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Soil temperature study in Puerto Rico[1]

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ABSTRACT

Soil temperature measurements from a climate monitoring network in Puerto Rico were evaluated and the difference between mean summer and mean winter soil temperature, known as isotivity value, was calculated. Air and soil temperature was collected from five weather stations of the USDA-Natural Resources Conservation Service from sea level to 1,019 m above sea level and from different soil moisture regimes. Isotivity values ranged from 1.2 to 3.9° C with an average of 2.6° C. The 750-m elevation was identified as the limit between the isohyperthermic and isothermic soil temperature regimes in the perudic soil moisture regime in Puerto Rico. The greatest differences between mean annual soil temperature and mean annual air temperature were observed at Guánica, Combate and Guilarte (2.1° C) stations. The smallest differences were observed at Maricao (0.8° C) and Isabela (1.8° C) stations. The study also indicated that the mean annual soil temperature in Puerto Rico can be estimated by adding 1.8° C to the mean annual air temperature or by the equation $y = -0.007x + 28.0°$ C. The equation indicates that 97 percent of the time the behavior of the mean annual soil temperature is a function of elevation. According to the updated soil temperature regime boundaries, eight soil series were established in the Soil Survey of San Germán Area. In an area under the isothermic soil temperature regime, four soil series were classified as Oxisols (Haploperox), two soil series as Inceptisols (Eutrudepts) and two soil series as Mollisols (Argiudolls). This is the first field recognition of the Haploperox soil great group in the United States and its territories.

Key words: Soil temperature, soil temperature regime, isotivity

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RESUMEN

Estudio de la temperatura del suelo en Puerto Rico

Se evaluaron mediciones de temperatura del suelo de la red de monitoreo de clima en Puerto Rico y se calculó la diferencia entre la temperatura promedio del suelo de verano y de invierno, conocida como valor de isotividad. Se tomaron datos de temperatura del aire y del suelo de cinco estaciones climatológicas del Servicio de Conservación de Recursos Naturales del Departamento de Agricultura de los Estados Unidos desde el nivel del mar hasta 1,019 m de elevación sobre el nivel del mar y a diferentes regímenes de humedad del suelo. Los valores de isotividad oscilaron entre 1.2 y 3.9° C con una media de 2.6° C. El límite entre el régimen de temperatura de suelo isohipertérmico e isotérmico en el régimen de humedad perúdico en Puerto Rico fue identificado a una elevación de 750 m. En las estaciones de Guánica, Combate y Guilarte se observaron las mayores diferencias entre la media anual de la temperatura del suelo y la media anual de la temperatura del aire (2.1° C). En las estaciones de Maricao (0.8° C) e Isabela (1.8° C) se observaron las menores diferencias. El estudio también indica que la media anual de la temperatura del suelo en Puerto Rico puede ser estimada añadiéndole 1.8° C a la media anual de la temperatura del aire o por la ecuación $y = -0.007x + 28.0°$ C. La ecuación indica que el 97 por ciento del tiempo el comportamiento de la media anual de la temperatura del suelo es una función de la elevación. De acuerdo con la actualización de los límites de los regímenes de temperatura de suelo, se establecieron ocho series de suelo en el Catastro de Suelos del Área de San Germán. Cuatro series de suelo clasificaron como Oxisoles (Haploperox), dos series de suelos como Inceptisoles (Eutrudepts) y dos series de suelos como Molisoles (Argiudolls) en el área bajo régimen de temperatura isotérmico. Este es el primer reconocimiento en el campo del gran grupo de suelos Haploperox en los Estados Unidos de América y sus territorios.

Palabras clave: Temperatura del suelo, regímenes de temperatura del suelo, isotividad

INTRODUCTION

Soil temperature can be estimated from air temperature (Soil Survey Staff, 1999) and from the average of four readings equally spaced throughout the year, at about 50-cm or greater depth (Soil Survey Staff, 1999; 2006a). Mean annual soil temperature in tropical regions can be estimated by adding 2 to 4° C to the mean annual air temperature (Comerma and Sánchez, 1981; Van Wambeke, 1981, 1982 and 1985; Murtha and Williams, 1986; Nullet et al., 1990). In most of the United States, 1° C is added to the mean annual air temperature to estimate the mean annual soil temperature (Buol et al., 1997). In 2005, Lugo-Camacho reported that the mean annual soil temperature in Puerto Rico can be estimated by adding 1.6° C to the mean annual air temperature.

Soil temperature influences biological, chemical and physical processes in the soil and the establishment and adaptation of vegetative species. Therefore, soil temperature has implications on soil genesis as well as on the use and management of the soils for crop production (Comerma and Sánchez, 1981).

The isotivity concept implies that the mean summer and mean winter soil temperatures differ by less than 6° C at a depth of 50 cm or at a densic, lithic or paralithic contact, whichever is shallower (Soil Survey Staff, 1999). Murtha and Williams (1986) and Lugo-Camacho (2005) suggested that the difference of less than 5° C between the mean annual soil temperature of the summer (June, July and August) and that of winter months (December, January and February) is a better representation of the isotivity concept as reported in the first edition of Soil Taxonomy (Soil Survey Staff, 1975). Comerma and Sánchez (1981) reported for tropical conditions in Venezuela from sea level to 4,000 m above sea level, and for different soil moisture regimes, isotivity values ranging from 0.7 to 4.2° C with an average isotivity value of 2.3° C. Lugo-Camacho (2005) reported an average isotivity value of 2.4° C and a smaller range variation from 1.3 to 2.9° C. Mount et al. (1992) reported an isotivity of 2.0° C for two sites in the United States Virgin Islands and 4.3° C for one station during 1994 (Mount et al., 1995).

The objective of this work was to evaluate the isotivity value and analyze soil temperature measurements from a climate-monitoring network in Puerto Rico. The soil temperature data was collected for a period ranging from three to six years. The results were used to verify and update current taxonomic classification and to provide reference data for research in tropical areas.

MATERIALS AND METHODS

In order to evaluate soil temperature, we installed five automated weather stations. These stations provided hourly data on air and soil temperature. The location of the stations is shown in Table 1 and the instrumentation and configuration of the stations are summarized in Table 2.

The data were collected for a six-year period with the exception of the Isabela station, where the data were collected for a four-year period. The

TABLE 1.—*Puerto Rico soil climate analysis network.*

Station	Municipality	Coordinates	Elevation (m)
Guánica State Forest	Guánica	17°58’20” N; 66°52’05” W	164
Combate	Cabo Rojo	17°58’45” N; 67°10’08” W	10
Maricao State Forest	Maricao	18°09’26” N; 67°00’14” W	746
Guilarte State Forest	Adjuntas	18°08’54” N; 66°46’04” W	1,019
Isabela	Isabela	18°28’24” N; 67°03’03” W	120

TABLE 2.—*Puerto Rico Soil Climate Analysis Network configuration (USDA-NRCS, 2001).*

Parameter	Description
Precipitation (inches)	TE 525 Tipping bucket precipitation gage at 3 m above the ground.
Air Temperature (° C) / Relative Humidity (%)	Vaisala HMP45C sensor at 1.6 m above the ground.
Wind Speed (mph) and Direction	Met One sensor (propeller-type anemometer) at 3 m above the ground.
Solar Radiation (W/m^2)	LI-COR pyranometer at 3 m above the ground.
Soil Moisture (Volts)/ Soil Temperature (Volts)	Vitel Dielectric constant soil moisture sensors at 5, 10, 20, 50 and 100 cm with the exception of Guánica station where the sensors were at 5, 10, 20, 25 and 30 cm.
Soil Temperature	Campbell 107 soil temperature sensors at 5, 10, 20, 50 and 100 cm with the exception of the Guánica station, where the sensors were at 5, 10, 20, 25 and 30 cm.
Data Transmission	MCC 545 RF modem.

Vaisala HMP45 air temperature sensors were calibrated annually, an environmental chamber within a ± 2° C precision range. The Campbell 107 soil temperature sensors were calibrated by the manufacturer before the installation. CS107 thermisters were installed adjacent to the soil temperature sensors to validate the soil temperature data. The data were automatically validated against limits and were flagged if the value were outside the preset. Any flagged value was examined to determine accuracy, and the appropriate corrections were made. The data were graphed and comparisons were made among sensors to verify that the data were within an acceptable range. Soil temperature readings that were determined to be unreasonable were removed from the data set, and the sensor was replaced. Routine maintenance of the stations was performed periodically to verify the status of batteries and sensors. Close communication was maintained with the National Water and Climate Center to detect irregularities on data collection. Data were summarized and statistically analyzed by using InfoStat version 2004 (InfoStat, 2004) to determine standard deviation, coefficient of variation and mean comparisons by the Tukey test.

RESULTS AND DISCUSSION

Guánica State Forest Station

The soil series at Guánica State Forest Station is La Covana (clayey-skeletal, carbonatic, isohyperthermic Calcic Lithic Petrocalcids) (Soil Survey Staff, 2006b). Table 3 summarizes the soil temperature statistics at 30 cm, and summarizes air temperatures during the period of evaluation. Since this soil is Lithic Petrocalcids, the soil temperature was measured at 30-cm depth, whereas at the other sites it was measured at 50-cm depth.

The mean annual soil temperature for the evaluated period was 27.8° C. The mean summer and mean winter soil temperatures at this site differed by 2.3° C at 30-cm depth meeting the definition for the isotivity concept. A similar isotivity value (2.8° C) was reported by Lugo-Camacho

TABLE 3.—*Air and soil temperature statistics at Bosque Seco State Forest Station, Guánica, Puerto Rico (March 2001 to June 2007).*

Month	Mean Temp (° C)	Number of observations (years)	Standard deviation	Variance (n-1)	Coefficient of variation	Standard Error
	Mean Air Temp (° C)					
January	24.22	6	0.79	0.63	3.27	0.32
February	24.06	6	0.93	0.86	3.86	0.38
March	24.47	7	0.50	0.25	2.03	0.19
April	25.03	7	0.60	0.36	2.40	0.23
May	25.99	7	0.65	0.42	2.50	0.25
June	26.62	7	0.26	0.07	0.99	0.10
July	26.81	6	0.25	0.06	0.92	0.10
August	27.07	6	0.33	0.11	1.20	0.13
September	27.02	6	0.20	0.04	0.73	0.08
October	26.25	6	0.42	0.18	1.62	0.17
November	25.27	6	0.83	0.70	3.30	0.34
December	24.79	6	0.92	0.85	3.71	0.38
Mean	25.63	6.33	0.56	0.38	2.21	0.22
	Mean Soil Temp at 30 cm (° C)					
January	26.17	6	0.98	0.96	3.75	0.40
February	26.45	6	0.98	0.96	3.71	0.40
March	27.47	6	0.63	0.40	2.29	0.26
April	27.73	7	0.99	0.97	3.56	0.37
May	27.84	7	0.71	0.50	2.55	0.27
June	28.04	7	0.38	0.14	1.35	0.14
July	28.66	6	0.86	0.74	2.99	0.35
August	29.38	6	0.84	0.71	2.87	0.34
September	29.66	6	0.60	0.37	2.04	0.25
October	28.20	6	0.77	0.59	2.72	0.31
November	27.10	6	1.09	1.20	4.04	0.45
December	26.50	6	0.99	0.97	3.72	0.40
Mean	27.77	6.25	0.82	0.71	2.97	0.33

(2005) for this station from March 2001 to September 2004. This site is a representative of an isohyperthermic soil temperature regime.

Figure 1 shows the mean monthly air temperature and soil temperatures at different depths. The Tukey-Cramer test indicated no significant differences in mean monthly soil temperatures among soil depths ($p < 0.05$). This station did not register the fluctuations in soil temperature that usually occur near the surface and are expected to be fewer as soil depth increases. Shallow soils are expected to be more influenced by fluctuations in air temperature than deep soils (Brady and Weil, 2002).

Figure 1 also shows the buffer capacity of the soil against air temperature changes. The highest mean air temperature occurs during the month of August (27.1° C), but the highest mean soil temperature

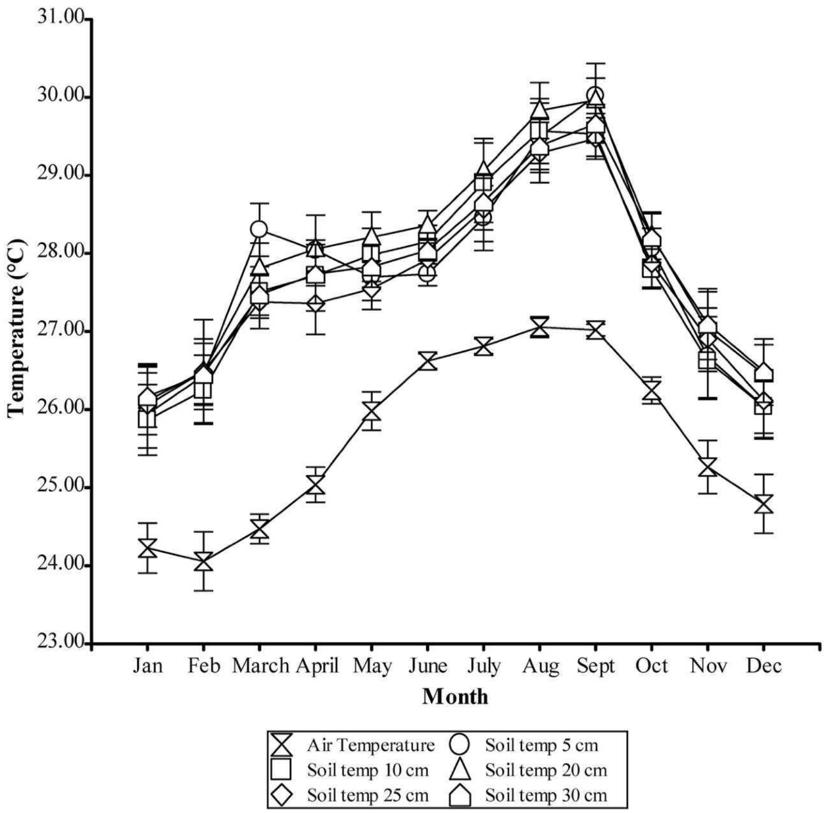

FIGURE 1. Guánica state forest station air and soil temperature data at different depths (2001-2007).

(29.7° C) is observed in September. The opposite effect occurs during the cooler months. The lowest mean air temperature occurs during the month of February (24.1° C) and the lowest mean soil temperature was recorded during the month of January (26.2° C).

The mean annual air temperature for the evaluated period was 25.6° C and the mean annual precipitation was 770 mm. The results at this site demonstrate that the mean annual soil temperature can be estimated by adding 2.1° C to the mean annual air temperature (Table 4). This value was obtained by averaging the temperature difference for each month. This procedure was performed for the five stations, and a mean value for the five stations was also calculated. The 2.1° C estimated value agrees with values reported by Comerma and Sánchez (1981), Van Wambeke (1981, 1982 and 1985), Murtha and Williams (1986) and Lugo-Camacho (2005).

Combate Station

The soil series at this site is Sosa (fine, kaolinitic, isohyperthermic Aridic Haplustalfs) (Beinroth et al., 2003). Table 5 summarizes the soil temperature statistics at 50 cm, and summarizes mean monthly air temperature for Combate station during the period of evaluation.

The mean annual soil temperature for the evaluated period was 28.1° C. The mean summer and mean winter soil temperatures at this site differed by 3.4° C at 50-cm depth, thus coinciding with the definition for the isotivity concept. A similar isotivity value (2.9° C) was reported by Lugo-

TABLE 4.—*Difference between soil temperature at 30 cm and air temperature at the Guánica State Forest Station.*

Month	Mean Monthly Soil Temp at 30 cm (° C)	Mean Monthly Air Temp (° C)	Temperature Difference (° C)
January	26.17	24.22	1.95
February	26.45	24.06	2.39
March	27.47	24.47	3.00
April	27.73	25.03	2.70
May	27.84	25.99	1.85
June	28.04	26.62	1.42
July	28.66	26.81	1.85
August	29.38	27.07	2.31
September	29.66	27.02	2.64
October	28.20	26.25	1.95
November	27.10	25.27	1.83
December	26.50	24.79	1.71
Mean	27.77	25.63	2.1

TABLE 5.—*Air and soil temperature statistics at Combate Station, Cabo Rojo, Puerto Rico (March 2001 to June 2007).*

Month	Mean Temp (° C)	Number of observations (years)	Standard deviation	Variance (n-1)	Coefficient of variation	Standard Error
	Mean Air Temp (° C)					
January	24.12	5	0.79	0.63	3.28	0.35
February	24.21	5	0.89	0.79	3.67	0.40
March	24.95	7	0.61	0.37	2.45	0.23
April	25.38	7	0.66	0.43	2.59	0.25
May	26.51	6	0.54	0.29	2.04	0.22
June	27.54	6	0.39	0.15	1.43	0.16
July	27.48	5	0.49	0.24	1.79	0.22
August	27.46	5	0.52	0.27	1.89	0.23
September	27.42	5	0.40	0.16	1.46	0.18
October	26.94	5	0.26	0.07	0.95	0.11
November	25.51	6	0.78	0.61	3.05	0.32
December	24.75	5	0.77	0.59	3.09	0.34
Mean	26.02	5.58	0.59	0.38	2.31	0.25
	Mean Soil Temp at 50 cm (° C)					
January	25.76	5	0.66	0.43	2.56	0.29
February	26.02	5	0.32	0.10	1.24	0.14
March	27.57	7	1.10	1.21	4.00	0.42
April	28.21	6	1.31	1.72	4.64	0.53
May	28.63	6	1.17	1.36	4.08	0.48
June	29.27	6	1.22	1.50	4.18	0.50
July	29.30	5	1.17	1.36	3.98	0.52
August	29.64	5	0.90	0.81	3.03	0.40
September	29.95	5	1.03	1.06	3.43	0.46
October	29.17	4	0.91	0.82	3.11	0.45
November	27.61	4	0.77	0.59	2.79	0.38
December	26.27	5	0.51	0.26	1.94	0.23
Mean	28.12	5.25	0.92	0.94	3.25	0.40

Camacho (2005) for this station from March 2001 to August 2004. This station is also a representative site of an isohyperthermic soil temperature regime.

Table 5 summarizes the air temperature statistics, and Figure 2 shows the mean monthly air temperature versus the mean soil temperatures at different depths for the evaluation period. The Tukey-Cramer test indicated no significant differences in mean monthly soil temperatures among soil depths ($p < 0.05$). This station did not show fluctuations in soil temperature that may occur at the soil surface, and are expected to be less as the depth increases.

Figure 2 also shows the buffer capacity of the soil. The highest mean air temperature occured during the month of June (27.5° C), but the effect on the soil was observed three months later at a depth of 50 cm with a mean soil temperature of 29.9° C. This effect was not observed during the cooler months. The lowest mean air temperature (24.1° C) and the lowest mean soil temperature (25.8° C) were observed in January.

The mean annual air temperature for the evaluated period was 26.0° C and the mean annual precipitation was 625 mm. The results at this site demonstrate that the mean annual soil temperature can be estimated by adding 2.1° C to the mean annual air temperature (Table 6). This value agrees with values reported by Comerma and Sánchez

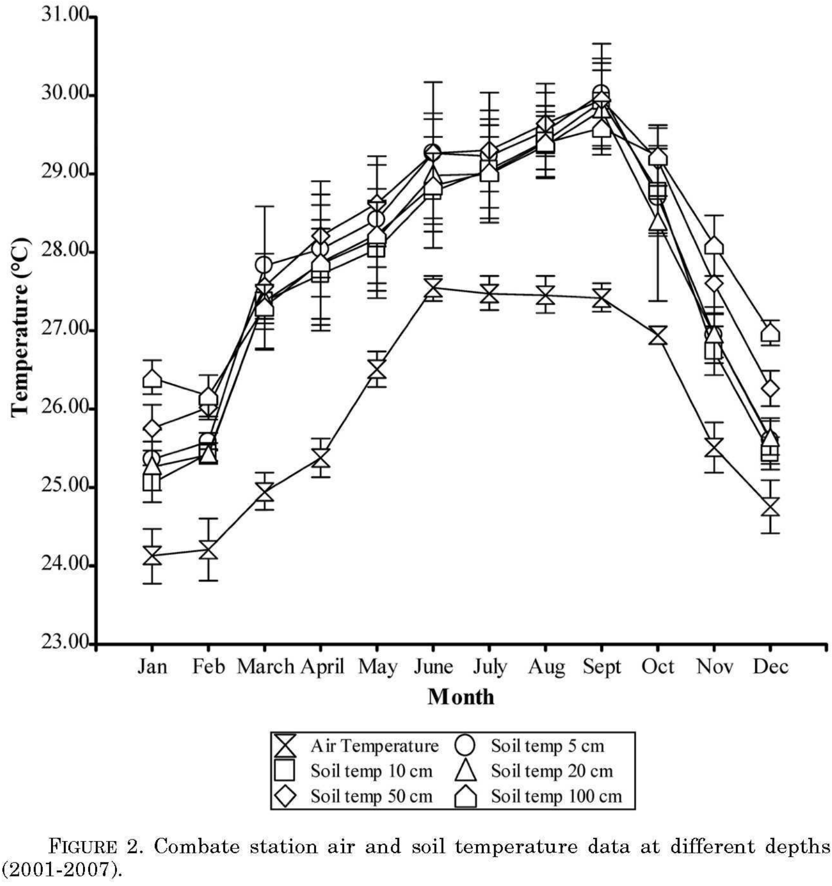

FIGURE 2. Combate station air and soil temperature data at different depths (2001-2007).

TABLE 6.—*Difference between soil temperature and air temperature at the Combate, Monte del Estado, Guilarte and Isabela Stations.*

	Combate Station			Monte del Estado State Forest Station		
Month	Mean Monthly Soil Temp at 50 cm (° C)	Mean Monthly Air Temp (° C)	Temperature Difference (° C)	Mean Monthly Soil Temp at 50 cm (° C)	Mean Monthly Air Temp (° C)	Temperature Difference (° C)
January	25.76	24.12	1.64	21.11	19.30	1.81
February	26.02	24.21	1.81	20.96	19.60	1.36
March	27.57	24.95	2.62	21.08	20.20	0.88
April	28.21	25.38	2.83	21.37	20.48	0.89
May	28.63	26.51	2.12	21.64	21.31	0.33
June	29.27	27.54	1.73	22.20	22.16	0.04
July	29.30	27.48	1.82	22.38	22.13	0.25
August	29.64	27.46	2.18	22.73	22.45	0.28
September	29.95	27.42	2.53	22.83	22.60	0.23
October	29.17	26.94	2.23	22.72	21.97	0.75
November	27.61	25.51	2.10	22.21	20.90	1.31
December	26.27	24.75	1.52	21.59	20.26	1.33
Mean	28.12	26.02	2.10	21.90	21.11	0.80
	Guilarte State Forest Station			Isabela Station		
January	19.88	17.04	2.84	23.81	22.60	1.2
February	19.76	17.00	2.76	23.81	22.81	1.0
March	20.20	17.71	2.49	25.18	23.43	1.8
April	20.49	18.31	2.18	26.31	24.22	2.1
May	21.08	19.18	1.90	27.14	24.98	2.1
June	21.90	20.48	1.42	27.97	25.86	2.1
July	22.16	20.48	1.68	27.89	25.92	2.0

TABLE 6.—*(Continued) Difference between soil temperature and air temperature at the Combate, Monte del Estado, Guilarte and Isabela Stations.*

Month	Guilarte State Forest Station			Isabela Station		
	Mean Monthly Soil Temp at 50 cm (° C)	Mean Monthly Air Temp (° C)	Temperature Difference (° C)	Mean Monthly Soil Temp at 50 cm (° C)	Mean Monthly Air Temp (° C)	Temperature Difference (° C)
August	22.48	20.35	2.13	28.04	25.84	2.2
September	22.31	20.52	1.79	27.92	25.66	2.2
October	21.89	20.01	1.88	27.26	24.96	2.3
November	21.11	18.75	2.36	25.82	24.18	1.6
December	20.45	18.75	1.70	24.58	23.97	0.6
Mean	21.14	19.05	2.10	26.31	24.54	1.8

(1981), Van Wambeke (1981, 1982 and 1985), Murtha and Williams (1986) and Lugo-Camacho (2005).

Maricao Station

The soil series at this site is Rosario (Clayey, ferruginous, isohyperthermic, shallow Inceptic Hapludox) (Beinroth et al., 2003). Table 7 presents the air and soil temperature statistics for the Maricao station. The mean annual soil temperature for the evaluated period was 21.9° C, which is at the borderline of the isothermic and isohyperthermic soil

TABLE 7.—*Air and soil temperature statistics at Monte del Estado State Forest Station, Maricao, Puerto Rico (May 2001 to June 2007).*

	Mean Air Temp (° C)					
Month	Mean Temp (° C)	Number of observations (years)	Standard deviation	Variance (n-1)	Coefficient of variation	Standard Error
January	19.30	6	1.30	1.70	6.75	0.53
February	19.60	4	1.73	3.01	8.85	0.87
March	20.20	6	0.70	0.49	3.45	0.28
April	20.48	6	0.44	0.19	2.14	0.18
May	21.31	6	0.70	0.49	3.30	0.29
June	22.16	7	0.15	0.02	0.69	0.06
July	22.13	6	0.35	0.12	1.59	0.14
August	22.45	6	0.35	0.13	1.58	0.14
September	22.60	5	0.30	0.09	1.31	0.13
October	21.97	5	0.58	0.33	2.62	0.26
November	20.90	6	1.02	1.05	4.90	0.42
December	20.26	6	0.76	0.58	3.76	0.31
Mean	21.11	5.75	0.70	0.68	3.41	0.30
	Mean Soil Temp at 50 cm (° C)					
January	21.11	6	0.59	0.35	2.80	0.24
February	20.96	4	0.81	0.66	3.87	0.41
March	21.08	6	0.37	0.14	1.75	0.15
April	21.37	6	0.27	0.07	1.25	0.11
May	21.64	6	0.25	0.06	1.14	0.10
June	22.20	7	0.19	0.04	0.85	0.07
July	22.38	6	0.07	0.00	0.32	0.03
August	22.73	6	0.19	0.04	0.83	0.04
September	22.83	5	0.27	0.07	1.18	0.12
October	22.72	5	0.19	0.04	0.85	0.09
November	22.21	6	0.38	0.14	1.69	0.15
December	21.59	6	0.41	0.17	1.90	0.17
Mean	21.90	5.75	0.33	0.15	1.54	0.14

temperature regimes at the elevation of 746 m above sea level. The data indicate that, in a perudic soil moisture regime, an elevation of 750 m better represents the limit between the isohyperthermic and the isothermic soil temperature regimes than the 900-m limit established for the udic soil moisture regime (Lugo-Camacho, 2005).

The mean summer and mean winter soil temperatures at this site differ by 1.2° C at 50-cm depth, thus coinciding with the definition for the isotivity concept. A similar isotivity value (1.6° C) was reported by Lugo-Camacho (2005) for this station from May 2001 to October 2004.

Figure 3 shows the mean annual monthly air temperature versus the mean soil temperatures at different depths at this station for the study period. The Tukey-Cramer test did not show significant differ-

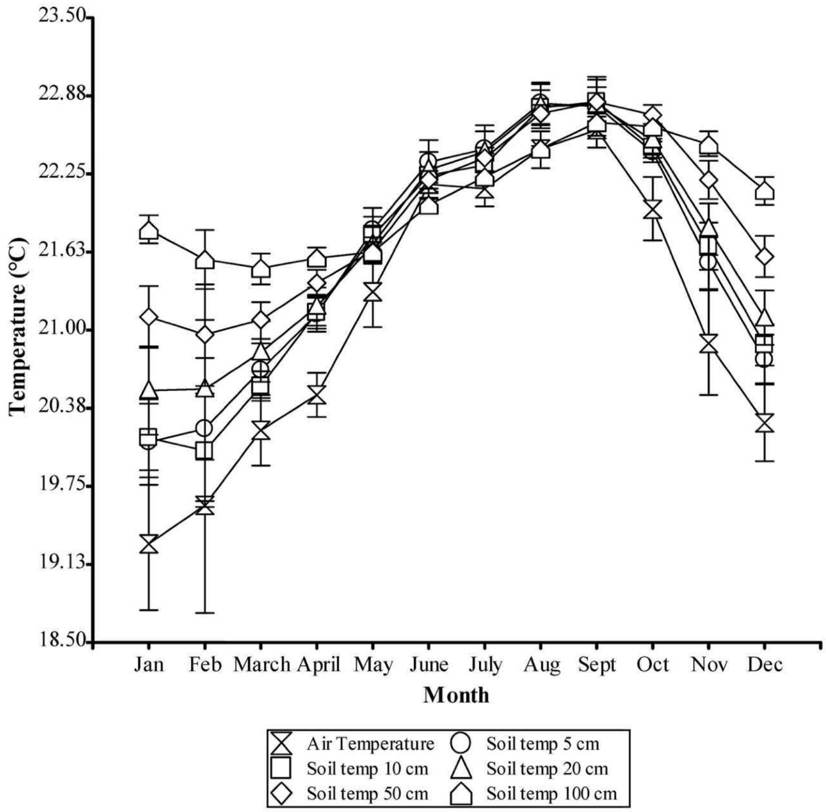

FIGURE 3. Maricao station air and soil temperature data at different depths (2001-2007).

ences between the mean monthly soil temperatures and soil depth ($p < 0.05$) during the months of April to October. During the month of November the mean soil temperature at 50 cm and at 100 cm was significantly different from the mean soil temperature at 5 cm. There were no significant differences in the mean soil temperature at 5, 10, and 20 cm. During the months of December, January and March the mean soil temperatures at 50 cm and 100 cm were significantly higher than the mean soil temperature at 5 and 10 cm. This station shows greater fluctuations in soil temperature near the surface as expected. Less fluctuation is observed during the cooler months as soil depth increases. From April to October the variation in soil temperature as a function of depth was minor. As soil depth increased the variation in soil temperature among months also decreased.

Figure 3 also shows that the highest mean air temperature (22.6° C) and the highest soil temperature at a depth of 50 cm (22.8° C) occurred in September. The lowest mean air temperature for this station was recorded in January (19.3° C), but the lowest soil temperature (21.0° C) at a depth of 50 cm, was recorded in February. The fact that the highest mean air temperature and the highest mean soil temperature, contrary to the finding at Guánica and Combate stations, were observed during the same month can be attributed to the high soil water content in late summer and early fall at the Maricao station. Soil temperature changes are controlled by soil water high specific heat capacity and high solar radiation input (Brady and Weil, 2002).

The mean annual air temperature for the evaluated period was 21.1° C and the mean annual precipitation was 1,832 mm. The mean annual soil temperature at this site can be estimated by adding 0.8° C to the mean annual air temperature (Table 6). This value is lower than the mean values reported by Comerma and Sánchez (1981), Van Wambeke (1981, 1982 and 1985) and Murtha and Williams (1986). This value is in the range of 0.7 to 4.2° C reported by Comerma and Sánchez (1981).

Monte Guilarte Station

The soil series at this site is Maricao (very-fine, mixed, subactive, isothermic Typic Haplohumults) (Beinroth et al., 2003). Table 8 summarizes the air and soil temperature statistics for the Monte Guilarte station. The mean annual soil temperature for the evaluated period was 21.1° C. The mean summer and mean winter soil temperatures at this site differed by 2.2° C at 50-cm depth meeting the definition for the isotivity concept. A similar isotivity value (2.3° C) was reported by Lugo-Camacho (2005) for this station from May 2001 to August 2004. This station is a representative site for an isothermic soil temperature regime.

TABLE 8.—*Air and soil temperature statistics at Monte Guilarte State Forest Station, Adjuntas, Puerto Rico (May 2001 to June 2007).*

	Mean Air Temp (° C)					
Month	Mean Temp (° C)	Number of observations (years)	Standard deviation	Variance (n-1)	Coefficient of variation	Standard Error
January	17.04	5	0.69	0.47	4.04	0.31
February	17.00	5	0.88	0.78	5.21	0.40
March	17.71	5	0.65	0.42	3.65	0.29
April	18.31	5	0.58	0.34	3.18	0.26
May	19.18	5	0.38	0.14	1.96	0.17
June	20.48	5	0.83	0.68	4.03	0.37
July	20.48	5	0.64	0.41	3.12	0.29
August	20.35	5	0.16	0.03	0.79	0.07
September	20.52	4	0.22	0.05	1.05	0.11
October	20.01	4	0.19	0.04	0.96	0.10
November	18.75	6	0.51	0.26	2.71	0.21
December	18.75	5	0.53	0.28	2.92	0.24
Mean	19.05	4.92	0.52	0.33	2.80	0.24
	Mean Soil Temp at 50 cm (° C)					
January	19.88	4	0.84	0.70	4.20	0.42
February	19.76	5	0.39	0.15	1.96	0.17
March	20.20	5	0.68	0.46	3.35	0.30
April	20.49	5	0.82	0.67	3.98	0.36
May	21.08	5	0.68	0.46	3.22	0.30
June	21.90	5	0.56	0.31	2.56	0.25
July	22.16	5	0.51	0.26	2.29	0.23
August	22.48	5	0.61	0.38	2.73	0.27
September	22.31	4	1.16	1.35	5.20	0.58
October	21.89	4	0.98	0.96	4.48	0.49
November	21.11	6	0.86	0.74	4.07	0.35
December	20.45	5	1.13	1.28	5.54	0.51
Mean	21.14	4.83	0.77	0.64	3.63	0.35

Figure 4 shows the mean monthly air temperature versus the mean soil temperatures at different depths at this station for the study period. The Tukey-Cramer test did not show significant differences between the mean monthly soil temperature among soil depths ($p < 0.05$) from February to December. During the month of January the mean soil temperature at 5 cm was significantly different from the mean soil temperature at depths of 20 and 50 cm. This station did not show significant fluctuations in soil temperature near the surface, probably because of the high water content in the

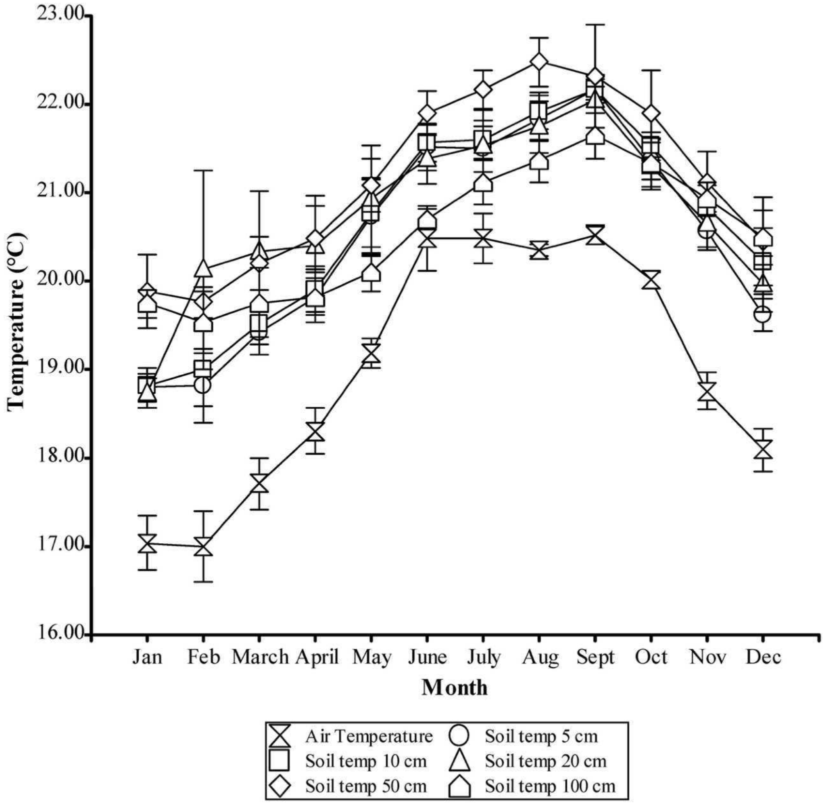

FIGURE 4. Monte Guilarte station air and soil temperature data at different depths (2001-2007).

soil through the year, a typical condition in a perudic soil moisture regime (Lugo-Camacho, 2005).

Figure 4 also shows the buffer capacity of the soil. The highest mean air temperature (20.5° C) occured during June and July, but the highest soil temperature (22.5° C) was observed in August, at a depth of 50 cm. This effect was not observed during the cooler months. The lowest mean air temperature (17.0° C) occurs during February as well as the lowest mean soil temperature (19.8° C).

The mean annual air temperature for the evaluated period was 19.0° C, and the mean annual precipitation was 2,153 mm. The results at this site demonstrated that the mean annual soil temperature can be estimated by adding 2.1° C to the mean annual air temperature (Table 6). This value agrees with those reported by Comerma and Sánchez

(1981), Van Wambeke (1981, 1982 and 1985), Murtha and Williams (1986) and Lugo-Camacho (2005).

Isabela Station

The soil series at this site is Coto (very-fine, kaolinitic, isohyperthermic Typic Eutrustox) (Beinroth et al., 2003). Table 9 summarizes the air and soil temperature statistics for the Isabela station.

The mean annual soil temperature for the evaluated period was 26.3° C. The mean summer and mean winter soil temperatures at the

TABLE 9.—*Air and soil temperature statistics at Isabela Station, Isabela, Puerto Rico (August 2003 to June 2007).*

	Mean Air Temp (° C)					
Month	Mean Temp (° C)	Number of observations (years)	Standard deviation	Variance (n-1)	Coefficient of variation	Standard Error
January	22.60	4	0.74	0.54	3.26	0.37
February	22.81	3	0.89	0.79	3.90	0.51
March	23.43	4	0.17	0.03	0.74	0.09
April	24.22	4	0.22	0.05	0.92	0.11
May	24.98	4	0.33	0.11	1.32	0.17
June	25.86	4	0.26	0.07	1.02	0.13
July	25.92	3	0.23	0.06	0.91	0.14
August	25.84	4	0.46	0.21	1.77	0.23
September	25.66	4	1.02	1.05	3.99	0.51
October	24.96	3	1.09	1.19	4.36	0.63
November	24.18	4	0.75	0.56	3.10	0.37
December	23.97	4	0.69	0.47	2.93	0.34
Mean	24.54	3.75	0.57	0.43	2.35	0.30
	Mean Soil Temp at 50 cm (° C)					
January	23.81	4	0.41	0.17	1.73	0.21
February	23.81	3	1.10	1.20	4.60	0.63
March	25.18	4	0.13	0.02	0.53	0.07
April	26.31	4	0.21	0.04	0.79	0.10
May	27.14	4	0.56	0.32	2.08	0.28
June	27.97	4	0.52	0.28	1.88	0.26
July	27.89	3	0.27	0.07	0.96	0.15
August	28.04	4	0.45	0.20	1.59	0.22
September	27.92	4	0.50	0.25	1.80	0.25
October	27.26	3	0.47	0.22	1.73	0.27
November	25.82	4	0.49	0.24	1.91	0.25
December	24.58	4	0.34	0.12	1.39	0.17
Mean	26.31	3.75	0.45	0.26	1.75	0.24

Isabela station differed by 3.9° C at 50-cm depth, thus coinciding with the definition for the isotivity concept. This station is also a representative site for an isohyperthermic soil temperature regime.

Figure 5 shows the mean monthly air temperature versus the mean soil temperatures at different depths at this station for the study period. The Tukey-Cramer test did not show significant differences among the mean monthly soil temperatures among soil depths ($p < 0.05$) from February to November. During January and December the mean soil temperature at 50 cm was significantly higher than the mean soil temperatures at 5- and 10-cm depths. This station did not show significant fluctuations in soil temperature near the surface, although temperature was expected to be lower as the depth increased during

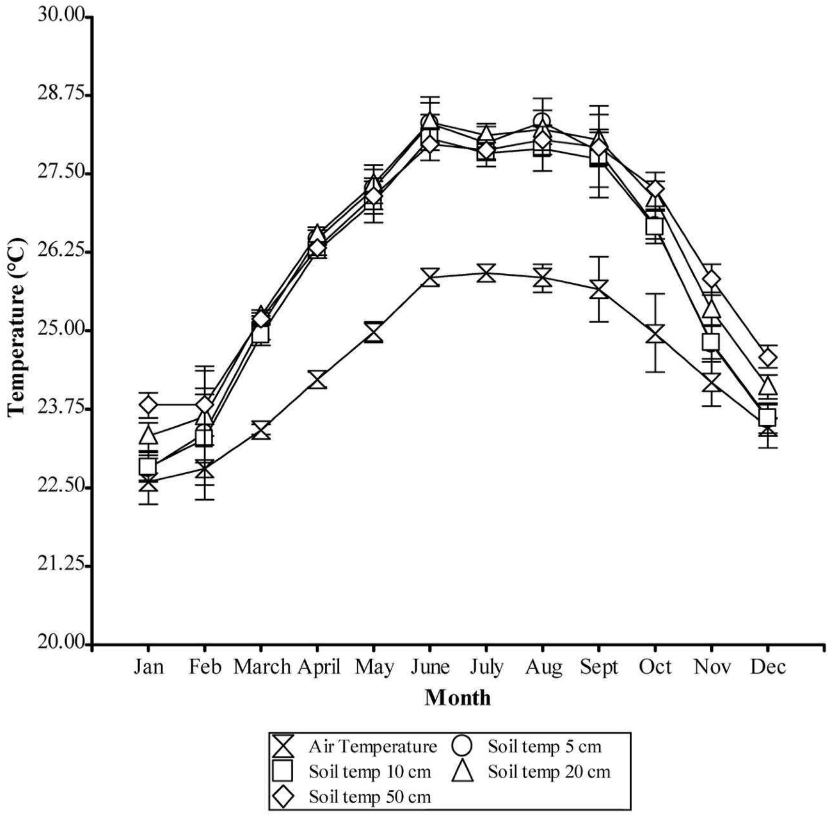

FIGURE 5. Isabela station air and soil temperature data at different depths (2003-2007).

the months from February to November. More years of observation are needed at this station in order to confirm the lack of fluctuation in soil temperature near the surface.

Figure 5 also shows the buffer capacity of this soil. The highest mean air temperature (25.9° C) occurred during July, but the highest mean soil temperature (28.0° C) was observed in August. This effect was not observed during the winter months. The lowest mean air temperature (22.6° C) was recorded in January as well as the lowest mean soil temperature (23.8° C).

The mean annual air temperature for the evaluated period was 24.5° C and the mean annual precipitation was 1,618 mm. The results of this site demonstrated that the mean annual soil temperature can be estimated by adding 1.8° C to the mean annual air temperature (Table 6). This value agrees with values reported by Comerma and Sánchez (1981), Van Wambeke (1981, 1982 and 1985), Murtha and Williams (1986) and Lugo-Camacho (2005).

Soil Taxonomy Implications

According to the updated isothermic and isohyperthermic soil temperature regime boundaries, eight soil series were established in the Soil Survey of the San Germán Area (Lugo-Camacho et al., 2008) (Table 10) and we expect that new soil series will be established on the basis of the climatic data obtained and reported in this study. Four soil series were classified as Oxisols (Haploperox), two soil series as Inceptisols (Eutrudepts) and two soil series as Mollisols (Argiudolls) in an area under isothermic soil temperature regime. This is the first field recognition of the Haploperox soil great group in the United States and its territories. The Inceptisols order covers an area of 913 ha, equivalent to 62.1 percent of the 1,470 ha updated by the USDA-NRCS. The Mollisols order covers an area of 415 ha (28.3 percent) and the Oxisols order covers an area of 142 ha (9.6 percent) (Lugo-Camacho et al., 2008). The acreage of land occupied by the different soil orders will also change as the soil survey for the whole island is updated.

Air Temperature Relationships

Figure 6 shows the relationship between the elevation above sea level and the mean annual air temperature. This figure shows a good coefficient of correlation of $r = -0.983$. The linear regression equation indicates that each increment of one meter in elevation results in a mean annual air temperature decrease of 0.007° C.

TABLE 10.—*New soil series in the isothermic soil temperature regime in Puerto Rico.*

Updated soil series classification with isothermic soil temperature regime in Puerto Rico			
Before		Present	
Series	Taxonomic Classification	Series	Taxonomic Classification
Caguabo	Loamy, mixed, active, isohyperthermic Lithic Eutrudepts	Chiquito	Clayey-skeletal, mixed, active, isothermic Lithic Eutrudepts
Caguabo	Loamy, mixed, active, isohyperthermic Lithic Eutrudepts	Rubias	Fine, mixed, active, isothermic, shallow Humic Eutrudepts
Nipe	Very-fine, ferruginеous, isohyperthermic Typic Acrudox	Cerro Gordo	Very-fine, ferruginеous, isothermic Typic Haploperox
Rosario	Clayey, ferruginеous, isohyperthermic, shallow Inceptic Hapludox	Aljibe	Clayey, ferruginеous, isothermic, shallow Rhodic Haploperox
Rosario	Clayey, ferruginеous, isohyperthermic, shallow Inceptic Hapludox	Guamá	Very-fine, ferruginеous, isothermic Rhodic Haploperox
Rosario	Clayey, ferruginеous, isohyperthermic, shallow Inceptic Hapludox	Indiera	Very-fine, ferruginеous, isothermic Typic Haploperox
Serpentinite outcrop	N/A	El Descanso	Clayey-skeletal, magnesic, isothermic Lithic Argiudolls
Serpentinite outcrop	N/A	Hoconuco	Clayey, magnesic, isothermic, shallow Typic Argiudolls

Soil Temperature Relationships

Figure 6 shows the relationship between the elevation above sea level and the mean annual soil temperature. This figure shows a good coefficient of correlation of r = -0.973. The linear regression equation indicates that each increment of one meter in elevation results in a mean annual soil temperature decrease of 0.007° C.

CONCLUSIONS

The soil temperature regime classes identified in this study are the isohyperthermic and the isothermic regimes. The elevation limit between the isohyperthermic and the isothermic soil temperature regimes in the perudic soil moisture regime is 750 m above sea level, thus supporting the findings reported by Lugo-Camacho (2005).

The difference between soil and air temperature for the two coastal stations (Combate and Isabela) was less during the coldest months, whereas at the three other stations, located farther from the coast, it was higher. This finding is indicative of a coastal effect favoring the equilibrium between air and soil temperature during the coldest months.

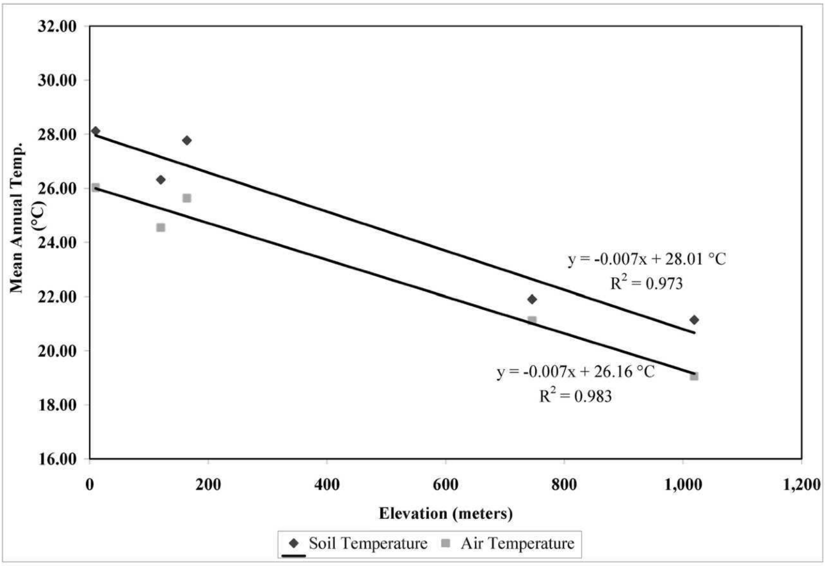

FIGURE 6. Relationship between elevation above sea level and the mean annual air temperature and the mean annual soil temperature in Puerto Rico.

The mean annual soil temperature in Puerto Rico can be estimated by adding 1.8° C to the mean annual air temperature or by the equation $y = -0.007x + 28.0° C$.

The mean isotivity value in Puerto Rico is 2.6° C, which is close to the value reported by Lugo-Camacho (2005) of 2.4° C for four of the five stations. The isotivity values have a range from 1.2° C to 3.9° C. This finding demonstrates that the soils of Puerto Rico have an isotivity value of 5° C or lower as defined by the Soil Survey Staff (1975) or 6° C or lower as established by the Soil Survey Staff (1999).

Eight soil series were established in the Soil Survey of San Germán Area; four soil series were classified as Oxisols (Haploperox), two soil series as Inceptisols (Eutrudepts), and two soil series as Mollisols (Argiudolls) in an area under isothermic soil temperature regime. This is the first field recognition of the Haploperox soil great group in the United States and its territories.

One limitation of the study is the amount of available data on soil temperature, especially at the Isabela station. At this station soil temperature has been collected for only three to four years. The results of this study will improve significantly as more temperature data are collected in future years.

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