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Abstract

RECENT developments in water and carbon trading and biofuel production highlight the need to document the water and carbon balances of Australia's cropping systems including sugarcane. This paper presents the results of studies of evaporation and CO2 exchange throughout the growing seasons of two sugarcane crops, a 1st ratoon crop at Murwillumbah where burnt-cane was practised and a 5th ratoon crop at Mackay where trash blanketing was employed. At both locations, a micrometeorological eddy covariance technique was employed to measure water vapour and CO2 exchange between crop and atmosphere and manual and automatic chambers to measure CO2 emission from the canopy floor. The measurement period extended from the time of fertilising to harvest and was 342 days long at Murwillumbah and 292 at Mackay. Evaporation from the Murwillumbah crop was 1281 mm and the net assimilation of CO2 was 132 t CO2/ha, with 38 t/ha coming from the canopy floor and 94 t/ha from the atmosphere. At Mackay, evaporation was 970 mm and net assimilation only 60 t CO2/ha, with the canopy floor contributing 10 t/ha and the atmosphere 50 t/ha. It is suggested that apart from the shorter season at Mackay, the differences in evaporation and CO2 exchange between the two crops was probably due to the presence of a near-surface water table and higher available soil water contents at Murwillumbah, and the age of the plants (1st ratoon versus 5th ratoon). Despite differences between crops in average daily evaporation rate, reference crop evapotranspiration was found to be a reasonably good estimator of crop evaporation, overestimating it by 10% at Mackay and underestimating by 10% at Murwillumbah. The very large difference in net assimilation between the crops was responsible for a drop in water use efficiency, from 103 kg CO2/ha assimilated per mm of water evaporated at Murwillumbah to 62 at Mackay.

Keywords

dioxide, exchange, carbon, evaporation, crops, sugar, cane, GeoQUEST

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

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EVAPORATION AND CARBON DIOXIDE EXCHANGE BY SUGARCANE CROPS

By

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**KEYWORDS: Eddy Covariance, Energy Balance,
Net Assimilation, Soil Respiration, Water Use Efficiency.**

Abstract

RECENT developments in water and carbon trading and biofuel production highlight the need to document the water and carbon balances of Australia's cropping systems including sugarcane. This paper presents the results of studies of evaporation and CO_2 exchange throughout the growing seasons of two sugarcane crops, a 1st ratoon crop at Murwillumbah where burnt-cane was practised and a 5th ratoon crop at Mackay where trash blanketing was employed. At both locations, a micrometeorological eddy covariance technique was employed to measure water vapour and CO_2 exchange between crop and atmosphere and manual and automatic chambers to measure CO_2 emission from the canopy floor. The measurement period extended from the time of fertilising to harvest and was 342 days long at Murwillumbah and 292 at Mackay. Evaporation from the Murwillumbah crop was 1281 mm and the net assimilation of CO_2 was 132 t CO_2/ha, with 38 t/ha coming from the canopy floor and 94 t/ha from the atmosphere. At Mackay, evaporation was 970 mm and net assimilation only 60 t CO_2/ha, with the canopy floor contributing 10 t/ha and the atmosphere 50 t/ha. It is suggested that apart from the shorter season at Mackay, the differences in evaporation and CO_2 exchange between the two crops was probably due to the presence of a near-surface water table and higher available soil water contents at Murwillumbah, and the age of the plants (1st ratoon versus 5th ratoon). Despite differences between crops in average daily evaporation rate, reference crop evapotranspiration was found to be a reasonably good estimator of crop evaporation, overestimating it by 10% at Mackay and underestimating by 10% at Murwillumbah. The very large difference in net assimilation between the crops was responsible for a drop in water use efficiency, from 103 kg CO_2/ha assimilated per mm of water evaporated at Murwillumbah to 62 at Mackay.

Introduction

Climate change and the advent of water trading and carbon credits have heightened the need to document the water and carbon balances of Australia's cropping systems.

Sugarcane is important in this context. Renouf *et al.* (2008) rank it as higher than US corn and UK sugar beet as a producer of sugars for fermentation. It is grown on 430,000 ha in sub-tropical and tropical regions of the east coast of Australia. Most of the regions have high rainfall, but supplemental irrigation is employed in about 40% of the area (Inman-Bamber and McGlinchey, 2003). Sugarcane is a C4 plant with relatively low stomatal resistance. Coupled with high air temperatures, high solar radiation levels and high and frequent rainfall in the Australian sugar belt, these characteristics make for high transpiration and photosynthetic rates. Inman-Bamber and McGlinchey (2003) found that for the main growth period, evaporation from Australian sugarcane crops was 1.25 times the FAO reference crop evapotranspiration, a measure of the potential evaporation from well-watered crops, while Weier (1998) estimated that sugarcane crops assimilate as much as 135 t CO_2/ha/y. As well, high nitrogen fertiliser rates, warm, moist soils and high available carbon can be expected to enhance production of CO_2 in the soil. We report on measurements and drivers of evaporation and CO_2 exchange made over the whole of the growing seasons of two sugarcane crops: one in the south of the sugarcane belt near Murwillumbah, NSW and one in the central region near Mackay, Qld. Eddy covariance techniques were used to measure whole of crop evaporation and CO_2 exchange rates continuously through the season and chambers were used to measure CO_2 exchange at the soil surface. Burnt cane was practiced at Murwillumbah while trash blanketing was employed at Mackay. Differences between the two crops will be explored. Sugarcane is one of the crops favoured for biofuel production (Renouf *et al.*, 2008) and the study provides data for assessing the water needs and carbon sequestration to be expected from this activity.

Methods

Sites and crop management

The measurements at Murwillumbah were made on a farm at Blacks Drain within the Condong Mill District. The soils on the farm that are used for cane production are classified as acid sulfate soils (ASS) and, during periods of high rainfall, are often inundated. A water table at a depth of 0.5 to 0.7 m was usually present. The soils are characterised by a surface organic horizon with high porosity (around 60%) and pH of 5, a strongly acidic A2 horizon (pH<4), and a reduced B horizon. The acidic A2 horizon is formed from the oxidation of pyrite.

The gas exchange measurements were made in a block of 1st ratoon cane that had been burnt before harvest. The trash residues remaining on the ground after harvest amounted to 2.9 t DM/ha (determined from field sampling, Wang *et al.*, 2008). The micro-meteorological techniques employed require large, uniform source areas. Hence the measurement block was located amidst other blocks of burnt cane harvested at the same time and receiving the same fertiliser treatment. Measurements commenced on 14 October 2005 just prior to the application of urea fertiliser on 18 October. The application rate was equivalent to 160 kg N/ha. At that time, the mean height of the plants was 0.44 m. The measurements reported here are for the 342 days between 14 October 2005 and 20 September 2006. By the end of the investigation, the cane had grown to a height of 4 m. Rainfall for the period was 1859 mm and the mean air temperature was 19.3 ^{o}C.

At Mackay, emissions were measured in a block of 5th ratoon cane on a farm in the Racecourse Mill District. The trash blanket on the soil surface after harvest was 9.5 t DM/ha (Wang *et al.*, 2008). The rate of fertiliser application was 150 kg N/ha, mostly as urea.

Measurements commenced on 8 November 2006 and fertiliser was applied on 19 November 2006. At the start of the measurement period, the plants were 0.45 m high. Measurements continued until 7 September 2007 when the plants were 4.1 m high. Rainfall during the measurement period totalled 2142 mm and the mean air temperature was 22.6 ^{o}C.

A synopsis of the microclimate at each site is provided in Table 1. During our studies, the Mackay site was warmer and more humid and, despite the shorter growing season, received more solar radiation and more rain than the site at Murwillumbah. A significant difference between the sites was the higher soil moisture content at Murwillumbah due to the very high porosity of the surface soil, reduced evaporation during the winter months and perhaps the presence of a near-surface water table.

Table 1—Seasonal averages of microclimatic elements at the Murwillumbah and Mackay sites.

	Units	Murwillumbah	Mackay
Air temperature at 1.5 m above crop	^{o}C	19.3	22.4
Vapour pressure at 1.5 m above crop	hPa	17.8	19.7
Soil temperature at depth of 0.05m	^{o}C	19.7	22.6
Soil water content at depth of 0.05m	% v/v	52	27
Wind speed at 1.5 m above crop	m/s	1.2	2.0
Available solar energy	MJ/m^2/d	12.0	14.2
Rain	mm/d	5.45	7.33

Eddy covariance measurements

The measurement techniques employed in these studies were described by Denmead *et al.* (2006). The aim at both sites was to measure the average fluxes of water vapour and CO_2 between crop and atmosphere in continuous 30-min runs by a micrometeorological eddy covariance technique in which the flux is calculated as the product of vertical wind speed in the air layer above the crop, measured with a 3-D sonic anemometer, and the water vapour or CO_2 concentration, both measured simultaneously at the same point as the wind speed with a LICOR 7500 open-path infrared gas analyser.

In the present studies, we applied more stringent quality controls to the data than in our previous analysis. First, we noted that rain drops and dew collecting on the windows of the open-path sensor invalidated measurements of water vapour and CO_2 exchange made during such periods. As well, measurements made during periods of light winds and low turbulence were considered unreliable.

The data sets have been filtered to remove measurements made in any of these circumstances. Finally, many studies, e.g. Wilson *et al.* (2002), have indicated that eddy covariance measurements often underestimate the true flux by 10 to 30% due to a variety of causes, including interference between instruments and from support structures, separation of the paths of the open-path sensor and the sonic anemometer, and sampling frequencies. We checked this by comparing eddy fluxes of heat and water vapour at both sites with independent measurements of their magnitude.

The energy for evaporation is supplied by solar radiation. The available energy is the net radiation *Rn* (the difference between incoming and outgoing short- and long-wave radiation) less the flux of heat into the soil *G*. The available energy is partitioned between that used in evaporation *LE* (*L* being the latent heat of evaporation of water and *E* the rate of evaporation) and the flux of heat into the air *H*. Environmental and physiological mechanisms control the partitioning and these are discussed briefly in a later section of the paper. We compared the sum of the energies required for the 30-min measured heat and water vapour fluxes, *i.e. H+LE*, with the available energy, *Rn-G*.

Figure 1 shows the comparison for Murwillumbah. The eddy covariance measurements underestimated the available energy by close to 20% (r^2 = 0.90). A similar result was obtained for Mackay. Accordingly, the raw eddy fluxes of water vapour and CO_2 at both sites have been adjusted upwards by 25%.

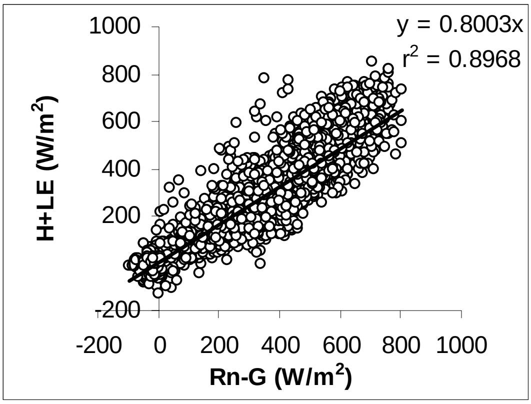

Fig. 1—Energy closure at Murwillumbah: the sum of sensible and latent heat *H+LE* compared with the available energy *Rn-G* for 30-min sampling periods during the period December 2005 to September 2006.

Chamber measurements

At Murwillumbah, the seasonal flux of CO_2 from the soil surface was estimated from measurements at the site made at intervals of a few days with manual chambers described by Wang *et al*. (2008). These authors and Denmead *et al*. (2007) describe different ways of interpolating between the measurements to obtain whole of season estimates of soil CO_2 emission. Wang *et al*. (2008) based their estimates on extrapolation of the (approximately) one-hour measurements to the whole day (24 h), while Denmead *et al*. (2007) based theirs on a comparison of the manual chamber data with whole day measurements made with automatic chambers over a period of 15 days. The figures reported here are the means of the two estimates which differ from the overall mean by approximately ± 25%. At Mackay, soil CO_2 fluxes were measured continuously with six automatic chambers linked to a closed-path Fourier transform infrared spectrometer for gas concentration measurements. Operation of the automatic chambers is described by Denmead *et al*. (2006).

Fluxes for periods when either micrometeorological or chamber data were missing due to equipment failure or unfavourable weather were estimated by interpolation procedures. This was necessary on 66 days at Murwillumbah and 55 at Mackay.

Other measurements

Ancillary meteorological measurements made on a continuous basis include the flux of heat between crop and atmosphere, air temperature and humidity, soil moisture content at three depths, soil temperature at three depths, wind speed and direction, solar radiation, soil heat flux and rainfall. Relevant data are shown in Table 1.

Results and discussion

Daily and seasonal cycles

Figure 2 illustrates the detailed information revealed by the eddy covariance technique. It shows the 30-min fluxes of water vapour and CO_2 for the whole of the growing season at Murwillumbah.

For November and early December an open-path CO_2/H_2O sensor was not available, so a Krypton open-path water vapour sensor was employed for evaporation measurement and an alternative micrometeorological flux-gradient technique (described in Denmead *et al.*, 2007) was employed for measuring CO_2 exchange.

Measurements made during that period are indicated by the grey lines in Figure 2. Gaps exist in the data due to filtering for wet periods and low turbulence levels as described earlier. In order to estimate whole-season totals, the gaps were filled by linear interpolation. Both evaporation and crop photosynthesis followed the annual solar cycle, exhibiting maximum rates during the summer, declining during the winter and increasing again in spring.

Evaporation rates were near zero overnight and at their peak, exceeded 1 mm/h by day. Night-time respiration rates (crop plus soil) were typically 0.2 to 0.5 mg $CO_2/m^2/s$, while peak net exchange rates during the day exceeded –2 mg $CO_2/m^2/s$, the negative sign indicating that the direction of the exchange was from atmosphere to crop.

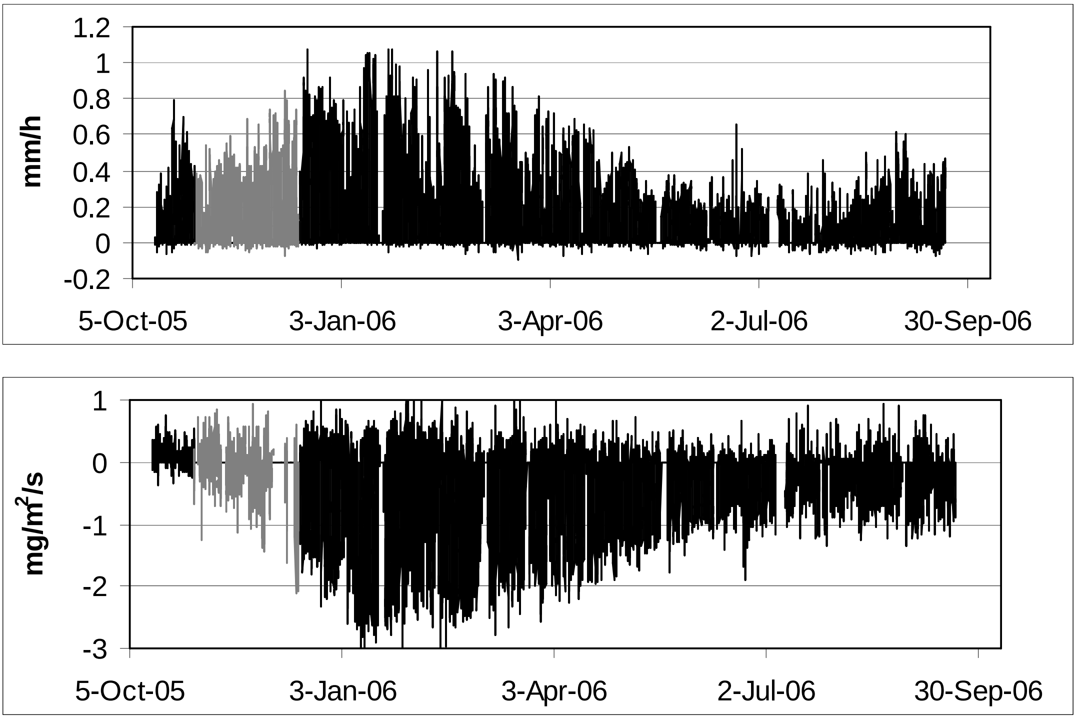

Fig. 2—30–min averages of eddy covariance measurements throughout the growing season of the rates of evaporation (top) and CO_2 exchange (bottom) for the sugarcane crop at Murwillumbah. Grey lines indicate periods when alternative instrumentation was employed; details in text.

Comparative evaporation rates

Climatic conditions were more conducive to higher rates of evaporation at Mackay than Murwillumbah, but this was not reflected in the measurements at the two sites, which are shown in Figure 3. Although the average seasonal available energy was higher at Mackay, as too were the temperature, wind speed and rainfall (Table 1, Figure 3), the average evaporation rate of 3.32 mm/d was 11% less than that at Murwillumbah, 3.75 mm/d, and more of the available energy was returned to the atmosphere as heat. The total seasonal evaporation at Mackay was 970 mm over 292 days and at Murwillumbah, 1281 mm over 342 days. Possible reasons for the lower daily evaporation rate at Mackay include the absence of a water table, lower available soil water contents (Table 1) and the age of the plants (5th ratoon versus 1st ratoon).

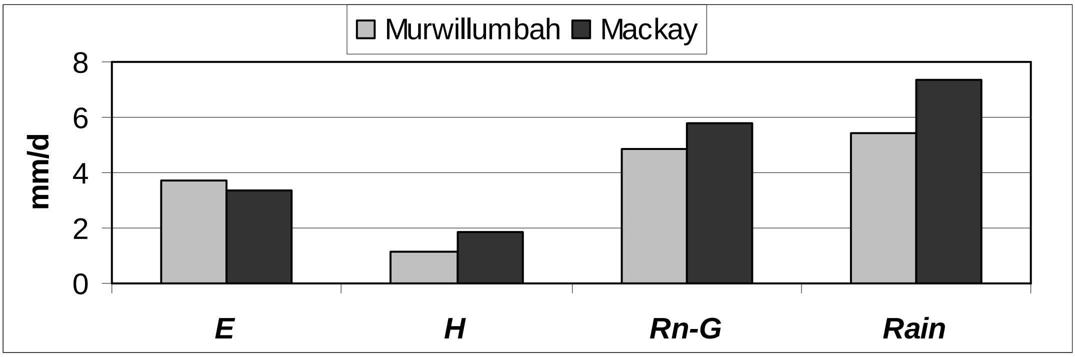

Fig. 3—Whole of season averages of evaporation *E*, heat flux to the atmosphere *H*, the supply of available energy *Rn-G* and rainfall at Murwillumbah and Mackay expressed in units of mm/d; explanation in text.

Comparative CO_2 exchange rates

In Figure 4, which compares the fluxes of CO_2 from the soil or canopy floor and the atmosphere for the two sites, the contrast between the crops is much more pronounced than it was for evaporation. Soil respiration was much higher at Murwillumbah and more CO_2 was sequestered from the atmosphere than at Mackay. The net assimilation of CO_2 by the crop at Murwillumbah, i.e. the algebraic difference between the CO_2 fluxes from the canopy floor and from the atmosphere, amounted to 132 t CO_2/ha, which was more than twice as much as the 60 t/ha assimilated at Mackay even though the crops were similar in height and appearance. The Murwillumbah assimilation is quite close to Weier's (1998) estimate of 135 t CO_2/ha. These rates are different from those quoted by Denmead *et al.* (2008) because of the more stringent filtering employed in the present analysis. However, the ranking of the sites is the same, with larger fluxes from soil and atmosphere measured at Murwillumbah. As noted by Denmead *et al.* (2008), the differences between sites probably reflect in part the different ages of the ratoons and the longer growing season at Murwillumbah.

At both sites, a large proportion of the CO_2 assimilated by the crop over the season came from the soil and/or trash blanket; 29% or 38 t/ha at Murwillumbah and 17% or 10 t/ha at Mackay. Assuming a C content in the trash of 40% of the dry matter and a trash residue of 2.9 t DM/ha (as measured), the Murwillumbah emission rate is much higher than would be expected from the analysis of trash decomposition by Robertson and Thorburn (2007) who found that most of the trash C was lost from the system as CO_2 during the year after harvest. However, the Mackay rate accords with their expectations of C loss from a trash blanket containing 9.5 t DM/ha (as measured). The almost 4 to 1 difference in the soil flux between the sites indicates that other mechanisms of CO_2 production must be at work at Murwillumbah, such as oxidation of the high organic C in the soil.

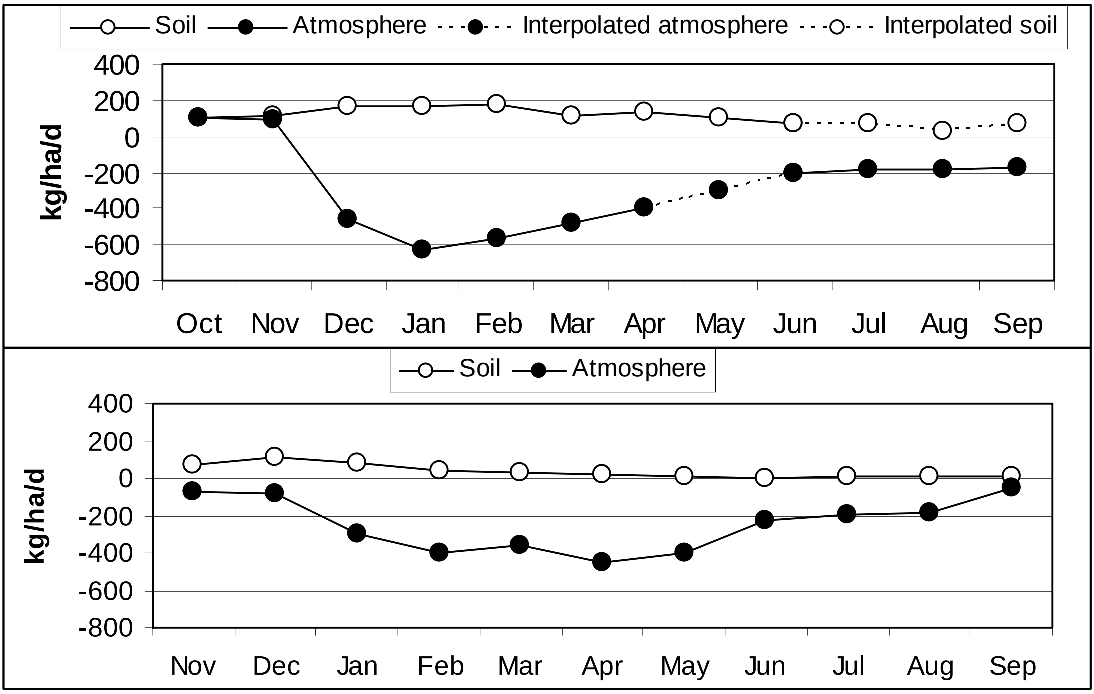

Fig. 4—Monthly fluxes of CO_2 from the soil (or canopy floor) and the atmosphere at Murwillumbah (top) and Mackay (bottom).

An outcome of the study important for assessing the resource trade-offs of biofuel production from sugarcane is the water use efficiency (WUE) of the two crops. The WUE at Murwillumbah was 103 kg CO_2/ha assimilated per mm water evaporated, and at Mackay, only 62. The seasonal water uses differed by just 24%, but the WUEs differed by more than 60% due to the very large decline in CO_2 assimilation.

Estimating evaporation rates

As indicated in an earlier section, the partitioning of the available energy between evaporation and heating the air depends on microclimatic and physiological factors. These are included in the method adopted by FAO to calculate a reference crop evapotranspiration rate. It employs a form of the Penman–Monteith equation due to Allen *et al.* (1998) to estimate the evapotranspiration from a hypothetical grass surface with a surface resistance of 70 s/m and an albedo of 0.23. The equation accounts for physiological properties of the crop through the surface resistance and albedo, and for the microclimate through the factors influencing evaporation: air temperature and humidity, wind speed and available energy. Average crop evaporation rates at the two sites are compared with the reference evapotranspiration rate in Figure 6. Apart from the first month of the season when canopy cover was incomplete, reference evapotranspiration provided a reasonable estimate of crop evaporation, underestimating it at Murwillumbah by only 10% for the whole season and overestimating it by 10% at Mackay. Since reference crop evapotranspiration accounts for differences in microclimate between the two sites, it seems possible that the difference in measured crop evaporation was due to the age of the crop at Mackay and perhaps soil water stress, both of which would manifest themselves through a higher surface resistance.

The results from both sites differ somewhat from those of Inman-Bamber and McGlinchey (2003) who found that measured evaporation from sugarcane crops was 1.25 times reference crop evapotranspiration. A crop coefficient of that magnitude would be appropriate for Murwillumbah for the high evaporation period, January through April, but at other times there and at Mackay, a crop coefficient closer to 1 would fit the data better. There are differences in the measurement technology employed in their study and the present one: a gradient Bowen ratio technique in the former and eddy covariance in the latter, but the discrepancy warrants further examination.

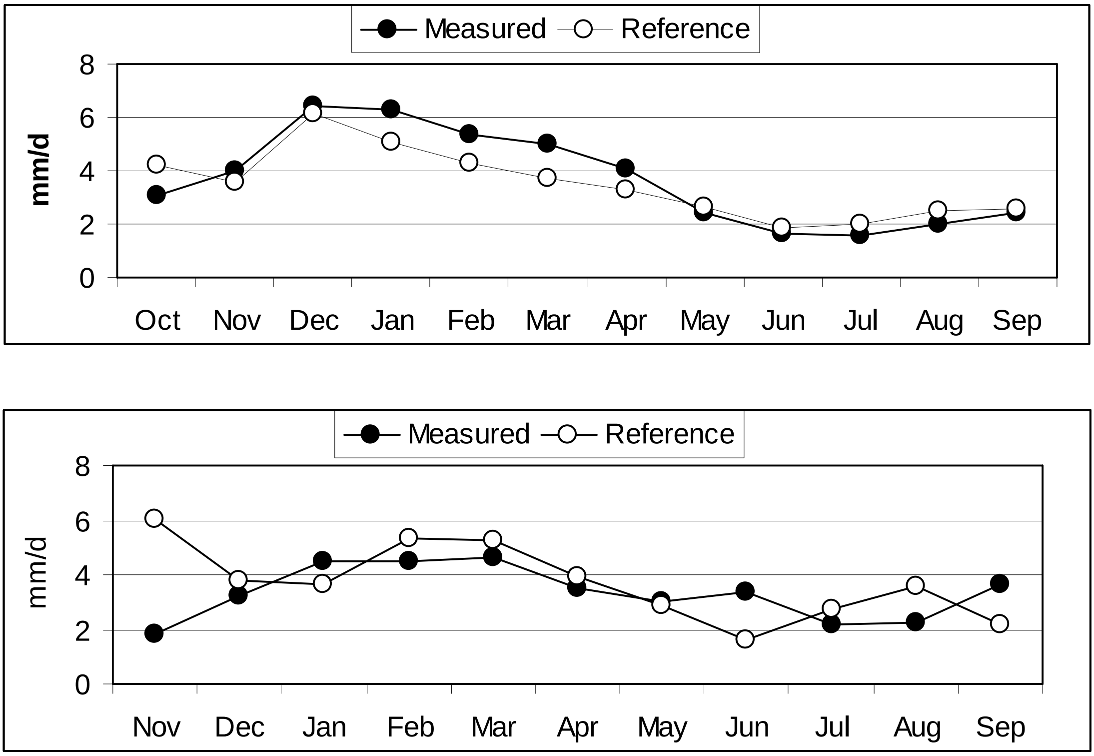

Fig. 5—Comparison of monthly averages of measured evaporation rate with reference evapotranspiration for Murwillumbah (top) and Mackay (bottom).

Conclusions

The study has confirmed the high rates of evaporation expected for sugarcane and that evaporation rates can be predicted to within 10% by a biophysical model: the FAO reference crop evapotranspiration equation. It has also shown that CO_2 assimilation by an early ratoon crop is high, also as expected, but declines with age. Assimilation by a 5th ratoon crop was less than half that of a 1st ratoon crop due probably to a decline in photosynthetic capacity. The decline in CO_2 assimilation with only a relatively small decline in evaporation rate greatly increased the quantity of water used per unit of CO_2 assimilated.

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