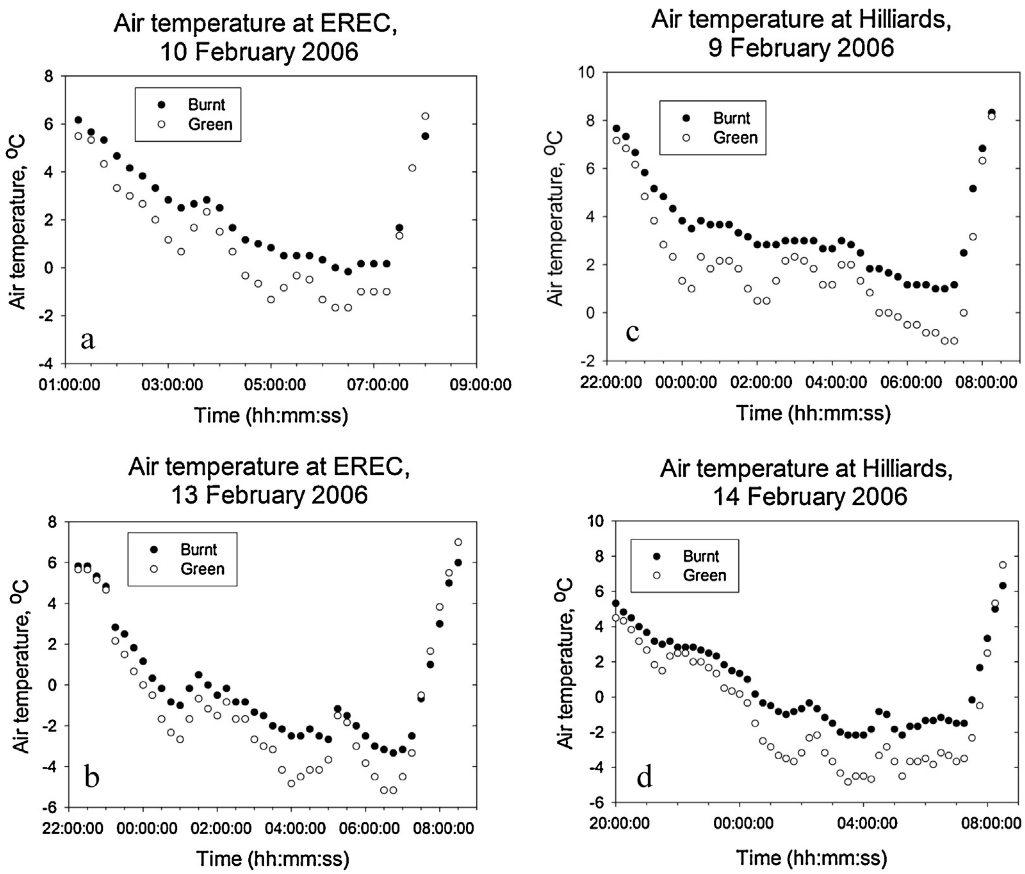

Fig. 3. Mean air temperatures (10-cm above the soil surface) during several freeze events in plots previously subjected to burnt or green cane harvest (EREC and Hilliards).

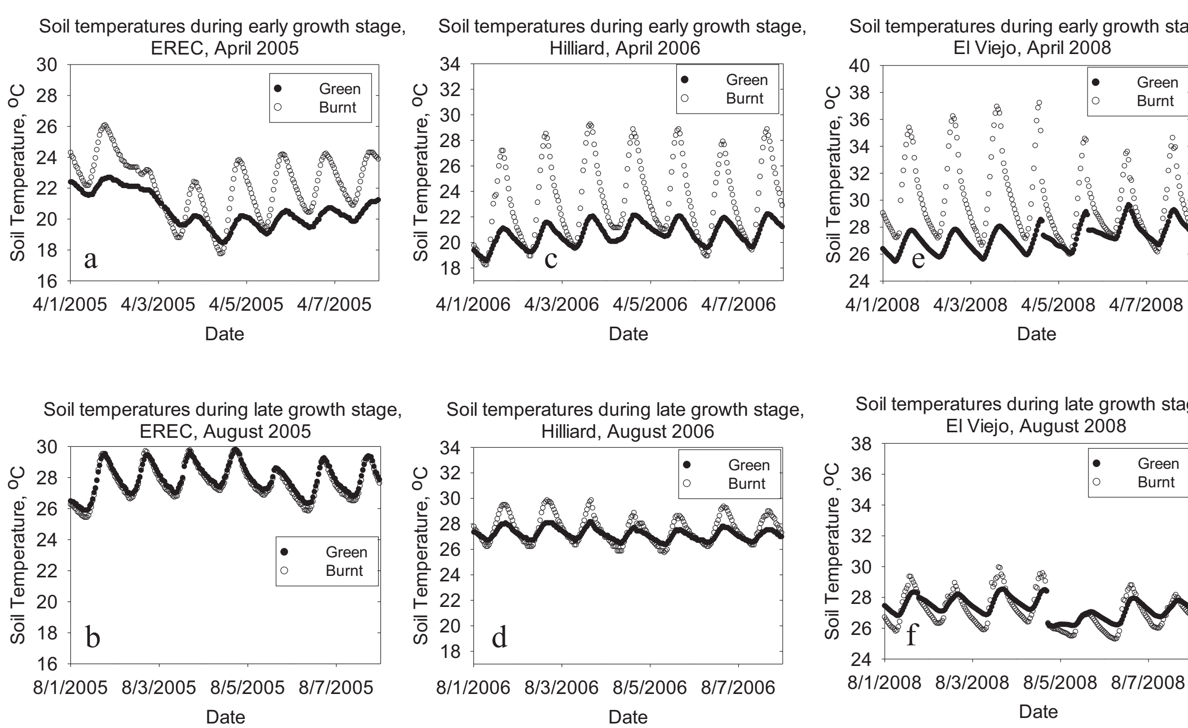

Fig. 4. Diurnal soil temperatures (15-cm soil depth) in April (early sugarcane growth stage) and August (late sugarcane growth stage) for plots previously subjected to burnt or green cane harvest (EREC, Hilliards and El Viejo).

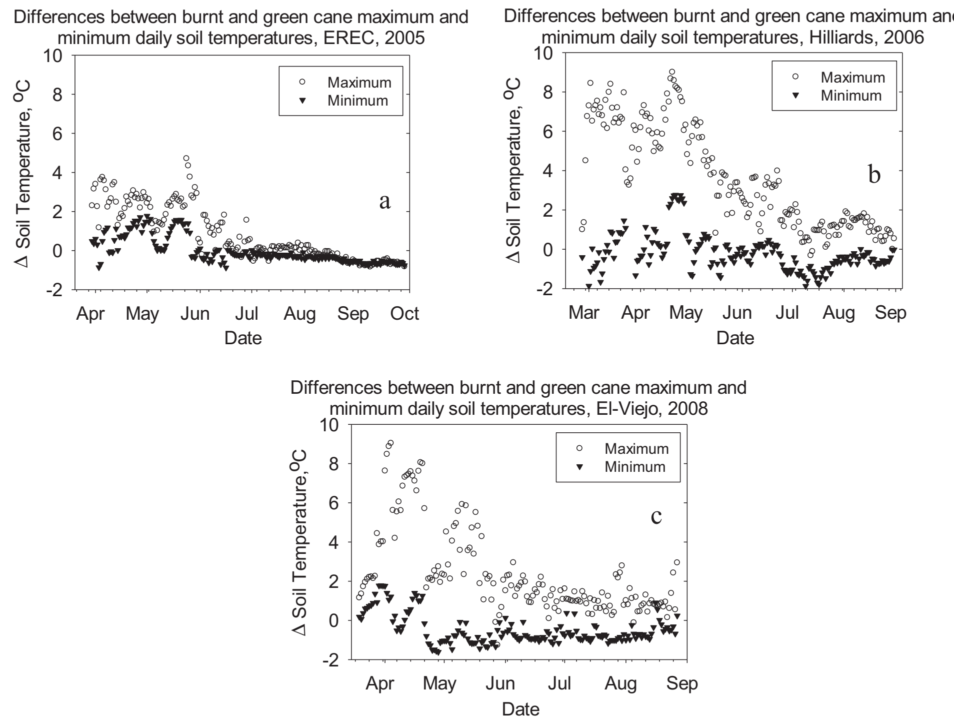

Fig. 5. Difference between burnt cane and green cane maximum and minimum daily soil temperatures (15-cm depth) from April through September–October (EREC, Hilliards, and El Viejo).

4. Discussion

The quantity of harvest residue produced by the green cane harvest treatments was greatest at EREC, followed by Hilliards and then El Viejo (Table 2). Residue levels obtained at EREC (11.6–23.3 t/ha) and Hilliards (13.2–20.8 t/ha) were greater than the 7–16 t/ha recorded in Argentina (Romero et al., 2007) and 7–12 t/ha obtained in Australia (Robertson and Thorburn, 2007). Residue levels recorded at El Viejo (7.6–12.9 t/ha) were similar to those recorded in the aforementioned Argentina and Australia studies. Green cane harvest residues at all three locations of this study exceeded the 4–8 t/ha of residue recorded in Louisiana (Johnson et al., 2007).

Soil temperature increases with pre-harvest burning were greatest in sand (Hilliards) followed by clay (El Viejo) and then muck (EREC) soil (Figs. 1 and 2). This temperature variability with soil type is likely due to different thermal conductivities of these soils. The thermal conductivities of these soils are in the order of sand > clay > peat (muck) (Van Duin, 1963). The differences in the conductivities are due to difference in volumetric proportion of solid, liquid and gaseous phases of these soils. Thermal conductivity diminishes with decreasing soil particle size, which decreases the air filled porosity (Patten, 1909).

The rise in soil temperature during pre-harvest burning is dampened with soil depth (Figs. 1 and 2) because the temperature at any depth is a periodic sine wave with amplitude '*A*' and it is inversely related to soil depth '*d*' (Jury et al., 1991). Similarly, Jury (1973) summarized that rapidly changing temperatures do not penetrate as deeply into the soil as slowly changing temperatures of the same amplitude. Seasonal soil temperature differences (up to 9 °C, Fig. 5b) between burnt and green cane during the sugarcane growing season exceeded the transient soil temperature increase during burn events (up to 7.5 °C, Figs. 1 and 2), suggesting that the actual burn event may not have as great an effect on soil microbial populations as normal seasonal temperature variation at the soil depths measured.

Diurnal maximum soil temperatures were always greater in burnt cane than green cane harvested fields. The difference in soil temperatures in green cane compared to burnt cane harvest at a given location was mainly effected by harvest treatment, as soil type and weather conditions were the same for both the treatments at a particular location. Also the procedure and time to install the temperature sensors were similar for both treatments, and any differences in advection or any other heat transfer process was only due to the treatment. Residue effects on temperature are also supported by Pezzopane et al. (1996), who reported that soil cover provided by sugarcane harvest residue in green cane harvest affects the radiation balance due to modifications in thermal conductivities and reflection coefficients. As a consequence, harvest residue influences all other energy balance components.

Decreases in soil temperatures with post-harvest residue were also reported by Wood (1991), which ultimately resulted in cane yield reductions. Morandini et al. (2005) reported 0.6–3.6 °C (average 1.5 °C) lower soil temperature in green cane harvesting than burnt cane harvesting. Viator et al. (2005) also reported that soil temperatures in plots with harvest residues (mean = 16.8 °C) were lower than plots without harvest residues (mean = 17.5 °C) in early season growth in Louisiana. However in winter months, the presence of harvest residue resulted in increased soil temperatures. Similar insulating effects of harvest residue on soil temperature were reported earlier in sugarcane (Wood, 1991) and in forests (Proe et al., 2001; Devine and Harrington, 2007).

Seasonal soil temperature data in our study indicates that differences between burnt cane and green cane maximum temperatures were greater early in the season (April) than late-season (August) (Figs. 4 and 5). Late in the growth season, the sugarcane canopy shielded the soil surface from direct sunlight and acted as an insulator to reduce soil heat loss. Similarly, Thompson (1966) reported that the soil temperature differences between burnt cane and green cane at a 2.5-cm soil depth was approximately 4 °C during the spring period when the cane canopy was still developing, but temperature differences subsequently declined with increasing canopy development. Declining soil temperature differences between green cane and burnt cane as the growing season progressed were also reported by Page et al. (1986), Wood (1991) and Morandini et al. (2005). Similarly Porté et al. (2004) also reported that the presence of vegetation in pine plantations typically causes a decrease in the amplitude of diurnal soil temperature fluctuation during summer. Also, our results concur with Cabral et al. (2003) who reported that the change in soil heat flux and albedo are directly affected by changes in soil surface cover. They compared the soil heat flow and albedo in a sugarcane field during March, when the plantation was highly developed, with May, when sugarcane was harvested by burnt cane harvesting and the soil was fully exposed. Soil heat flow was increased from 60 W m^{-2} (7% of net radiation, R_n) in March to 140 W m^{-2} (30% of R_n) in May, and albedo reduced from 0.22 in March to 0.12 in May.

During freeze events, air temperature was greater in burnt cane than green cane (Table 3). This likely reflects a more rapid heat from low-residue soil surfaces during cold nights, which subsequently maintains elevated air temperatures in burnt cane plots. Conversely, in green cane plots, soil surfaces were covered with insulating harvest residues, which reduced heat losses from the soil, resulting in lower air temperatures above the crop canopy. Our results support earlier qualitative statements regarding an increased potential for sugarcane frost damage with green harvesting (Beater and Maud, 1962; Thompson, 1966). In citrus, O'Connell and Snyder (1999) also reported that the cover crops lowered the minimum nighttime temperatures by 0.5–1.2 °C, which increased the threat of freeze damage.

5. Conclusion

We conclude that soil temperature increases at burning were greatest in sand soils (Hilliards) followed by clay (El-Viejo) and then muck (EREC), and this effect dampened with soil depth. Temperature increases dissipated much faster in clay soil than muck soil. Transient soil temperature increases following burning were less than normal seasonal soil temperature variation, indicating that burn events have minimal impacts on soil microflora and fauna at the 2- and 10-cm soil depths. Young shoots emerged from green cane harvest may suffer from frost damage which delays growth at air temperatures near freezing. Crop canopy damage by frost is more likely to occur with green cane harvest than with traditional burnt cane harvest.

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