ASSESSMENT OF THE ACCURACY OF SITE-SPECIFIC ESTIMATES OF RAINFALL, AIR TEMPERATURE, RELATIVE HUMIDITY, AND WETNESS DURATION IN THE NORTHERN PACIFIC REGION OF COSTA RICA[1]

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Key words: Site-specific estimates, weather parameters, Costa Rica.

RESUMEN

Precisión de la estimación en sitio específico de lluvia, temperatura del aire, humedad relativa y período de humedad en el Pacífico Norte de Costa Rica. Se evaluó la exactitud de las estimaciones de variables meteorológicas horarias en sitios específicos, calculadas por el sistema computarizado SkyBit Inc. La evaluación se hizo mediante la comparación con datos reales obtenidos sobre el terreno en 5 sitios ubicados en la región del Pacífico Norte de Costa Rica, de abril a septiembre de 1999. Las variables estimadas fueron lluvia, temperatura del aire, humedad relativa (HR) y duración del período de humedad. El sistema SkyBit identificó incorrectamente la presencia o ausencia de lluvia en un 29% de los días considerados, principalmente por la identificación de lluvia en días en que no fue registrada. El índice crítico de éxito (CSI, por sus siglas en inglés) indicó que la exactitud de la predicción de lluvia fue mayor (0.68) que en el caso de un conjunto de datos comparable obtenido en la región del medio oeste de los Estados Unidos (0.56). Los errores medios de SkyBit, al estimar la duración y cantidad de la lluvia diaria, fueron relativamente bajos, pero se incrementaron con la cantidad de lluvia medida por día. El sistema SkyBit subestimó la temperatura

ABSTRACT

Accuracy of hourly, site-specific estimates of rainfall, air temperature, relative humidity (RH), and wetness duration by SkyBit, Inc. was assessed with respect to on-site measurements of these parameters at 5 sites in the Northern Pacific Region of Costa Rica during April-September 1999. SkyBit misidentified the occurrence or absence of measured rain on 29% of the days in the Costa Rica data set, primarily due to misidentification of rainfall occurrence on days when none was recorded. The Critical Success Index (CSI) indicated that accuracy of daily rainfall occurrence estimation was higher (0.68) than for a comparable data set obtained in the midwestern USA (0.56). Mean errors of SkyBit estimates of rainfall duration and amount per day were relatively small, but increased with the amount of rain measured per day. SkyBit underestimated mean daily temperature by about 1.8° C but underestimated minimum daily temperature by about 4.4° C, primarily due to underestimation between midnight and 6:00. The duration of daily periods of RH>90% was underestimated by an average of 6.0 h/day, and the RH error was largest during the night and on days

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media diaria en aproximadamente 1.8°C y la temperatura mínima en aproximadamente 4.4°C, principalmente por una subestimación entre la medianoche y las 6:00 h. La duración de períodos de HR>90% fue subestimada en 6 h/día en promedio, y el error fue mayor en la noche o en días con lluvia. El CSI para la exactitud en la identificación de horas con HR>90% fue de 0.40, lo cual excedió el CSI observado en el medio oeste de los Estados Unidos (0.27). SkyBit sobrestimó la duración de la humedad foliar en 1.9 h/día, mientras que la subestimó en 1.4 h/día en el medio oeste de los Estados Unidos. La proporción de horas clasificadas correctamente como húmedas o secas, 70.9%, fue casi idéntica a la observada en los Estados Unidos (70.1), pero el CSI para los datos de Costa Rica fue 2 veces mayor (0.56 vs. 0.27). En Costa Rica, los errores de estimación de humedad fueron mayores durante días con lluvia, y ocurrieron con más frecuencia en el día que durante la noche. La mayor cantidad de identificaciones incorrectas de horas secas o húmedas se dieron entre las 8:00 y las 10:00 y entre las 15:00 y las 21:00 h. Estos resultados aportan información de base a partir de la cual se puede refinar la estimación de parámetros meteorológicos en sitios específicos, para su aplicación en la agricultura de Costa Rica.

when rainfall was recorded. The CSI for accuracy of identification of hours with RH>90% was 0.40, which exceeded that reported for the midwestern U.S. (0.27). SkyBit overererestimated wetness duration by 1.9 h/day, whereas it was underestimated by 1.4 h/day in the midwestern U.S. The proportion of hours correctly classified as wet or dry, 70.9%, was nearly identical to that in the midwestern U.S. (70.1%), but CSI for the Costa Rica data was >2x that in the midwestern U.S. (0.56 vs. 0.27). Wetness estimation errors in Costa Rica were larger during days without than with measured rainfall, and occurred primarily during the day rather than at night. The rate of misidentification of hours as either wet or dry peaked from 8:00 to 10:00 and from 15:00 to 21:00 h. The results provide a baseline from which to refine site-specific estimation of weather parameters for application in Costa Rican agriculture.

INTRODUCTION

Monitoring the weather is indispensable to application of many Integrated Pest Management (IPM) tactics in agriculture. Insect-warning systems are frequently timed according to degree days, a concept which utilizes the fact that air temperature regulates the rate of development of many insect pests. Rainfall, relative humidity, and the duration of periods of crop wetness, as well as air temperature, are inputs to many disease-warning systems because they influence dissemination and infection by many crop pathogens. Many weather-based IPM systems can reduce the frequency of pesticide spraying and save input costs in comparison to conventional, calendar-based spray timing (e.g. Gleason 2000, Gleason et al. 1995, Campbell and Madden 1990).

Grower implementation of weather-based IPM systems has been quite limited, however. Perceptions that weather monitoring is inconvenient, expensive, unreliable, and difficult have contributed to growers' lack of enthusiasm for such systems (Campbell and Madden 1990, Gleason et al. 1994, Gleason et al. 1995, Huber and Gillespie 1992, Gleason 2000).

Computer-estimated, site-specific weather data are now commercially available, raising the hope that this new technology can overcome barriers to implementation of weather-based IPM systems. Hourly simulations (e.g. by SkyBit Inc. Boalsburg, PA, USA), calculated for specified localities at a spatial resolution of 1 km^2 based on weather station measurements, mesoscale meteorological models, and Geographic Information Systems software, are delivered daily to clients by electronic mail or fax. Before they can be recommended for grower use, however, these simulations require through validation in field studies. One survey, at 19 sites in northeastern North America during 1995, found that SkyBit estimates of mean, maximum, and minimum daily temperatures differed from on-site measurements by <0.7°C, whereas wetness duration was underestimated by an average of 3.4 h/day (Gleason et al. 1997). A subsequent, 3-yr (1997-1999) evaluation of Skybit accuracy at 15 sites in the midwestern U.S. found smaller mean errors for mean, maximum, and minimum daily temperatures (0.2, 0.2, and 0.3°C, respectively) and wetness duration underestimation (1.4 h/day) (Wegulo et al. 2001).

In field experiments assessing application of site-specific weather data to disease-warning systems, model-estimated air temperature and relative humidity data operated warning systems for black rot of grapes as effectively as on-site measurements (Truxall 1995). Field trials using Skybit wetness-duration estimates in a warning system for the sooty blotch/flyspeck complex on apples (Gleason et al. 2000b), and temperature and wetness-duration estimates in a warning system for watermelon anthracnose (Gleason et al. 2000a), reported disease control equivalent to that obtained by using on-site measurements as inputs. In addition, computer models have been used to simulate the consequences of using site -specific data in disease-warning systems on apples (Truxall and Travis 1994), tomatoes, and melons (Gleason et al. 1997). These efforts have focused only on North America, however; no efforts have been reported to evaluate the potential value of site-specific weather data in Central American agriculture.

The objective of the present study was to quantify the accuracy of site-specific estimates of hourly rainfall, air temperature, relative humidity, and wetness duration data at 5 sites in the Northern Pacific Region of Costa Rica, as a preliminary step toward implementing this technology in IPM systems to reduce pesticide use, lessen environmental pollution, and improve profitability in Costa Rican agriculture.

MATERIALS AND METHODS

On-site measurements

Meteorological measurements were recorded from April 11 or 12 to September 23 or 24, 1999, at 5 sites in the Northern Pacific Region of Costa Rica. Each site -Puntarenas, Garza, Santa Cruz, Liberia, and Mojica (Figure 1, Table 1) was a permanent weather station maintained by the Instituto Meteorológico Nacional of Costa Rica. All sites were approximately level and unobstructed except Garza, where trees surrounded the station approximately 100 m away and low hills (≤100 m height) were located about 250 m from the sensors. Wetness duration was measured by electronic sensors (Model 237, Campbell Scientific, Logan, UT, USA) which had been spray-painted with 3 layers of latex paint and oven-dried for 24 h between each coat (Gillespie and Kidd 1978, Lau et al. 2000); the first coat was black and the other coats, of proprietary composition (R. Olson, Savannah, GA, personal communication), were white. Each wetness sensor was mounted on a section of 5-cm-diameter PVC pipe, clamped to a metal stake, and deployed at 0.5-m height and a 45° angle to horizontal. Relative humidity and air temperature at 1.5-m height were measured with a relative humidity/temperature sensor (Model CS-500, Campbell Scientific, with a Vaisala capacitive humidity sensor (Intercap) within a PVC radiation shield. Rainfall was measured with tipping bucket gauges (Model TR525M, Texas Electronics, Dallas TX, USA). Dataloggers (Model CR10, Campbell Scientific) recorded data at 10-sec intervals and stored hourly data summaries.

Site-specific estimation of weather data

SkyBit Inc. (Boalsburg, PA) processed data from weather stations in Central America

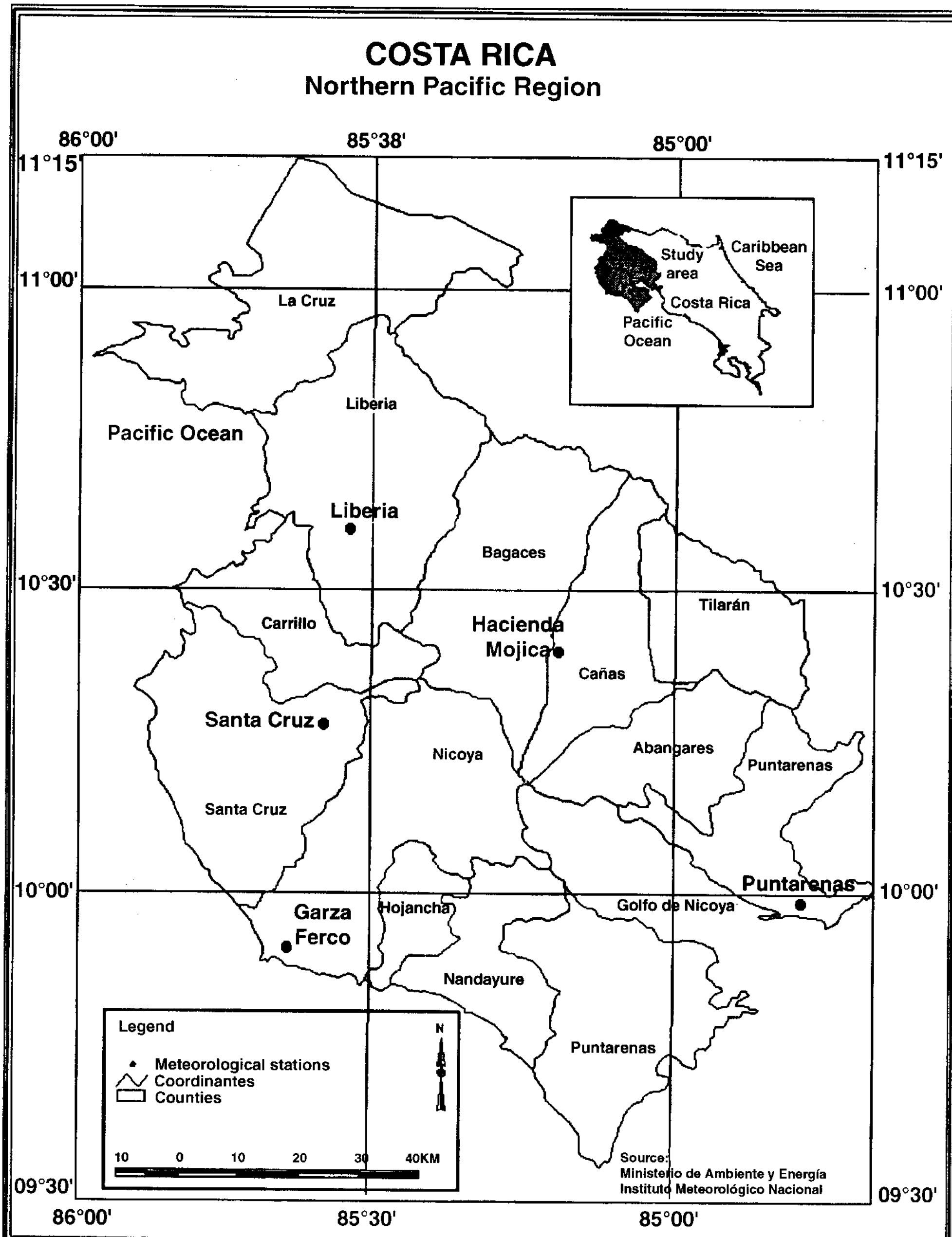

Fig. 1. Map of the Northern Pacific Region of Costa Rica, showing locations of the 5 monitoring sites.

Table 1. Coordinates and altitude of the 5 weather stations of the Instituto Meteorólogico Nacional in the Northern Pacific Region of Costa Rica.

Location	Latitude (north)	Longitude (west)	Altitude (m)
Garza	9° 54' 49.6"	85° 36' 55.5"	10
Liberia	10° 35' 54.1"	85° 32' 23.2"	144
Mojica	10° 27' 6.0"	85° 9' 55.1"	40
Puntarenas	9° 59' 0"	84° 46' 0"	3
Santa Cruz	10° 17' 2.9"	85° 35' 30.5"	54

using computer programs based on a weather model called MASS, which was developed for remote sensing applications (Kaplan et al. 1982, Gleason et al. 1997). The MASS model simulates finer scale, near-surface weather data than U.S. National Weather Service models and provides detailed representation of mesoscale phenomena such as surface energy and water budgets; turbulent processes in the planetary boundary layer; deep moisture convection; atmospheric condensation, evaporation, and precipitation; and long- and short-wave radiation under clear and cloudy sky conditions. SkyBit combines the MASS simulations with high-resolution and topological interpolation techniques (Kelley et al. 1988). After obtaining latitude, longitude, and altitude of each of the 5 sites in the Northern Pacific Region of Costa Rica, SkyBit prepared summaries of hourly, computer-simulated observations of wetness duration (0= dry, 1= wet), rainfall amount, relative humidity, and air temperature for each site during the period 11 April-23 September 1999 and sent them to the investigators by electronic mail.

Analysis of weather data

On-site measurements of wetness duration, air temperature, rainfall amount, relative humidity, and wind speed were assumed to approximate reality. This is a reasonable assumption because all sensors except the wetness sensors were calibrated and maintained regularly by technical personnel of the Instituto Meteorológico Nacional, and the wetness sensors had been calibrated in the field prior to use. Deviations of SkyBit estimates from the measured values were assumed to be errors. SkyBit estimates were compared with wetness duration measurements at 0.5-m height and relative humidity and temperature measurements at 1.5-m height. Accuracy of SkyBit relative humidity estimates was evaluated in terms of h/day>90% RH, since the RH>90% threshold is sometimes utilized as a surrogate for crop wetness (Wilks and Shen 1991). Differences between measured and SkyBit-simulated values were summarized at time scales of 1, 12, 24 h (arbitrarily designated as 12:00 to 11:00), or the entire monitoring period. For compatibility with SkyBit wetness data, hourly records of measured wetness as a proportion of the period that was wet (0 to 1) were converted to 0 and 1 by rounding all values <0.5 to 0 and all values ≥0.5 to 1. The Critical Success Index (CSI) (Schaefer 1990) was used to quantify the accuracy of Skybit classification of days on which rain was measured, hours in which RH>90% was measured, and hours in which wetness was measured. CSI expresses estimation accuracy as a proportion of time periods in which the occurrence of a phenomenon (e.g., wetness, RH>90%, rainfall) is determined correctly. For example, CSI for wetness estimation was calculated as follows:

$$CSI = A/(A+B+C)$$

where A= the number of hours in which wetness was both measured and estimated, B= the number of hours in which wetness was measured but not estimated, and C= the number of hours in which wetness was estimated but not measured.

RESULTS

Quality control of data sets

The experimental period included 166 days, for a total of 830 days of weather data for the 5 sites. Days were excluded from the comparison data set if they included missing, out-of-range or otherwise clearly erroneous measurements for the parameters of interest. After exclusion, a total of 674 to 698 days of measurements were used for comparison with SkyBit data.

Rainfall

Overall, SkyBit estimated that rainfall occurred on 171 days on which no rainfall was measured, compared to estimating no rainfall on only 25 days on which rainfall was measured, for a net overestimation of 146 rainfall days (Table 2). SkyBit's rate of misclassification of days with recorded rainfall was 21.7%, and its overall rate of misclassification of days with or without rain was 29%. On 19 of the 25 days on which rainfall was recorded but not predicted by SkyBit, <5 mm rainfall was recorded. The critical success index (CSI) value for SkyBit's overall accuracy in predicting the occurrence or absence of daily rainfall was 0.68. The 5 sites varied considerably in the SkyBit error rate for misclassification of days as rainy. SkyBit underestimated rainfall duration by an average of only 0.2 h/day, but the magnitude of this error differed with the amount of measured rain per day. For days without measured rain and with <5 mm measured rain, SkyBit overestimated rain duration by 1.9 and 0.6 h/day, respectively. On days when measured rainfall was 5-10, 10-15, 15-20, and >20 mm, SkyBit underestimated duration of the rainfall period by averages of -0.8, -1.1, -1.5, and -3.7 h, respectively. Overall, SkyBit underestimated mean amount of rainfall by 4.4 mm/day. On days with <5 mm and 5-10 mm measured rainfall, SkyBit's mean overestimates were 3.8 and 1.3 mm/day, respectively; for days with 10-15, 15-20, and >20 mm measured rainfall, on the other hand, SkyBit underestimated by 3.9, 6.8, and 47.9 mm/day, respectively.

Air temperature

SkyBit underestimated daily mean air temperature at 1.5-m height by approximately 1.8°C (Table 3). SkyBit underestimated mean daily minimum and maximum temperatures by 4.4°C and 0.8°C, respectively. Underestimation of the mean night temperature was considerably greater than that of the mean daytime temperature, and underestimation of the minimum night temperature was nearly 2.5x greater than that of the minimum daytime temperature.

Table 2. SkyBit errors in estimating accuracy of rainfall timing and amount.

Data set	N (days)	SkyBit rain days days-measured rain days	% non-rain days mis-classified as rainy	Duration of SkyBit rain-measured rain (h/day)	Mean absolute error (h/day)	SkyBit rainfall-measured rainfall (mm/day)	SEM*
ALL	674	146	21.7	0.2	4.5	2.6	0.6
Garza	158	19	12.0	-1.0	5.6	8.8	1.9
Liberia	160	41	25.6	0.6	4.3	-2.4	1.3
Mojica	127	35	27.6	0.5	4.4	0.0	0.9
Puntarenas	103	21	20.4	0.7	4.5	1.4	0.9
Santa Cruz	126	30	23.8	0.5	3.7	-0.6	1.0

* Standard error of the mean.

Table 3. Mean differences between SkyBit and measured values of air temperature

Data set	N (days)	Mean daily temperature (°C)	SEM*	Mean maximum daily temperature (°C)	SEM	Mean minimum daily temperature (°C)	SEM
ALL	698	-1.79	0.04	-0.78	0.06	-4.37	0.06
Garza	163	-1.28	0.06	0.35	0.19	-4.01	0.11
Liberia	161	-1.52	0.06	-0.70	0.08	-4.42	0.14
Mojica	138	-2.15	0.07	-1.24	0.10	-4.92	0.13
Puntarenas	108	-2.82	0.07	-1.88	0.12	-4.39	0.12
Santa Cruz	128	-1.51	0.07	-0.88	0.12	-4.15	0.13
Day (6:00-17:00)	698	-1.46	0.04	-0.81	0.06	-2.04	0.06
Night (18:00-5:00)	692	-2.12	0.04	-0.03	0.08	-4.51	0.06

* Standard error of the mean.

Relative humidity

SkyBit underestimated the duration of daily periods of RH>90% by 6.0 h (Table 4). The magnitude of these errors varied widely among sites, but was about 2x larger for days with measured rainfall than for days without rainfall. In addition, the mean SkyBit error was about 50% larger at night than during the day. The overall CSI value for correctly estimating hours having RH>90% was 0.40.

Wetness duration

SkyBit overestimated the duration of periods of wetness by an average of 1.9 h/day (Table 5). This mean error varied among stations from an underestimate of 1.0 h/day at Garza to an overestimate of 5.9 h/day at Mojica. The mean magnitude of estimation errors was smaller, and the mean percentage of hours correctly classified as dry or wet was higher, on days with measured rainfall than on days without measured rainfall.

Table 4. Mean daily difference between SkyBit and measured values of duration of periods with relative humidity >90%.

Data set	N (days)	Mean daily error, time RH > 90% (h)	Mean absolute error (h/day)
ALL	698	-6.0	7.4
Garza	163	-10.9	10.9
Liberia	161	-6.0	7.1
Mojica	138	-1.8	5.0
Puntarenas	108	-3.7	6.5
Santa Cruz	128	-6.1	6.8
Days with measured rainfall	454	-7.3	8.4
Days without measured rainfall	244	-3.6	5.7
Day (6:00-17:00)	698	-2.3	2.7
Night (18:00-5:00)	692	-3.7	4.7

Table 5. Mean errors in estimation of daily duration of periods of environmental wetness.

Data set	N (days)	Mean error, Sky-Bit-measured (h/day)	Mean absolute error (h/day)	% hours classified correctly by SkyBit
ALL	698	1.9	7.0	70.9
Garza	163	-1.0	6.7	71.9
Liberia	161	2.2	6.5	73.1
Mojica	138	5.9	8.2	66.2
Puntarenas	108	1.1	7.1	70.3
Santa Cruz	128	1.4	6.6	72.4
Days with measured rainfall	454	1.5	6.5	72.8
Days without measured rainfall	244	2.6	7.8	67.4
Day (6:00-17:00)	698	1.8	3.4	71.3
Night (18:00-5:00)	692	0.1	3.6	70.2

Almost all of the mean estimation errors for wetness duration occurred during the day. Overall, SkyBit correctly classified 70.9% of total hours as either wet or dry. The mean CSI value for accuracy in estimating occurrence of wet hours was 0.56.

Diurnal patterns in estimation errors

SkyBit estimation errors for several parameters exhibited strong diurnal periodicity. The diurnal pattern of wetness errors was bimodal, with pronounced peaks of overestimation from 8:00 to 10:00 and 15:00 to 19:00 (Figure 2). The tendency for SkyBit to fail to identify hours with RH>90% was greatest during the night (18:00 to 6:00 h). The tendency for SkyBit to misidentify rainfall when it was not measured peaked in the late afternoon to early evening (15:00 to 21:00). SkyBit underestimated air temperature most during the early morning hours (1:00 to 5:00). Several of these trends were evident in a plot of single day's data from Puntarenas in July (Figure 3). For example, SkyBit failed to identify 6 consecutive hours (1:00 to 6:00) during which measured relative humidity exceeded 90%. Underestimation of air temperature was pronounced during the night and morning. The onset of wetness during the night was estimated to occur 5 h before sensors recorded wetness, and dryoff in the morning was estimated to occur 2 h before it was measured (Figure 3).

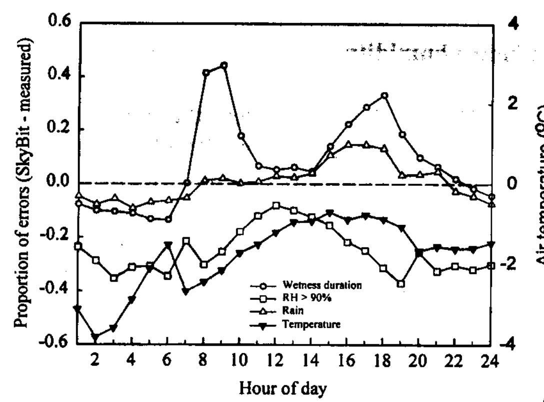

Fig. 2. Summary of diurnal variation in SkyBit estimation errors. Data shown are means of all days and stations in the data set. Wetness, RH, and rainfall data are represented as the mean proportion of hours in which measured data were misclassified by SkyBit; i.e., measured wetness was misclassified as dryness (means <0) or measured dryness classified as wetness (>0); hours with measured RH >90% were misclassified as having RH< 90% (<0) or vice versa (>0); and presence (<0) or absence (>0) of measured (> 0.25 mm) rainfall was misclassified. Errors in estimating mean air temperature are represented as °C.

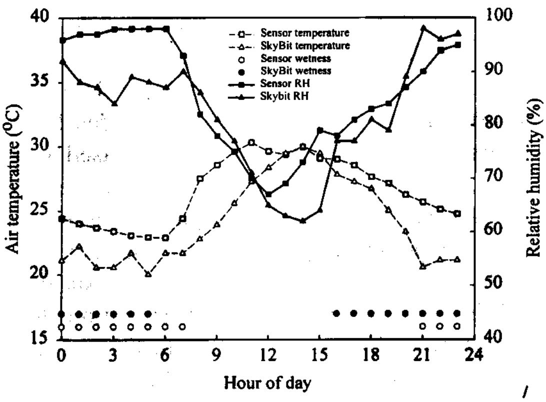

Fig. 3. Diurnal patterns of change in measured and SkyBit-estimated data for air temperature, wetness, and RH at Puntarenas on 8 July 1999.

DISCUSSION

This is the first evaluation of the accuracy of site-specific weather-estimation technology in Central America. The technology was evaluated previously in eastern and midwestern North America for accuracy and precision of estimating wetness duration (Gleason et al. 1997, Wegulo et al. 2001), RH, air temperature, and rainfall (Wegulo et al. 2001) and for application of wetness and air temperature estimates to disease-warning systems for apples, watermelons, and muskmelons (Truxall 1995, Gleason et al. 2000a, 2001). Our focus in Costa Rica was to evaluate accuracy of SkyBit estimates of weather variables that are common inputs to pest and disease-warning systems– rainfall, air temperature, wetness duration, and relative humidity. Such evaluations are necessary precursors to application of site-specific weather estimates to warning systems in Central American agriculture.

SkyBit showed a strong tendency to estimate occurrence of rainfall on days when it was not measured at a weather station. These errors occurred almost 7 times more frequently than failure to detect days with measured rainfall (data not shown). It is possible that rain actually fell on some days on which SkyBit erroneously estimated rainfall, but that the total amount was less than the minimum (0.25 mm) required to activate the tipping bucket rain gauges used at the weather stations. However, this possible artifact seems unlikely to account for the majority of the 171 days on which rain was reported erroneously. The CSI value for overall accuracy of estimating rainfall occurrence per day, 0.68, exceeded the value of 0.56 obtained in a 3-yr, 15-site study in the midwestern U.S. (Wegulo et al. 2001), indicating estimation of rainfall occurrence by SkyBit was more accurate in Costa Rica during the April-September study period. The relatively small mean errors in SkyBit estimation of rain duration and amount per day mask the fact that the size of these errors was highly dependent on rainfall amount, and that underestimation became larger as rainfall amount increased (data not shown).

SkyBit's tendency to underestimate air temperature was primarily noticeable as pronounced underestimation of the minimum daily temperature, which typically occurred at night. In midwestern North America, the magnitude of SkyBit maximum-daily-temperature estimation errors were fairly similar to those in Costa Rica (0.2 and 0.8°C, respectively) but were much smaller than in Costa Rica (0.3°C vs. 4.4°C) for minimum daily temperature (Wegulo et al. 2001). A sample profile of night temperatures (Figure 3) illustrates that SkyBit estimates often fell more sharply than on-site measurements after sunset. This divergence of SkyBit estimates from on-site temperature at night, which is also shown in Figure 2, may have been caused by erroneous assumptions about relative humidity or cloud cover. SkyBit's pronounced tendency to underestimate periods of RH>90%, especially at night, suggests that SkyBit underestimated atmospheric moisture at night; in reality, high RH may have slowed radiative cooling, effectively slowing temperature decline near the ground. The CSI value for SkyBit estimation of hours in which RH>90%, 0.40, exceeded that for the midwestern U.S. (0.27) (Wegulo et al. 2001).

SkyBit's mean overestimate of wetness duration, 1.9 h/day, contrasts to mean underestimates of 3.4 h/day in northeastern North America (Gleason et al. 1997) and 1.4 h/day in the midwestern U.S. (Wegulo et al. 2001). In the previous studies, unlike the present one, dew rather than rain was the predominant source of wet hours. As in the North American results, SkyBit errors is LWD estimation per day in Costa Rica were larger during days without rain than days with rain, but the LWD errors in Costa Rica were overestimates, rather than underestimates as in the North American data sets. In Costa Rica, SkyBit's tendency to overestimate daily wetness duration may appear contradictory to its underestimation of the duration of periods with RH>90%, since RH>90% is sometimes assumed to be associated with the presence of dew on crop surfaces (Wallin 1963, Sutton et al. 1984). However, almost all of SkyBit's mean wetness duration error occurred in the daytime rather than at night, so dew formation, which occurs only at night, cannot account for the error. These differences emphasize the inherent differences in patterns of wetness occurrence between a temperate and a tropical climate. Nevertheless, SkyBit's mean percentage of hours identified correctly as either wet or dry was nearly identical in Costa Rica (70.9%), northeastern North America (71.9%) (Gleason et al. 1997), and mid western North America (70.1%) (Wegulo et al. 2001). In our study, SkyBit wetness-estimation errors peaked after sunrise (6:00) and around sunset (18:00), the times of day often associated with transition between wet and dry conditions (Gleason et al. 1994). These periods of fluctuation in wetness conditions are more difficult to estimate accurately than periods of stable wet or dry conditions (Lau et al. 2000), so the location of these peaks makes intuitive sense. The afternoon-to-evening peak in SkyBit wetness overestimation also coincided with the diurnal peak in rainfall overestimation (Figure 2), suggesting that rainfall errors contributed to wetness errors during this period.

Several factors may affect the utility of SkyBit estimates as inputs to disease-warning systems in Costa Rica. One factor is the particular weather parameters needed as inputs to specific warning systems. In Iowa, for example, SkyBit data has been used successfully in a disease-warning system for sooty blotch and flyspeck on apples that inputs only wetness-duration data (Brown and Sutton 1995, Gleason et al. 2000b). The fact that SkyBit mean wetness-duration errors in Costa Rica (1.9 h) were comparable in magnitude to those in the midwestern U.S. (1.4 h) (Wegulo et al. 2001), which includes Iowa, offers encouragement that wetness-based warning systems might be operated effectively in Costa Rica. Large SkyBit errors in estimating night temperatures, rainfall occurrence, and periods of relative humidity >90% in Costa Rica suggest, however, that SkyBit's estimation algorithms need further refinement to Costa Rican climate before these data are applied to warning systems that depend on these inputs. An additional influence is the season. The April-September monitoring period in our study encompassed primarily the rainy season (May-November) in the Northern Pacific region of Costa Rica. Because the pattern of SkyBit errors is likely to differ during the dry season (December-April), comparisons with on-site measurements must be made during that season in order to evaluate SkyBit's usefulness for dry-season warning systems. At specific locations, the suitability of SkyBit data to disease- and pest-warning systems may also be influenced by large-scale features such as the distance to oceans, mesoscale factors such as local topography, and microenvironmental factors such as the height and density of the crop canopy. Nevertheless, our study provides a baseline from which to evaluate future refinement of site-specific estimation of weather parameters in Costa Rica.

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