

**The content of this document includes:**

1. A response to reviewer and editor Prof. Ying Fan
2. Response to reviewer Prof. Bruce Kelbe
3. A point by point list of corrections applied
4. A marked up version of the document.

## 1. Response to reviewer and editor Prof Ying Fan

Many thanks for your input into this paper. Your review of the document was greatly appreciated particularly in terms of being more specific with the ET terms and the new Fig.1 which we think will assist readers to conceptualise the paper in its entirety more easily. The main points are addressed below, followed by the minor points.

### Different forms of ET

The different forms of ET were indeed confusing and it was often not clear which form of ET was being referred to in the original manuscript. In both reviews this was noted and has been amended throughout and there are now only three forms of ET considered:

$$\text{Actual ET} - \text{ET}_a$$
Potential ET – ET<sub>p</sub>Reference evaporation -  $ET_o$ 

These are captured clearly in the new Fig. 1 for readers to refer to. The different measurement techniques and methodologies followed in this paper are complex and difficult to conceptualise. We believe that Fig. 1 will significantly assist readers in conceptualising the process followed, link the processes to the 3 aims of the research and provide a reference to abbreviations used for variables and site names.

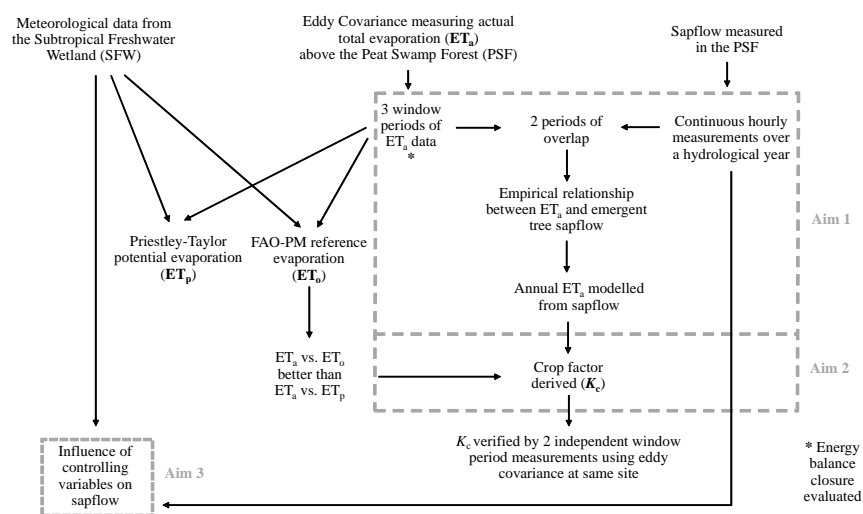


Fig. 1. Flow diagram of the research strategy indicating the different measurement techniques, their combination, and link to the aims of the research.

### Penman-Monteith equation

Our aim was not to use any form of an evaporation model such as the Penman-Monteith or Priestley-Taylor to understand the controlling variables on ET. For this we compare the climatic variables directly to sapflow. The Priestley-Taylor and FAO Penman-Monteith models are included in the paper only to provide a recommendation on which model and with what advective term ( $\alpha$ ) or crop factor they should be applied to estimate the swamp forest  $ET_a$  as is stated in Aim 3.

### $ET_a$ versus $ET_p$

In this study both the use of  $ET_o$  and  $ET_p$  were considered. They are described in the Materials and Methods section in 2.6 and the results of their evaluation are described in section 3.5. A much better relationship was found between the FAO Penman-Monteith  $ET_o$  versus  $ET_a$  measured at the site, and it was therefore chosen as the most appropriate model to apply, and monthly crop factors were the natural progression, allowing the estimation of  $ET_a$  for the swamp forest vegetation type using meteorological data – this is an important requirement of the research for future modelling of  $ET_a$  and management of the water-balance in the area.

For the empirical Priestley-Taylor model, the swamp forest  $ET_p$  was found to be on average close to  $ET_a$  with advective ( $\alpha$ ) terms of 1.0, 1.0 and 1.1 during the three field campaigns. However, the statistical relationships at an hourly ( $R^2$  between 0.54 and 0.74) and daily ( $R^2=0.56$ ) level were poor. Our confidence in predicting  $ET_a$  more accurately with the FAO Penman-Monteith  $ET_o$  approach was therefore higher. This is documented in the Abstract and in section 3.5.

“The  $\alpha$ , also estimated by the slope of the linear regression, was similar during the August (1.0) and November 2009 (1.0) field campaigns (Table 2) while during March 2010,  $\alpha$  was slightly higher (1.1). The standard deviations and root mean square errors of  $\alpha$  were higher than those of the  $K_c$  (Table 2). Therefore, the FAO Penman-Monteith  $ET_o$  model was adopted as most suitable for use over the Nkazana PSF in this study.”

There is general consensus in the literature supporting the use of the FAO Penman-Monteith  $ET_o$  over that of the Priestley-Taylor method where possible including:

Suleiman, A. and Hoogenboom, G. (2007) who found the FAO56 Penman-Monteith method more accurate than the Priestley-Taylor.

Sentelhas et al. (2010) who state that, ‘the FAO Penman-Monteith (FAO PM) method has been considered as a universal standard to estimate  $ET_o$  for more than a decade.’

Trajkovic and Kolakovic (2009) who use the FAO56 Penman-Monteith equation as a reference against which to test other models such as the Hargreaves, Thornthwaite, Turc, Priestley-Taylor and Jensen Haise.

The FAO Penman-Monteith  $ET_o$  is internationally considered the standard used to determine country-wide  $ET_a$  and is used in remote sensing models such as SEBAL and SEBS and in most hydrological models where  $ET_a$  is required, and there has been a great effort to establish a universal form of the equation which was achieved by Allan et al. (2006). The  $ET_p$  calculation is a simplified and empirical form of the FAO Penman-Monteith  $ET_o$  and is mostly only preferred due to its simplicity and minimal data requirements. The FAO Penman-Monteith  $ET_o$  describes the atmospheric demand of the atmosphere independent of crop type, development stage and management practice and includes variables such as windspeed and relative humidity which are not considered in the Priestley-Taylor model and  $ET_o$  is in a sense a more sophisticated form of  $ET_p$ . We feel that our results, which are in support of using the FAO Penman-Monteith  $ET_o$  over the Priestley-Taylor model, together with its

acceptance as the international standard for estimating  $ET_a$  from not only agricultural crops (see Drexler et al., 2004) justifies its use over the Priestley-Taylor model. Drexler et al. (2004) further support the use of the FAO Penman-Monteith  $ET_o$  method with the greatest barrier being the availability of crop factors for wetland species and plant communities, to which this manuscript contributes in its derivation of a crop factor for the Swamp Forest.

In terms of the meaning of the crop factor, it provides an indication of the  $ET_a$  with respect to atmospheric demand in the same way as the  $\alpha$  term of the Priestley-Taylor model compares  $ET_a$  with  $ET_p$ . A crop factor of 1 means that  $ET_a$  is equal to  $ET_o$ . This has been clarified in the manuscript where we suggest the following inclusion so that referral to Allan et al. is not required:

Pg 13629 Line 15:

The paragraph should continue.....When  $K_c = 1$  the Nkazana PSF  $ET_a$  equals the evaporative demand, or in other words  $ET_o$ . However, a  $K_c$  of  $<1$  or  $>1$  indicates that the PSF  $ET_a$  is  $<$  than or  $>$  than the  $ET_o$ , respectively. Fig. 10 shows that the Nkazana PSF  $ET_a$  is at or just less than  $ET_o$  for eight months of the year (June to January) and greater than  $ET_o$  for four months of the year (February to May).

#### Comparison of $ET_a$ vs $ET_p$ for insights into atmospheric versus land controls on $ET_a$

Our current approach was to compare long-term measured sapflow to climatic variables – all measured. We believe this is more appropriate than comparing the long-term record of  $ET_a$  (which is modelled from sapflow) against another modelled result -  $ET_p$ .

#### Overly cluttered with too many analysis

It is our hope that the inclusion of Fig. 1 will provide the reader with a clearer picture of the analysis included in this paper and assist in reducing the cluttered feel.

A section that could be removed without jeopardising the aims of the paper is the energy balance closure aspect, which is included in:

- section 2.3 and consists of 438 words,
- the end of section 3.2 consisting of 70 words,
- a paragraph in the Discussion consisting of 223 words and
- the Conclusion consisting of 78 words.

We found it a useful result that contributes to the controversial aspect of energy balance closure, particularly that  $D$  increased with increasing  $ET_a$  from August 2009 through November 2009 to March 2010, whereas most studies report a  $D < 1$ . It is also used to support the direct measure of  $ET_a$  rather than the energy balance method but this could be supported by referencing other research. However, we acknowledge that it deviates from the main concepts of the paper and could be excluded?

Drastic reduction in the number of analysis could further be achieved by removing the regression tree analysis and the 3<sup>rd</sup> aim completely, which is to investigate the controlling climatic variables and their influence on sapflow as well as the energy fluxes and microclimate within the swamp forest? The focus of the paper would then only be the interpolation of window periods of measurement, and the derivation of the crop factor allowing estimation of Swamp Forest  $ET_a$  from meteorological data.

#### Minor corrections recommended:

1. Appendix of variables, definitions and abbreviations:

The schematic (now Fig. 1) provides a summary which we hope is more engaging than an appendix. It describes the structure and concepts behind the methodology as well as providing a description of the variables while linking it all to the aims of the research. This is now referred to in the introduction as well as throughout the methodology sections.

2. Combine tables 1-3:  
Good idea, thanks. Tables 1-3 were combined. Table numbering through the document was therefore amended. All references to Table 2 or 3 were changed to Table 1 and all references to Table 4 were changed to Table 2.
3. Combine Figures 7 with 8 and 9 with 10.  
Another good idea. Figures 7 and 8, 9 and 10 were combined. References through the document from Figures 1 to 11 were corrected.
4. Explain the concept of the regression tree  
Concept of regression tree was explained in more detail in the methodology section 2.7 as shown below;

Pg 13623 Line 20:

In addition, the predictor variables ( $I_s$ , RH,  $T_{air}$  and  $\theta$ ) were broken up into sets of data with different ranges using regression tree analysis. In regression tree analysis a different model is applied to individual ranges of data rather than a global model (such as in regression analysis), in which a single model is applied to the entire range of each variable. The relationship for a linear regression model is assumed to be the same no matter what the value of any of the predictor variables is. The consequence thereof, is that a good midday relationship between sapflow and a variable (such as  $I_s$ ) for example, may be missed due to a poor relationship during the early morning and late afternoon periods. The regression tree analysis provides an alternative approach, in which the predictor variables are broken up into different sets, and a different model applied to each individual set. In the regression tree analysis output, which is represented by a hierarchical tree diagram, the longer the line, the greater the difference between the two subsets and the higher in the hierarchy a split occurs, the more significant is the split.

## 2. Response to reviewer Prof. Bruce Kelbe

Kelbe was thanked for his review, which were mainly typographical and are included in the point by point corrections in the section below.

## 3. Point by point corrections (Pg and Line numbers refer to the published HESSD paper on 11 Dec 2014.

General corrections applied throughout:

- Three types of ET have been defined: Actual ET – ET<sub>a</sub>, potential ET – ET<sub>p</sub>, reference evaporation - ET<sub>o</sub>. These have been standardised throughout the document.
- In addition, all Figs required renumbering due to the insertion of a new Fig. 1. References have been changed throughout the document.
- In a number of cases the unit of RMSE was changed to mm h<sup>-1</sup>

Pg 13608 line 2:

Remove (ET)

Pg 13608 line 5:

Total evaporation (ET) was...

Pg 13608 line 9:

Additional text has been inserted and grammar has been altered to emphasise the two components of the relationship ie ET and sapflow.

Previous: An empirical model was derived, describing the relationship between the observed ET of the Nkazana PSF measured during two of the window periods ( $R^2 = 0.92$  and  $0.90$ ) which, overlapped with sapflow measurements, thereby providing hourly estimates of predicted ET of the Nkazana PSF for a year, totalling 1125mm (while rainfall was 650 mm)

Corrected: An empirical model was derived, describing the relationship between  $ET_a$  from the Nkazana PSF and sapflow measurements, which overlapped during two of the window periods ( $R^2 = 0.92$  and  $0.90$ ), providing hourly estimates of  $ET_a$  from the Nkazana PSF for a year, totalling 1125mm (while rainfall was 650 mm). In building the empirical model, it was found that including the understory tree sapflow provided no benefit to the model performance. In addition, the relationship between the emergent tree sapflow with  $ET_a$  between the two field campaigns was consistent and could be represented by a single empirical model ( $R^2=0.90$ ;  $RMSE=0.08 \text{ mm h}^{-1}$ ).

Adjusted second paragraph of abstract significantly.

Pg 13608 line 16:

‘Observed ET’ should be ‘ $ET_a$ ’

Pg 13608 line 17:

$RMSE = 0.08 \text{ mm h}^{-1}$ )

Pg 13608 line 17:

Wording of some sentences of first paragraph of abstract changed.

Pg 13608 line 23:

Clarification was added.

Corrected: From the extended record of  $ET_a$  (derived in this study from sapflow) and  $ET_o$ , a monthly crop factor ( $K_c$ ) was derived for the Nkazana PSF providing a method of estimating long-term swamp forest water-use from meteorological data.

Pg 13608 line 25:

Comma added in after ‘PSF’

Pg 13609 line 7:

‘ET’ should be ‘ $ET_a$ ’

Pg 13609 line 8:

‘the contrast in ET and rainfall emphasises’ should be ‘the contrast in  $ET_a$  and rainfall emphasised’

Pg 13609 line 22:

The reviewer is correct that Allen et al., (2006) is the latest reference however in the study being described in the text by Dye et al., (2008) they used Allen et al., (1998) – this is missing from the references and was added.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration: Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations, Rome, Italy, 1998.

Pg 13610 line 22:

Inserted a comma before 'which'

Pg 13610 line 25:

modelled not predicted

Pg 13610 line 26:

Inserted a comma after 'sub-model'

Pg 13611 line 2:

Inserted a comma before 'which'

Pg 13611 line 2:

Reworded:

They concluded that the best technique for interpolating the periods between the three field campaigns would be the Penman-Monteith equation despite the problem of the variable canopy conductance and the recommended that further research into understanding the most appropriate techniques for interpolating measured data would be necessary.

Pg 13611 line 18:

Reference Farge et al. (2000) was incorrect and Falge et al. (2001) was added to the references as:

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N.-O., Katul, G., Keronen, P., Kowalski, A., Lai, C. T., Law, B. E., Meyers, T., Moncrieff, J., Moors, E., Munger, J. W., Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., and Wofsy, S.: Gap filling strategies for defensible annual sums of net ecosystem exchange, *Agricultural and Forest Meteorology*, 107, 43-69, 2001.

Pg 13611 line 26:

seem to provide

Pg 13611 line 27:

, above all at temporary sites - removed

Pg 13611 line 29:

Comma inserted after 'limitation'

Pg 13612 line 4:

Comma inserted after 'periods'

Pg 13612 line 4:

Wilson et al. (2001) applied EC and sapflow techniques in a deciduous forest of the south-eastern United States, and found that there was a qualitative similarity between actual total evaporation ( $ET_a$ ) derived using the EC techniques and tree transpiration.

Pg 13612 line 8:

Comma after 'believed' was removed.

Pg 13612 line 10:

Comma inserted after 'complexities'

Pg 13612 line 12:

To be added to the references:

Wullschlegel, S. D., Hanson, P. J., and Todd, D. E.: Transpiration from a multi-species deciduous forest as estimated by xylem sap flow techniques, *For. Ecol. Manage.*, 143, 205-213, 2001.

Pg 13612 line 14:

Citation corrected to:  
Čermák and Nadezhkina (1998)

Pg 13612 line 19:

Inserted measured  $ET_a$  to replace  $ET_{ec}$

Pg 13612 line 19:

.....Wilson et al. (2001).....

Pg 13612 line 26:

Comma inserted after 'instruments'

Pg 13612 line 27:

Previous: Two of these window periods overlapped in time and space with long-term sapflow measurements, and a nearby weather station provided measurements during the full period.

Corrected: Two of these window periods overlapped with long-term sapflow measurements, and a nearby weather station provided climatic data during the full period.

Pg 13613 line 13:

Edited:

It is one of the largest protected aquatic systems in southern Africa and, due to its biodiversity and natural beauty, has become an international tourist destination and is now a "regional economic hub" (Whitfield and Taylor, 2009).

Pg 13613 line 23:

.....and St. Lucia respectively from a 125 year raster database, and the.....

Pg 13613 line 25:

Clearly rainfall in the area is variable and figures depend on the length of the period in years over which the rainfall was measured and the particular location

Pg 13614 line 3:

Embomveni Dunes now labelled in Figure 1b and additional locations such as Fanies Island, Mission Rocks, Charters Creek included as recommended in the reviewer comments.

Pg 13614 line 4:

Comma added:

.....Mfabeni Mire, providing....

Pg 13614 line 13:

Grammar:

....(SWF) with vegetation.....

Pg 13614 line 18:

.....Azonal Forest, indicating.....

Pg 13614 line 25:

.....research, explaining....

Pg 13614 line 27:

.....research site as follows:

Pg 13616 line 5:

2.2 Measurement of energy fluxes and actual total evaporation

Pg 13616 line 14:

ET changed to 'evaporation'

Pg 13617 line 21:

The word 'the' should be removed in: site in ~~the~~ a predominantly downwind direction.

Pg 13618 line 13:

for a specified time period (Bowen, 1926).

Pg 13618 line 14:

.....study, providing.....

Pg 13618 line 22:

.....then  $R_n - G - H - LE = c$ , where.....

Pg 13619 line 5:



'Bar' should be 'Barr'

Pg 13619 line 7:

'corrected or adjusted' should be replace by 'corrected'

Pg 13619 line 10:

Reworded:

Cava et al. (2008). These reasons include: (1) sampling

Pg 13620 line 17:

Section 2.5 was reworded and modified mainly for consistency of the ET terms and clarity of the statistics applied.

#### *2.5 Modelling actual total evaporation from sapflow*

Polynomial regression (second order) analysis in the Genstat software (VSN International, 2011) was used to describe the relationship between measured  $ET_a$  and sapflow of the emergent and understory trees during the overlapping periods of the November 2009 and March 2010 field campaigns in order to understand the possibility of extending the record of  $ET_a$  from the Nkazana PSF using the long-term sapflow records. The hourly  $ET_a$  and sapflow data was checked for homoscedasticity and required a square root transformation to correct the variance distribution. The model derived was applied over a full year of sapflow data (October 2009 to September 2010) to obtain an annual  $ET_a$ .

Pg 13621 line 1:

applicability of ~~estimating~~ modelling  $ET_a$

Pg 13621 line 4:

was applied to the long-term  $ET_a$  discussed above

Pg 13621 line 11:

Heading changed to:

FAO Penman-Monteith reference evaporation:

Pg 13621 line 16:

Added to reference list:

Mao, L. M., Bergman, M. J., and Tai, C.C.: Evapotranspiration measurement and estimation of three wetland environments in the upper St. Johns River Basin, Florida, J. Am. Water Res. Ass., 38, 1271–1285, 2002.

Pg 13621 line 19:

Removed (FAO PM)

Pg 13621 line 26:

To be added to the reference list:

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration: Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations, Rome, Italy, 1998.

Pg 13621 line 20:

reference evapotranspiration (ET<sub>o</sub>) should read reference evaporation (ET<sub>o</sub>)

Pg 13622 line 9:

hourly calculations were introduced. It was this most recent form of the equation, now referred to as the FAO Penman-Monteith ET<sub>o</sub>, that was applied in the current study.

Pg 13622 line 10:

Using the FAO Penman-Monteith ET<sub>o</sub> in combination with the long-term ET<sub>a</sub> (from sapflow), K<sub>c</sub> was calculated (Eq. 5) for the Nkazana PSF at an hourly interval (while R<sub>n</sub> > 0 and ET<sub>a</sub> > 0.1 mm h<sup>-1</sup>) and summed to daily totals as recommended by Irmak et al. (2005).

Pg 13622 line 15:

.....data availability, but.....

Pg 13622 line 20 and 22:

Change ET to evaporation in both cases.

Pg 13622 line 24:

Equation 6 corrected to:

$$ET_p = \frac{\alpha}{L_v} \cdot \frac{\Delta}{\Delta + \gamma} \cdot (R_n - G)$$

Pg 13623 line 2:

Added to reference list:

Price, J. S.: Blanket bog in Newfoundland: Part 2. Hydrological processes, J. Hydrol., 135, 103-119, 1992.

Souch, C., Wolfe, C. P., and Grimmtind, C. S. B.: Wetland evaporation and energy partitioning: Indiana Dunes National Lakeshore, J. Hydrol., 184, 189-208, 1996.

Pg 13623 line 5:

Added to reference list:

Sumner, D. M., and Jacobs, J. M.: Utility of Penman–Monteith, Priestley–Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration, Journal of Hydrology, 308, 81-104, 2005.

Pg 13623 line 18:

The log of the sapflow measurements was modelled, as the variance of the measurements themselves was not homoscedastic and therefore required a variance stabilizing transformation.

Pg 13625 line 2:

In November, the dip occurred.....

Pg 13625 line 6:

..... August 2009, which...

Pg 13625 line 12:

Corrected sentence structure:

During the August 2009 field campaign the daily net radiant density, between 10.2 and 11.8 MJ m<sup>-2</sup>, was reasonably consistent at a daily level (Fig. 6a), despite the irregularity observed from the 30-minute data

Pg 13626 line 5:

3.3 Measured actual total evaporation

Pg 13626 line 6 and 7:

ET should be ET<sub>a</sub>

Pg 13626 line 9:

The standard deviation for.....

Pg 13626 line 13:

3.4 Relationship between sapflow and actual total evaporation measured during two field campaigns

Pg 13626 line 14:

The diurnal courses of the sapflow.....

Pg 13626 line 18:

Added comma:

.....footprint, whereas.....

Pg 13626 line 24:

Author addition as a final sentence to the paragraph: It is recommended that  $G$  be measured at numerous positions under swamp forest canopies in order to capture the variability in  $G$  and a representative average.

Pg 13626 line 26:

In a number of cases the unit of RMSE was changed to mm h<sup>-1</sup>

(RMSE = 0.05 mm h<sup>-1</sup>)

Pg 13627 line 1:

(RMSE = 0.06 mm h<sup>-1</sup>)

Pg 13627 line 2:

The polynomial regression was convex ( $R^2=0.89$ ) rather than linear ( $R^2=0.87$ ) in the case of the emergent tree (Fig. 9a) and concave ( $R^2=0.92$ ) rather than linear ( $R^2=0.90$ ) in the case of the understory tree (Fig. 9b). The increase in the rate of sapflow of the emergent tree was exponential for lower values of  $ET_a$  (morning and evening) but the rate of sapflow versus  $ET_a$  for higher values of  $ET_a$  slowed down as the tree reached its peak transpiration rate. In contrast the understory sapflow rate increased gradually per unit increase in  $ET_a$  at lower values but at higher values of  $ET_a$  the increase in sapflow was exponential. In March 2010 the results were similar with RMSE's of 0.07 and 0.08 mm for the emergent and understory trees, respectively. Convex and concave trendlines again fitted the data best (Fig. 10a and b). Lagging the sapflow by one hour as suggested by Granier et al. (2000) did not improve the regression of sapflow on  $ET_a$ .

Pg 13627 line 8:

RMSEs of 0.07 mm h<sup>-1</sup> and 0.08 mm h<sup>-1</sup>

Pg 13627 line 11:

3.5 Comparison of the FAO Penman-Monteith reference evaporation versus the Priestley-Taylor potential evaporation during the three field campaigns

Pg 13627 line 23:

The standard deviations and root mean square errors .....

Pg 13627 line 24:

Therefore, the FAO Penman-Monteith  $ET_o$  model was adopted as most suitable for use over the Nkazana PSF in this study.

The time interval (hourly and daily) at which the FAO Penman-Monteith  $ET_o$  and Priestley-Taylor models were computed resulted in different  $K_c$  and  $\alpha$  estimates.

Pg 13628 line 14:

3.6 Modelling long-term actual total evaporation and monthly crop factors

The long-term  $ET_a$  (October 2009 to September 2010) was modelled through the relationship between the observed  $ET_a$  and observed sapflow over the November 2009 and March 2010 field campaigns. In regressions of the emergent tree sapflow with  $ET_a$  over the two field campaigns (Figs. 10a and 11a), it was found that there was little gain in using separate linear models for the two periods ( $R^2 = 0.92$  and  $0.89$ ; RMSE = 0.05 mm h<sup>-1</sup> and 0.06 mm h<sup>-1</sup>) as a single, combined model, described  $ET_a$  equally well ( $R^2=0.90$ ; RMSE = 0.07 mm h<sup>-1</sup>). A similar result was found for the understory tree, indicating that for both trees a single relationship between  $ET_a$  and sapflow represented both field campaigns.

Pg 13628 line 19:

( $R^2 = 0.92$  and  $0.89$ ; RMSE = 0.05 mm h<sup>-1</sup> and 0.06 mm h<sup>-1</sup>)

Pg 13628 line 21:

RMSE = 0.07 mm h<sup>-1</sup>

Pg 13628 line 25:

RMSE = 0.08 mm h<sup>-1</sup>

Pg 13628 line 27:

0.08 mm h<sup>-1</sup>).

Pg 13629 line 5:

$$ET_a = (0.16341 \cdot T_r + 0.06)^2$$

where,  $ET_a$  is the estimated total evaporation (mm hr<sup>-1</sup>) and  $T_r$  the emergent tree sapflow (L hr<sup>-1</sup>).

The ~~estimated total~~ annual  $ET_a$  (October 2009 to September 2010) from the Nkazana PSF was 1125

Pg 13629 line 9:

Correct over-which to 'over which'

Pg 13629 line 9:

(well below the long-term average, reported to be between 844 and 1200 mm a<sup>-1</sup> for the area)

Pg 13629 line 10:

Finally,  $K_c$  was calculated at a daily interval from the extended  $ET_a$  and  $ET_o$  (Eq. 5), and averaged for each month of the year (Fig. 11).

Pg 13629 line 22:

Despite this difference in groundwater level, the  $K_c$  was 0.8 in August of 2008 and 0.9 during November 2008, validating the results derived for  $K_c$  (from the extended record of  $ET_a$  modelled from sapflow of the emergent tree), thus confirming that the  $K_c$  derived was applicable across wetter and drier years.

Pg 13630 lines 2 to 14:

Rewritten and corrected:

Equation 8 enabled the derivation of  $ET_a$  over the period during which there were sapflow measurements (October 2009 to September 2010). The purpose for this was to better understand the relationship between important climatic variables and  $ET_a$ . Three statistical approaches were used to determine these relationships with sapflow, which were directly related to  $ET_a$  and the climatic variables. The simple linear regressions of daily sapflow were considered with radiant flux density and VPD and it was found that these were poor, with coefficients of determination of only 0.51 and 0.52 respectively (not shown). Clearly the relationship between climatic conditions and sapflow is more complex. By applying multiple regression analysis  $I_s$ , RH,  $T_{air}$  and  $\theta$  at 0.075 m were found to be significant ( $p < 0.001$ ) with up to four-way interactions. Finally a regression tree analysis was applied of hourly log-transformed sapflow with the meteorological variables  $I_s$ , RH,  $T_{air}$  and  $\theta$  (Fig. 11).

Pg 13630 line 12:

Correction to include the soil water content measurement methodology and  $\theta$  symbol definition.

The following should be added to Pg 13620 Line 11:

Air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland) within the canopy, at a height of 2 m above the ground, and soil volumetric water content ( $\theta$ ) at the *Syzigium cordatum* tree

(where the roots were most dense at a depth of 0.075 m), were also measured. These were recorded hourly to coincide with the sapflow measurements.

Pg 13630 line 17:

Solar irradiance was clearly a key variable to include and the first split observed, essentially separates day and night-time data.

Pg 13630 line 20:

The next important splits ~~are~~ were for RH above and below 93.2% for the night time data (essentially when there was dew or rain and when there was not) and an additional split.....

Pg 13631 line 3 and 4:

‘ET’ should be ‘ET<sub>a</sub>’

Pg 13631 line 13:

....time). However the.....

Pg 13631 line 15:

With this approach, field campaigns could be extended should unusual weather conditions be encountered over the planned measurement period.

Pg 13631 line 25:

Harding et al., ~~1994~~ 1992

Pg 13631 line 26:

models are, however, uncoupled

Pg 13632 line 4:

Additional references required for the sentence:

aerodynamic resistance (Jacobs and De Bruin, 1992; Hall, 2002), shading of lower leaves (Cienciala et al., 2000) and wind stress (Kim et al., 2014).

Add to references:

Cienciala, E., Kučera, J., and Malmer, A.: Tree sap flow and stand transpiration of two *Acacia mangium* plantations in Sabah, Borneo, *Journal of Hydrology*, 236, 109-120, 2000.

Jacobs, C. M. J. and De Bruin, H. A. R.: The sensitivity of regional transpiration to land-surface characteristics: significance of feedback, *J. Climate*, 5, 683–698, 1992.

Kim, D., Oren, R., Oishi, A. C., Hsieh, C.-I., Phillips, N., Novick, K. A., and Stoy, P. C.: Sensitivity of stand transpiration to wind velocity in a mixed broadleaved deciduous forest, *Agricultural and Forest Meteorology*, 187, 62-71, 2014.

Hall, R. L.: Aerodynamic resistance of coppiced poplar, *Agricultural and Forest Meteorology*, 114, 83-102, 2002.

Pg 13632 line 8:

(Zweifel et al., ~~2002~~ 2005).

Pg 13632 line 21:

species-rich

Pg 13632 line 23 and rest of paragraph:

ET should be replaced with  $ET_a$

Pg 13632 line 26:

Up-scaling

Pg 13632 line 27:

Therefore, the empirical relationship between the single tree and  $ET_a$  provided an ideal opportunity to derive the annual  $ET_a$  of a vegetation type for which there has been until now, no information of the water-use characteristics. This relationship.....

Pg 13633 line 1:

‘ET’ should be replaced with ‘ $ET_a$ ’ in two cases.

Pg 13633 line 17:

.....forested area, so agreeing.....

Pg 13633 line 24:

An important observation, made.....

Pg 13633 line 25:

‘ET’ should be replaced with ‘ $ET_a$ ’

Pg 13633 line 27:

Change ‘indicated’ to ‘may indicate’

Pg 13634 line 1:

‘ET’ should be ‘ $ET_a$ ’

Pg 13634 line 8:

The high  $K_c$  is therefore likely a result of decreasing  $ET_o$  measured at the meteorological station, while transpiration rates in the Nkazana PSF were maintained into the late autumn period.

Pg 13634 line 12:

....the canopy, due.....

Pg 13634 line 24:

.....used, which concurs.....

Pg 13635 line 2:

Mfabeni Mire, which sufficiently

Pg 13635 line 19:

‘ET’ should be ‘ET<sub>a</sub>’

Pg 13635 line 19:

.....inclusion of both emergent and understory trees.....

Pg 13635 line 21:

.....empirical model was not found.....

Pg 13635 line 28:

.....October 2004, which are.....

Pg 13636 line 9:

difficult-to-access

Pg 13636 line 23:

‘ET’ should be ‘ET<sub>a</sub>’

Pg 13636 line 25:

The ~~empirical~~ model used to derive the annual ET<sub>a</sub> from sapflow (Eq. 8), and then monthly crop factors, was verified.....

Pg 13637 line 1:

Remove sentence:

The crop factors derived during these two field campaigns in 2008 (August and November) verified those derived from the empirical model calculations.

Pg 13637 line 3:

.....in 2008 ~~however~~ did not alter the  $K_c$  thus indicating.....

Pg 13637 line 4:

‘ET’ should be ‘ET<sub>a</sub>’

Pg 13637 line 9:

.....similar forest types and knowledge of the extent.....

Pg 13637 line 16:

Mire and also to the spread of fires

Pg 13637 line 16:

‘ET’ should be ‘ET<sub>a</sub>’

Pg 13637 line 18:

even higher than the range (844 to 1200 mm yr<sup>-1</sup>) of reported estimates of mean annual precipitation for the area (Lynch, 2004; Taylor et al., 2006; ARC-ISCW, 2011).

Pg 13637 line 19:



'ET' should be 'ET<sub>a</sub>'

Pg 13638 line 17:

Insert reference:

Allen, R., Walter, I., Elliott, R., Mecham, B., Jensen, M., Itenfisu, D., Howell, T., Snyder, R., Brown, P., and Echings, S.: Issues, requirements and challenges in selecting and specifying a standardized ET equation, Proc., 4th National Irrigation Symp, 201-208, 2000.

Pg 13638 line 21:

Remove reference:

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., and Vesala, T.: Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology, Adv. Ecol. Res., 30, 113-175, 1999.

Pg 13639 line 10:

Corrected in text

Pg 13639 line 13:

Corrected in text

Pg 13641 line 31:

Correction to reference:

Meiresonne, L., Nadezhdin, N., Čermák, J., Van Slycken, J., and Ceulemans, R.: Measured sap flow and simulated transpiration from a poplar stand in Flanders (Belgium), Agricultural and Forest Meteorology, 96, 165-179, 1999.

Pg 13644 line 9:

Remove reference:

Venter, C. E.: The vegetation ecology of Mfabeni peat swamp, St. Lucia, KwaZulu-Natal, Unpublished MSc. thesis, Faculty of Natural and Agricultural Science, University of Pretoria, Pretoria, South Africa, 140 pp., 2003.

Pg 13646 to 13648:

Combined tables 1 to 3 into one table.

Table 1. Summary of weather conditions during the August 2009, November 2009 and March 2010 field campaigns

Date	Solar radiant density (MJ m <sup>-2</sup> )	Wind speed (m s <sup>-1</sup> )	Wind direction (°)	VPD (kPa)	Air temperature (°C)		RH (%)		Rain (mm)
					Max	Min	Max	Min	
13/8/2009	14.2	4.6	199	1.5	21.9	13.0	88.7	33.7	0.8
14/8/2009	15.4	2.4	194	1.2	21.8	9.8	95.5	43.3	
15/8/2009	15.3	1.9	83	1.1	22.4	7.0	98.9	50.7	
16/8/2009	14.9	2.5	74	1.1	23.3	11.2	97.0	46.5	
17/8/2009	15.9	3.2	38	1.0	22.6	10.4	98.1	48.9	
18/8/2009	14.8	4.3	33	1.0	23.0	14.1	95.0	52.5	
19/8/2009	15.5	5.5	28	1.2	24.5	13.2	96.3	45.8	
<b>Average</b>	15.1	3.5		1.2	22.8	11.1	95.6	45.9	
4/11/2009	22.0	2.1	115	0.9	23.8	13.2	96.4	51.9	5.3
5/11/2009	16.7	4.2	40	0.6	25.2	17.7	93.3	66.7	
6/11/2009	18.1	5.3	37	0.6	25.8	19.9	93.3	73.0	
7/11/2009	19.0	6.9	36	0.6	25.9	21.6	93.2	70.5	
8/11/2009	25.3	7.4	37	0.7	26.4	21.3	90.5	69.0	
9/11/2009	21.1	6.2	34	0.7	25.3	21.0	94.7	69.2	
10/11/2009	16.2	4.4	223	0.6	24.7	19.4	95.6	61.6	
11/11/2009	21.2	2.3	47	0.5	26.1	15.5	97.1	64.6	0.3
<b>Average</b>	22.8	3.1		0.8	28.3	18.4	94.9	58.2	
16/3/2010	19.6	3.5	66	1.0	27.9	20.0	92.8	65.2	1.5
17/3/2010	14.6	2.3	245	0.8	28.7	18.4	96.0	60.3	4.6
18/3/2010	17.2	2.2	214	0.8	26.4	17.7	94.1	65.5	0.3
19/3/2010	20.2	3.0	58	0.8	28.6	16.1	96.8	62.6	
20/3/2010	20.6	3.8	66	1.0	30.0	22.1	93.2	59.0	
21/3/2010	16.2	1.9	90	1.0	28.6	21.9	92.8	59.9	
22/3/2010	22.5	1.7	97	0.8	28.9	16.4	96.7	59.6	
23/3/2010	19.9	2.3	234	1.0	28.8	16.8	97.3	63.9	
24/3/2010	21.2	2.1	79	1.0	30.2	18.6	96.7	56.6	
<b>Average</b>	19.1	2.5		1.1	28.7	18.7	95.2	61.4	

Fig. 1. Flow diagram of the research strategy indicating the different measurement techniques, their combination, and link to the aims of the research.

Figure corrected with additional place names added and changed to be Fig. 2

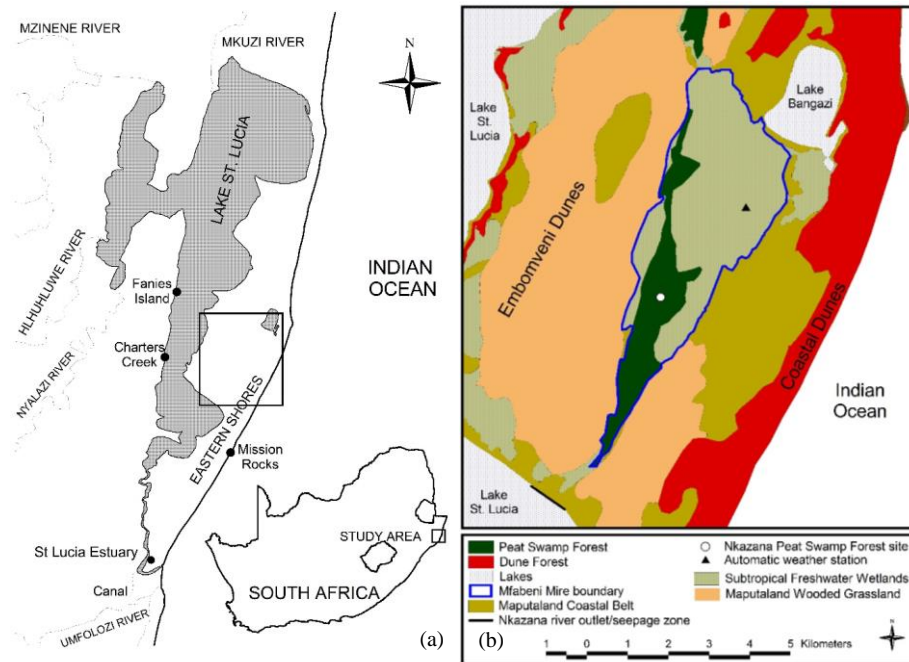


Fig. 2. (a) Location of the Eastern Shores within South Africa, (b) the Nkazana Peat Swamp Forest site (where the EC and sapflow systems were located) and the automatic weather station within the Mfabeni Mire on the Eastern Shores (data from Mucina and Rutherford, 2006).

Caption and Y-axis label corrected in Figure.

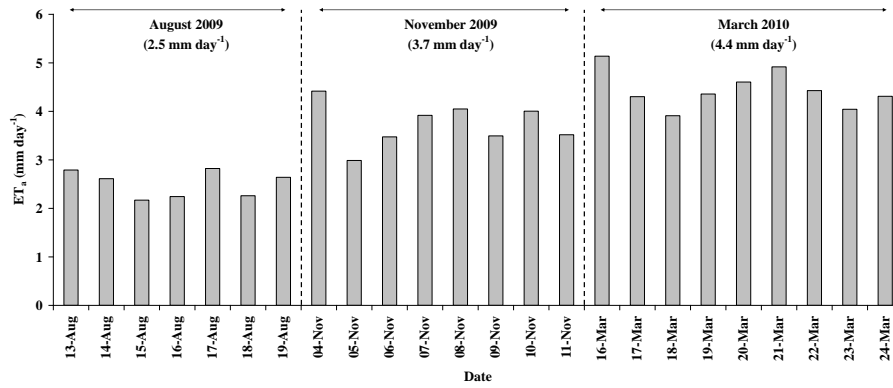


Fig. 7. Daily actual total evaporation (ET<sub>a</sub>) measured over the Nkazana Swamp Forest during three representative periods.

Combined previous Figs 7 and 8 and Y-axis label corrected.

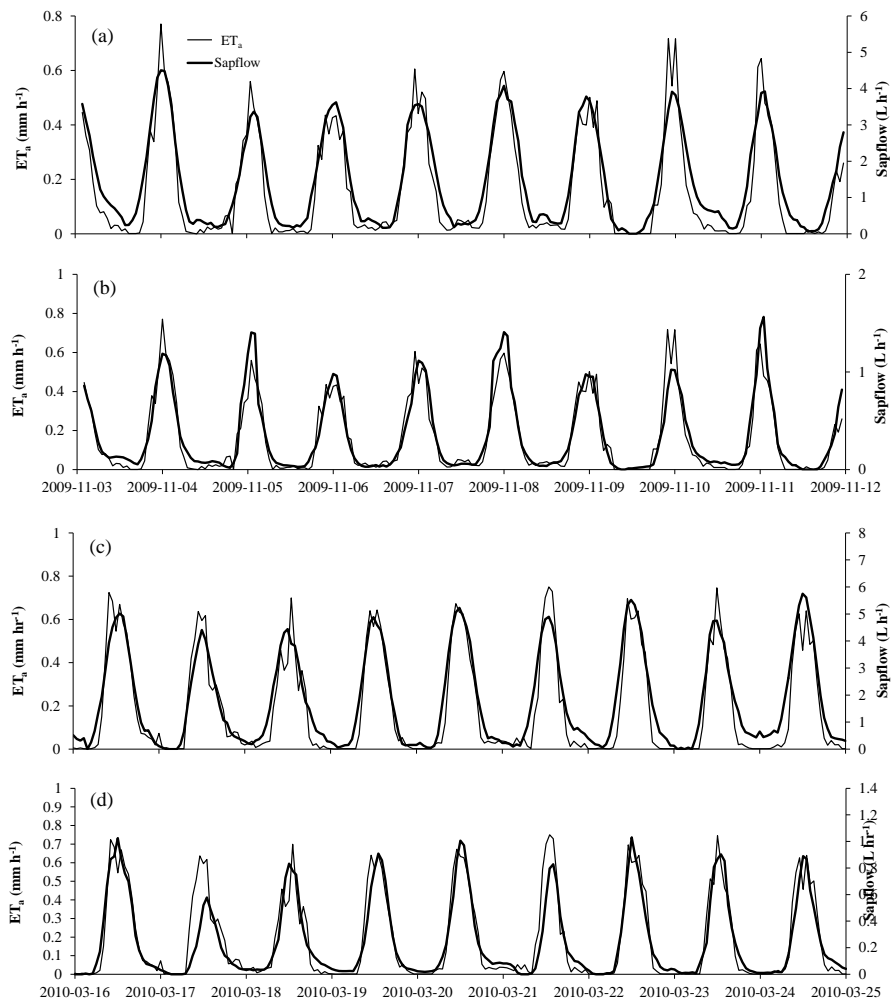


Fig. 8. Diurnal course of the hourly actual total evaporation ( $ET_a$ ) and sapflow in November 2009 (a and b) and March 2010 (c and d) for the emergent and understory trees, respectively.

Pg 13658 and 13659:

RMSE units should be  $\text{mm h}^{-1}$ , same as the y-axis of the graphs and Figs 9 and 10 were combined.

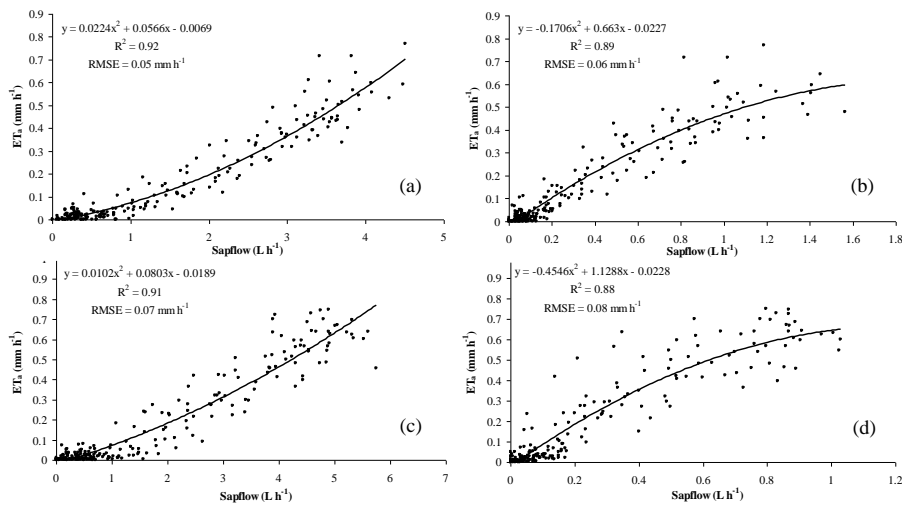


Fig. 9. Polynomial regressions of actual total evaporation ( $ET_a$ ) against the hourly sapflow for the (a) emergent and (b) understory trees during November 2009, and the (c) emergent and (d) understory trees in March 2010.

Pg 13661:

$I_s$  in the regression tree was italicised.

4. Marked up version of the manuscript of major corrections, but excluding minor punctuation and small alterations which are all listed in section 3 above.

## Extending periodic eddy covariance latent heat fluxes through tree sapflow measurements to estimate long-term total evaporation in a peat swamp forest

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### Abstract

A combination of measurement and modelling was used to find a pragmatic solution to estimate the annual total evaporation from the rare and indigenous Nkazana Peat Swamp Forest (PSF) on the east coast of Southern Africa to improve the water balance estimates within the area. Actual total evaporation ( $ET_a$ ) was measured during three window periods (between seven and nine days each) using an eddy covariance (EC) system on a telescopic mast above the forest canopy. Sapflows of an understory tree and an emergent tree were measured using a low maintenance heat pulse velocity system for an entire hydrological year (Oct 2009 to Sept 2010). An empirical model was derived, describing the relationship between  $ET_a$  from the Nkazana PSF and sapflow measurements. These overlapped during two of the window periods ( $R^2 = 0.92$  and  $0.90$ ), providing hourly estimates of  $ET_a$  from the Nkazana PSF for a year, totalling 1125mm (while rainfall was 650 mm). In building the empirical model, it was found that to include the understory tree sapflow provided no benefit to the model performance. In addition, the relationship between the emergent tree sapflow with  $ET_a$  between the two field campaigns was consistent and could be represented by a single empirical model ( $R^2=0.90$ ;  $RMSE=0.08 \text{ mm h}^{-1}$ ).

During the window periods of EC measurement, no single meteorological variable was found to describe the Nkazana PSF  $ET_a$  satisfactorily. However, in terms of evaporation models, the hourly FAO Penman-Monteith reference evaporation ( $ET_o$ ) best described  $ET_a$  during the August 2009 ( $R^2 = 0.75$ ), November 2009 ( $R^2 = 0.85$ ) and March 2010 ( $R^2 = 0.76$ ) field campaigns, compared to the Priestley-Taylor potential evaporation ( $ET_p$ ) model ( $R^2 = 0.54, 0.74$  and  $0.62$  during the respective field campaigns). From the extended record of  $ET_a$  (derived in this study from sapflow) and  $ET_o$ , a monthly crop factor ( $K_c$ ) was derived for the Nkazana PSF, providing a method of estimating long-term swamp forest water-use from meteorological data. The monthly  $K_c$  indicated two distinct periods. From February to May, it was between 1.2 and 1.4 compared with June to January, when the crop factor was 0.8 to 1.0. The derived monthly  $K_c$  values were verified as accurate (to one significant digit) using historical data measured at the same site, also using EC, from a previous study.

Commented [AD1]: Some grammatical and descriptive corrections for improved clarity

Commented [AD2]: Clarification added



The measurements provided insights into the microclimate within a subtropical peat swamp forest and the contrasting sapflow of emergent and understory trees. They showed that expensive, high maintenance equipment can be used during manageable window periods in conjunction with low maintenance systems, dedicated to individual trees, to derive a model to estimate long-term  $ET_a$  over remote heterogeneous forests. In addition, the contrast in annual  $ET_a$  and rainfall emphasised the reliance of the Nkazana PSF on groundwater.

**Commented [AD3]:** Corrected from .... the contrast in ET and rainfall emphasises

Keywords: indigenous forest, tree water-use, tree transpiration, evaporation modelling, energy balance closure, crop factor, groundwater dependent

## 1 Introduction

Severe water scarcity in parts of South Africa has threatened the health of internationally recognised environmental areas such as the iSimangaliso Wetland Park, a UNESCO world heritage site. To optimise the management of the water balance and understand the functioning of the area, there has been a need to quantify the water-use of the dominant vegetation types of the Park such as the endangered Peat Swamp Forests (Grundling et al., 1998; Clulow et al., 2012), a dominant plant type of the Mfabeni Mire. However, little is known about the water-use characteristics of the species diverse Peat Swamp Forests (PSFs) both locally and internationally in terms of model parameterisation. Despite significant improvements to measurement techniques over vegetated surfaces (Savage et al., 1997), these have not been of benefit for PSFs due to their remote and inaccessible nature. In addition, well documented extreme events (such as the Demoina floods in 1987) pose a real threat in the area. Sophisticated instruments are unfortunately vulnerable to damage and malfunction in such environments and PSFs are therefore not good locations for long-term deployment of sensitive equipment, a challenge facing researchers internationally and particularly in developing countries.

There are numerous, complex evaporation sources, which interact and contribute to actual total evaporation ( $ET_a$ ) in the Nkazana PSF. The areas of open water fluctuate, depending on groundwater levels. Open water evaporation is well described from the early work of Penman (1948) to the more recent work of Finch (2001) and Rosenberry et al. (2007) but none accounts for the effects of dense vegetation cover on radiative shading and the prevention of convection over the water surface by a tall and dense canopy. There are surface evaporation studies of peat (Nichols and Brown, 1980; Koerselman and Beltman, 1988; Lafleur and Roulet, 1992; Thompson et al., 1999, Clulow et al., 2012), but none in the context of a subtropical swamp forest. In addition the vegetated canopy is complex. There is a dense cover of ferns, of which little is understood in terms of transpiration (Andrade and Nobel, 1997). Above the ferns, the tree canopy consists of two levels described below (understory and emergent trees) and there are tree-climbing vines. Estimating  $ET_a$  of the Nkazana PSF is clearly multifaceted due to its diversity and our lack of understanding of the water-use of the specific plants, together with the potential variation in the evaporative demand within and above the canopy.

**Commented [AD4]:**  $ET_a$  defined

Within South Africa, the only comparable study took place over an evergreen indigenous mixed forest in the Southern Cape near the coast. Dye et al. (2008) measured  $ET_a$  using eddy covariance (EC), scintillometry and Bowen ratio over 18 days in total, during three different field campaigns, representing three different seasons within the year. The periods in-between were modelled using the FAO56 Penman-Monteith reference equation of Allen et al. (1998), which generally underestimated  $ET_a$  under high evaporative conditions and overestimated under low evaporative conditions. This was attributed to the assumption of a constant surface resistance. The Penman-Monteith equation (Monteith, 1965) was found to give the best match of modelled to observed daily  $ET_a$ , but required measurements or a sub-model, accounting for variable canopy conductance. The more complex WAVES (CSIRO, Canberra, Australia) process-based model simulated canopy growth and water-use processes in much more detail. However, successful parameterisation of the many model inputs was a significant challenge

**Commented [AD5]:** Changed from 'predicted'

and despite their best efforts, the WAVES output revealed an overestimation of daily  $ET_a$  under conditions of low evaporative demand, which could not be corrected. They concluded that the best technique for interpolating the periods between the three field campaigns would be the Penman-Monteith equation despite the problem of the variable canopy conductance and the recommended that further research into understanding the most appropriate techniques for interpolating measured data would be necessary.

**Commented [AD6]:** Reworded for improved clarity

Internationally, no studies were found with measurements over a comparable subtropical peat swamp forest. However, Vourlitis et al. (2002) provide a valuable study in which they attempted to measure the long-term  $ET_a$  with an EC system over a tropical forest in Brazil. Despite the proximity to the city of Sinop (offering a nearby base from which maintenance could be conducted), power issues hampered the data collection and EC data was only collected 26% of the time. Meteorological data was therefore used to estimate the latent energy flux (LE) using the Priestley-Taylor expression.

Since the beginning of the FLUXNET project, which was established to compile long-term measurements of water vapour, carbon dioxide and energy exchanges from a global network of EC systems, the problem of complete EC data sets and gap filling of records was recognised and is still an ongoing challenge (Baldocchi et al., 1996; Baldocchi et al. 2001). Falge et al. (2001) found the average data coverage for long-term EC systems to be only 65% due to system failure or data rejection with most of these located in developed countries. Clearly, despite the benefit of EC systems, long-term, continuous records of observed  $ET_a$  data over indigenous subtropical and tropical forests are improbable without significant research budgets allowing daily maintenance, gap filling and processing of data including complex spectral corrections, 3D corrections and coordinate rotation amongst others (Massman and Lee, 2002; Finnigan et al., 2003; Hui et al., 2004). Intensive, short-term field campaigns, offering reliable, continuous records, during different seasons seem to provide an appropriate strategy to determine the annual cycle of  $ET_a$ . This is particularly the case in South Africa, where theft of equipment and especially batteries from the foot of visible towers is a severe limitation, although this is overcome by employing 24-hour security guarding services to protect the equipment during the short-term measurement periods (Dye et al., 2008). However, this strategy only provides a viable solution if the  $ET_a$  during the in-between periods, can be adequately estimated.

**Commented [AD7]:** Corrected and added to references

**Commented [AD8]:** inserted

**Commented [AD9]:** some text removed

Wilson et al. (2001) applied EC and sapflow techniques in a deciduous forest of the south-eastern United States, and found that there was a qualitative similarity between  $ET_a$ , derived using the EC technique, and tree transpiration. With the recent advances in sapflow measurement techniques and upscaling of individual tree transpiration measurements to canopy  $ET_a$ , it is believed that sapflow techniques offer a reliable, standalone, long-term solution to estimating  $ET_a$  in uniform tree stands (Hatton and Wu, 1995; Meiresonne et al., 1999; Crosbie et al., 2007). There are however, numerous complexities, bringing some doubt as to the accuracy of the absolute sapflow results, such as the anisotropic properties of sapwood (Vandegehuchte et al., 2012), species composition effects (Wullschlegel et al., 2001), tree symmetry (Vertessy et al., 1997), radial patterns of sapflow (Čermák and Nadezhdina, 1998) and changes in spatial patterns of transpiration (Traver et al., 2010). In heterogeneous and complex canopies such as the Nkazana PSF described above, sapflow systems alone are impractical for the prediction of stand  $ET_a$  even with the recent advances in process based models of vegetation function such as the Measpa model (Duursma and Medlyn, 2012). However, whether it is possible to use the qualitative relationship of sapflow with measured  $ET_a$ , as found by Wilson et al. (2001), remains unknown.

**Commented [AD10]:** reworded for clarity

**Commented [AD11]:** grammar corrected

**Commented [AD12]:** was 2000

**Commented [AD13]:** Entirely new Fig. 1 inserted. The different measurement techniques and methodologies followed in this paper are complex and difficult to conceptualise. We believe that Fig. 1 will significantly assist readers in conceptualising the process followed, link the processes to the 3 aims of the research and provide a reference to abbreviations used for variables and site names in a way that is more interesting than an appendix.

For these reasons, a strategy to provide a measurement and modelling framework was developed and tested, in which detailed water flux measurements were recorded using EC instruments in an indigenous, heterogeneous forest over three window periods in August 2009, November 2009 and March 2010 (Fig. 1). This minimised the cost and risk of damage to these expensive systems, and provided continuous and reliable data from well-maintained instruments, operated by a team of

scientists, but were limited to three window periods. Two of these window periods overlapped with long-term sapflow measurements, and a nearby weather station provided climatic data during the full period (Fig. 1). The sapflow and weather station systems had lower maintenance and power requirements, were less delicate, less visible, able to withstand the harsh environment, and operated for longer periods unattended (one to two months) without compromising data quality. The aims were therefore to (1) establish whether the long-term  $ET_a$  of the Nkazana PSF could be determined by this combination of EC window periods and long-term sapflow measurements, (2) to provide a means of modelling the  $ET_a$  of surrounding PSFs from nearby meteorological data and (3) to investigate the controlling climatic variables and their influence on sapflow as well as the energy fluxes and microclimate within the swamp forest (Fig. 1).

Commented [AD14]: Reworded for clarity

### 1.1 The Study Area

The study area is located in Maputaland, South Africa, on the Eastern Shores of the iSimangaliso Wetland Park. It has held international status as a UNESCO World Heritage Site since 1999 (Taylor et al., 2006) and falls within the St Lucia Ramsar Site designated in 1986 (Taylor, 1991). It is one of the largest protected aquatic systems in southern Africa and, due to its biodiversity and natural beauty, has become an international tourist destination and is now a “regional economic hub” (Whitfield and Taylor, 2009).

Commented [AD15]: Reworded for clarity

The Eastern Shores area has a subtropical climate and lies in a summer rainfall area (Schulze et al., 2008). It has been reported that “the rainfall gradient westwards from the coast is strong, with a precipitation at Mission Rocks on the Indian Ocean coastal barrier dune exceeding 1200 mm year<sup>-1</sup> and decreasing to around 900 mm year<sup>-1</sup> at Fannies Island on the western shoreline of the estuary” (Taylor et al., 2006). However, Lynch (2004) provides mean annual precipitation values of 1056 mm a<sup>-1</sup>, 844 mm a<sup>-1</sup> and 910 mm a<sup>-1</sup> from the nearby Fannies Island, Charters Creek and St. Lucia respectively from a 125 year raster database, and the Agricultural Research Council measured an average annual rainfall at St. Lucia over a 22 year period of 975 mm a<sup>-1</sup> (ARC-ISCW, 2011). Clearly rainfall in the area is variable and figures depend on the length of the period in years over which the rainfall was measured and the particular location. During this study there was a well reported drought in the region (Grundling et al., 2014).

Commented [AD16]: Grammar corrected

The Eastern Shores area is flanked by the Indian Ocean to the east and Lake St. Lucia to the west (Fig. 2a). It includes coastal dunes (dune forest) to the east, the Embomveni Dunes (grassland) to the west and the Mfabeni Mire as an interdunal drainage line through the middle. The perennial Nkazana stream drains from the Mfabeni Mire, providing freshwater to Lake St. Lucia. This stream was recognised by Vrdoljak and Hart (2007) as an ecologically important source of freshwater to Lake St. Lucia during droughts. Clulow et al. (2013) state that “Organic matter and sediment have accumulated in the Mfabeni Mire over the past 45 000 years, forming one of South Africa’s largest peatlands and one of the oldest active peatlands in the world (Grundling et al., 1998)”. The Mfabeni Mire is approximately 8 km long (north-south direction) and 4 km wide in places (east-west direction). It comprises of subtropical freshwater wetland (SFW) with vegetation described by Vaeret and Sokolic (2008) and with a variable canopy height averaging approximately 0.8 m (Clulow et al., 2012). The Nkazana PSF is the other dominant vegetation type that runs down the western side of the Mfabeni Mire (Fig. 2b). The Nkazana PSF falls within the Indian Ocean Coastal Belt Biome, and is described as being a “mixed, seasonal grassland community” (Mucina and Rutherford, 2006). The Nkazana PSF is further classified by von Maltitz et al., (2003) and Mucina and Rutherford (2006) as an Azonal Forest, indicating its presence due to, and reliance on, the ground water surface within the Mfabeni Mire.

Commented [AD17]: added

Commented [AD18]: grammar corrected

### 1.2 Site description

The Swamp Forest site (28° 10.176’S, 32° 30.070’E) posed significant logistical challenges due to the 20 m high tree canopy, thick undergrowth, soft ground, dangerous animals and general inaccessibility

by road. The measurements were concentrated at its widest point (approximately 1 km) to maximize the fetch for the flux measurements above the tree canopy. Clulow et al. (2013) described previous botanical research, explaining the structure of the Nkazana PSF and the vegetation in the vicinity of the research site as follows:

Commented [AD19]: grammar corrected

Commented [AD20]: added

“Wessels (1997) classified the swamp forests of the area into three logical subgroupings based on dominant species, stand density and basal areas. The *Syzygium cordatum* subgroup is characterised by an irregular, broken canopy of predominantly *Syzygium cordatum* trees (known locally as the Water Berry) of up to 30 m, emerging above an intermediate canopy of approximately 6-15 m. Dominant tree species found in the Swamp Forest and in the vicinity of the site included: *Macaranga capensis*, *Bridelia macrantha*, *Tarenna pavettoides* and *Stenochlaena tenuifolia*. An impenetrable fern (*Nephrolepis biserrata*) covers the forest floor with a height of approximately 2.5 m and the *Stenochlaena tenuifolia* (Blechnaceae) fern grows up the tree stems to a height of approximately 10 m.”

The layer of peat at the Nkazana PSF site was approximately 2 m thick and underlain by sand. The water table depth was < 1.0 m but at the surface in low lying areas of the forest. The leaf area index (LAI-2200, LI-COR Inc., Lincoln, Nebraska, USA) beneath the ferns and trees was approximately 7.2 and below the trees approximately 3.3.

## 2 Materials and methods

### 2.1 Micrometeorological measurements

An automatic weather station provided supporting meteorological data (Fig. 1). It was located adjacent to the Nkazana PSF in the Mfabeni Mire over a reed, sedge and grass dominated vegetation, described broadly as SFW (Fig. 2b). Observations of rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA), air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland), solar irradiance (LI-200X, LI-COR, Lincoln, Nebraska, USA), net irradiance (NRLite, Kipp and Zonen, Delft, The Netherlands), windspeed and direction (Model 03002, R.M. Young, Traverse city, Michigan, USA) were made every 10 s. The appropriate statistical outputs were stored on a datalogger (CR1000, Campbell Scientific Inc., Logan, Utah, USA) at 30-minute intervals. Sensors were installed according to recommendations of the World Meteorological Organisation (WMO, 2008) with the raingauge orifice at 1.2 m and the remaining sensors 2 m above the ground. Vapour pressure deficit (VPD) was calculated on the datalogger from air temperature ( $T_{air}$ ) and relative humidity (RH) measurements according to Savage et al. (1997).

### 2.2 Measurement of energy fluxes and actual total evaporation

The shortened energy balance equation is commonly used in evaporation studies (Drexler et al. 2004) to describe the partitioning of energy at the earth's surface and provides an indirect method to determine  $ET_a$  (Eq. 1). The “shortened” version ignores those energies associated with photosynthesis, respiration and energy stored in plant canopies. However, these are considered small when compared with the other terms (Thom, 1975). The shortened energy balance equation is written as:

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$$R_n = G + H + LE \quad (1)$$

where,  $R_n$  is the net irradiance,  $H$  is the sensible heat flux,  $G$  is the ground heat flux and  $LE$  is the latent energy flux, which is the energy equivalent of evaporation by conversion (Savage et al., 2004).

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Eddy covariance is based on the estimation of the eddy flux which is expressed as:

$$F = \rho_a \overline{w's'} \quad (2)$$

where,  $\rho_d$  is the density of dry air,  $w$  is vertical wind speed (measured with the sonic anemometer described below) and  $s$  is the concentration of the scalar of interest (water vapour in this case). The primes indicate fluctuation from a temporal average (i.e.  $w' = w - \bar{w}$ ;  $s' = s - \bar{s}$ ) and the over-bar represents a time average. The averaging period of the instantaneous fluctuations, of  $w'$  and  $s'$  should be long enough (30 to 60 minutes) to capture all of the eddy motions that contribute to the flux and fulfil the assumption of stationarity (Meyers and Baldocchi, 2005).

The vertical flux densities of  $H$  ( $ET_a$  derived indirectly by the shortened energy balance equation) and  $LE$  ( $ET_a$  derived directly) were estimated by calculating the mean covariance of sensible (Eq. 2) and water vapour fluctuations respectively, with fluctuating vertical velocity (Baldocchi et al., 1988).

Soil heat flux was measured using two soil heat flux plates (HFT-3, REBS, Seattle, WA, USA) and a system of parallel thermocouples (Type E). The plates were placed at a depth of 0.08 m below the peat surface. The thermocouples were buried at 0.02 and 0.06 m and were used together with volumetric water content (CS615, Campbell Scientific Inc., Logan, Utah, USA) in the upper 0.06 m to estimate the heat stored above the soil heat flux plates. The measurements were stored every 10 s on a datalogger (CR23X, Campbell Scientific Inc., Logan, Utah, USA) and 30-minute averages were computed. During the measurements at the Nkazana Swamp Forest, the groundwater level was deeper than 0.1 m below the surface and therefore, the total  $G$  was determined using the calorimetric methodology described by Tanner (1960).

Over the corresponding time period,  $R_n$  was measured above the forest canopy, using a 21.3 m telescopic mast (WT6, Clark Masts Systems Limited, Isle of Wight, England). It was erected within the forest, on a fallen tree stump approximately 2.5 m high (Fig. 3a). This formed a firm base for the 90 kg mast which was carried into the forest from the nearest road approximately 1 km away. The computer box for the EC system (InSitu Flux Systems AB, Ockelbo, Sweden) was installed near the base of the mast (Fig. 3b) and a generator that automatically charged a bank of four 100 Ah deep-cycle lead-acid batteries (accumulators) was positioned approximately 50 m from the site in a predominantly downwind direction (the North-West) to minimise any possible influence from the exhaust fumes on the flux measurements. The generator was controlled by a logger (CR10X, Campbell Scientific Inc., Logan, Utah, USA) which was set to activate the charging system (220VAC petrol generator and 40 A 12 V charger) when the accumulators dropped below 12.4 V.

A “SATI-3VX” style, three-dimensional (3-D) sonic anemometer (Applied Technologies, Inc., Longmont, CO, USA) and open-path infrared gas analyser (LI7500, LI-COR, Lincoln, NE, USA) were mounted on the head of the mast (0.089 m diameter) orientated to face the east (predominant wind direction) to avoid air-flow distortion from the mast (Fig. 3c). In addition,  $T_{air}$  (PT-10, Peak Sensors Ltd., Chesterfield, UK) and  $R_n$  (NRLite, Kipp and Zonen, Delft, The Netherlands) were measured at the head of the mast. Data collection and analyses of the system was made in real time by the ECOFLUX software fully described by Grelle and Lindroth (1996) using a Flux Computer (In Situ Flux Systems AB, Ockelbo, Sweden). The system operated with a sampling rate of 10 Hz and the average fluxes were calculated every 30 min. The raw data were also stored for further processing. All the necessary corrections for air-density effects and 3-D coordinate rotation were performed on the Flux Computer to determine  $H$  (Grelle and Lindroth, 1996).

The Bowen ratio ( $\beta$ ) has historical significance in evaporation studies and is defined as:

$$\beta = \frac{H}{LE} \quad (3)$$

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for a specified time period (Bowen, 1926). It informs on the dominance of  $H$  or  $LE$  and was calculated at a daily time interval in this study, providing a useful means of showing changes in the distribution and weighting of the energy balance components within and between field campaigns.

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### 2.3 Energy balance closure

If each component of the energy balance is measured accurately and independently, then Eq. (1) should be satisfied, and closure is considered satisfied. However, energy balance closure could still be achieved if two or more terms have incorrect values and the terms in Eq. (1) still sum to zero (Savage et al., 2004). If the components of the shortened energy balance equation are measured independently then  $R_n - G - H - LE = c$ , where  $c$  is termed the energy balance closure ( $W m^{-2}$ ), and closure is satisfied if  $c = 0 W m^{-2}$ . By rearranging Eq. (1), closure is not achieved if the available energy  $R_n - G$  does not equal the turbulent fluxes  $H + LE$ . Another measure of the lack of closure is the closure ratio or the energy balance closure discrepancy  $D$  defined by Twine et al. (2000) as:

$$D = \frac{H+LE}{R_n-G} \quad (4)$$

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in which, a  $D$  of 1 indicates perfect closure. Several studies using numerous techniques over various surfaces have failed to achieve closure by up to 20 or 30 % (Wilson et al., 2001; Wilson et al., 2002; Barr et al., 2006). The vast majority have found higher energy input by radiation fluxes than loss by turbulent fluxes ( $H$  and  $LE$ ) and  $G$  (Oncley et al., 2007). Therefore, the measured fluxes should be corrected or the uncertainties in the measured fluxes accepted (Twine et al., 2000). Several reasons for lack of energy balance closure have been discussed by Twine et al. (2000), Wilson et al. (2002), and Cava et al. (2008). These reasons include: (1) sampling errors associated with different measurement source areas for the terms in Eq. 1, (2) a systematic bias in instrumentation, (3) neglected energy sinks, (4) the loss of low and/or high frequency contributions to the turbulent flux, (5) neglected advection of scalars, (6) measurement errors related to sensor separation, alignment problems, interference from tower or instrument-mounting structure, and (7) errors in the measurement of  $R_n$  and/or  $G$ . Despite concerns that the direct method of determining total evaporation ( $ET_{ec}$ ) by measuring water vapour concentrations using an Infrared Gas Analyzer may result in underestimates or overestimates of  $LE$ , in this study, it was considered that some of the closure pitfalls of the shortened energy balance method, such as (3) and (7) in particular, could be significant due to the tall canopy at the site (3) and point measurement location (7). Therefore, all  $ET_a$  results reported in this paper were calculated by the direct method. Energy balance closure discrepancy was determined during the day-time period ( $R_n > 0$ ) due to the potentially large nocturnal influences reported by Wilson et al. (2002).

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### 2.4 Measurement of tree sapflow

A heat pulse velocity system based on the heat ratio method (Burgess et al., 2001), was used to measure sapflow at various depths across the sapwood of two trees over 20 months from September 2009 to early May 2011 which overlapped with the November 2009 and March 2010 field campaigns (Fig. 1). The trees measured were located approximately 40 m from the mast where the EC and energy balance sensors were installed. Representative trees, in terms of species, stem diameter, canopy height and proximity to each other, were selected given the cable length limitations of the HPV system. The *Syzgium cordatum* tree selected was approximately 22.5 m tall and had a breast height stem diameter of 0.430 m. Sapflow was measured at four depths across the sapwood on both the eastern and western sides of the stem to account for differences in the sapwood depth around the tree. Sapflow was also measured in a nearby understory tree (*Shirakiopsis elliptica*) with a smaller stem diameter (0.081 m) at four depths within the sapwood. Air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland) within the canopy, at a height of 2 m above the ground, and soil volumetric water content ( $\theta$ ) at the *Syzgium cordatum* tree (where the roots were most dense at a depth of 0.075 m), were also measured. These were recorded hourly to coincide with the sapflow measurements. Further details

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of the installation, equipment used, wounding corrections applied and calculations to derive the tree sapflow are documented in Clulow et al. (2013). In this manuscript, following Dye et al. (2008), sapflow is assumed to equate with tree transpiration and tree water-use.

## 2.5 *Modelling actual total evaporation from sapflow*

Polynomial regression (second order) analysis in the Genstat software (VSN International, 2011) was used to describe the relationship between measured  $ET_a$  and sapflow of the emergent and understory trees during the overlapping periods of the November 2009 and March 2010 field campaigns in order to understand the possibility of extending the record of  $ET_a$  from the Nkazana PSF using the long-term sapflow records. The hourly  $ET_a$  and sapflow data was checked for homoscedasticity and required a square root transformation to correct the variance distribution. The model derived was applied over a full year of sapflow data (October 2009 to September 2010) to obtain an annual  $ET_a$  (Fig. 1).

## 2.6 *Evaporation models assessed*

Two well recognised evaporation models were tested for applicability of modelling  $ET_a$  from the Nkazana PSF (Fig. 1). After assessment of the models at an hourly temporal resolution, over the three field campaigns, the most applicable model was applied to the long-term  $ET_a$  discussed above and verified using historic data collected by the Council for Scientific and Industrial Research (CSIR) during a preliminary study over the Nkazana PSF from 8 to 12 August 2008 and 12 to 20 November 2008 (unpublished). The CSIR measured  $ET_a$  with the identical EC equipment used during the field campaigns in 2009 and 2010 described above and at the same site in the Nkazana PSF making the data ideal for verification of the models.

**FAO Penman-Monteith reference evaporation:** The original Penman evaporation model (Penman, 1948), assumed an absence of any control on evaporation at the earth's surface, in effect, an open water or wet surface situation. This was extended by Monteith (1965) to incorporate surface and aerodynamic resistance functions applicable to vegetated surfaces and was widely used in this form as the Penman-Monteith model. It is however, highly data intensive (Mao et al., 2002; Drexler et al., 2004) and the model was therefore standardised by the Food and Agriculture Organisation in Irrigation and Drainage Paper No. 56 (Allen et al., 1998) into a form known as the FAO56 Penman-Monteith model that could be applied at both hourly and daily time intervals. The model received favourable acceptance internationally in establishing a reference evaporation ( $ET_o$ ) index (atmospheric evaporative demand) as a function of weather variables measured at most standard weather station systems. The definition of a reference crop over which the weather variables should be measured was a "hypothetical crop with an assumed height of 0.12 m having a surface resistance of  $70 \text{ s m}^{-1}$  and an albedo of 0.23, closely resembling the evaporation of an extensive surface of green grass of uniform height, actively growing and adequately watered" (Allen et al., 1998). A nearby crop  $ET_a$  is calculated by adjusting  $ET_o$  by a crop factor ( $K_c$ ) in the form:

$$ET_a = ET_o \cdot K_c \quad (5)$$

where, the crop is not water-stressed. In Allen et al. (1998), values of  $K_c$  have been compiled for different vegetation types at different stages in crop development. Since recommendations by the American Society of Civil Engineers Evapotranspiration in Irrigation and Hydrology Committee (Allen, et al., 2000) and the work by Irmak et al. (2005) and Allen et al. (2006) amongst others, the tall crop reference (alfalfa height=0.5 m) and separate daytime ( $r=50 \text{ s m}^{-1}$ ) and night-time ( $r=200 \text{ s m}^{-1}$ ) resistances for hourly calculations were introduced. It was this most recent form of the equation, now referred to as the FAO Penman-Monteith  $ET_o$ , that was applied in the current study.

Using the FAO Penman-Monteith  $ET_o$  in combination with the long-term  $ET_a$  (from sapflow),  $K_c$  was calculated (Eq. 5) for the Nkazana PSF at an hourly interval (while  $R_n > 0$  and  $ET_a > 0.1 \text{ mm h}^{-1}$ ) and

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**Commented [AD37]:** Added to ref list

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summed to daily totals as recommended by Irmak et al. (2005). The reference evaporation approach has been successful internationally, partly due to technological advances leading to improvements in temporal and spatial data availability, but also because it provides a method for estimating  $ET_a$ , which is transferrable and can be applied to different vegetation types and locations across the world.

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**Priestley-Taylor potential evaporation:** Priestley and Taylor (Priestley and Taylor, 1972) simplified the theoretical Penman equation for specific conditions. They reasoned that, as an air mass moves over an expansive, short, well-watered canopy, evaporation would eventually reach a rate of equilibrium. In this case, where humid air moves over a wet surface, the aerodynamic resistances become negligible, while irradiance dominates, and the rate of evaporation would be equal to the potential evaporation ( $ET_p$ ) which is written as:

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$$ET_p = \frac{\alpha}{L_v} \cdot \frac{\Delta}{\Delta + \gamma} \cdot (R_n - G) \quad (6)$$

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where,  $\alpha$  is a constant,  $L_v$  is the specific latent heat of vaporisation of water ( $2.45 \text{ MJ kg}^{-1}$ ),  $\Delta$  is the slope of the saturation water vapour pressure versus  $T_{air}$ , and  $\gamma$  is the psychrometric constant.

The definition of the Priestley-Taylor model makes it suitable for estimation of evaporation from open water areas and wetlands (Price, 1992; Souch et al., 1996; Mao et al., 2002) but it has been applied over numerous other surfaces such as forests (Shuttleworth and Calder, 1979), cropped surfaces (Davies and Allen, 1973; Utset et al. 2004), pastures (Sumner and Jacobs, 2005) and even soil water limited conditions in forest clearcuts (Flint and Childs, 1991) with varied success and deviations from the originally proposed estimate for  $\alpha$  of 1.26. In this study it was applied in the form described by Savage et al. (1997) where  $(\Delta / (\Delta + \gamma))$  was estimated by:

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**Commented [AD45]:** Added to reference list

$$\frac{\Delta}{\Delta + \gamma} = 0.413188419 + 0.0157973 \cdot T_{air} - 0.00011505 \cdot T_{air}^2 \quad (7)$$

where,  $T_{air}$  is average air temperature over the interval of calculation (hourly in this study). By rearranging Eq. (6), and substituting  $ET_a$  for  $ET_p$ ,  $\alpha$  was estimated in the same way as  $K_c$  above.

## 2.7 Investigating climatic controls and drivers of sapflow

Sapflow was compared by simple linear regression to climatic variables (Fig. 1) generally considered to control sapflow in trees such as solar irradiance ( $I_s$ ) and VPD (Albaugh et al., 2013). Sapflow was also compared by multiple regression analysis to the micrometeorological parameters including  $I_s$ ,  $T_{air}$ , RH and soil volumetric water content ( $\theta$ ) to determine individual and combined drivers of sapflow. The log of the sapflow measurements was modelled, as the variance of the measurements themselves was not homoscedastic and therefore required a variance stabilizing transformation. Significance of variables, with up to four-way interactions were considered. In addition, the predictor variables ( $I_s$ , RH,  $T_{air}$  and  $\theta$ ) were broken up into sets of data with different ranges using regression tree analysis. In regression tree analysis a different model is applied to individual ranges of data rather than a global model (such as in regression analysis), in which a single model is applied to the entire range of each variable. The relationship for a linear regression model is assumed to be the same no matter what the value of any of the predictor variables is. The consequence thereof, is that a good midday relationship between sapflow and a variable (such as  $I_s$ ) for example, may be missed due to a poor relationship during the early morning and late afternoon periods. The regression tree analysis provides an alternative approach, in which the predictor variables are broken up into different sets, and a different model applied to each individual set. In the regression tree analysis output, which is represented by a hierarchical tree diagram, the longer the line, the greater the difference between the two subsets and the higher in the hierarchy a split occurs, the more significant is the split.

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### 3 Results

#### 3.1 Weather conditions during the study

The daily radiant densities (integrated solar irradiance over a day) were lowest in August 2009 ( $\sim 15 \text{ MJ m}^{-2}$ ) and most consistent (Table 1), whereas in November 2009 and March 2010 they were higher and more variable (between  $\sim 16$  and  $\sim 25 \text{ MJ m}^{-2}$ ), particularly in November 2009 (Table 1). The daily maximum temperatures were highest in March 2010 ( $\sim 29^\circ \text{C}$ ) and lowest in August 2009 ( $22.8^\circ \text{C}$ ). Average minimum RH was lowest in August 2009 ( $\sim 34\%$ ) and the average daytime VPD was highest ( $1.2 \text{ kPa}$ ). Average daily windspeeds were notably high in November 2009 ( $> 7 \text{ m s}^{-1}$ ) and the dominant wind direction for the site was from the north-east and the south. Some rainfall ( $< 7 \text{ mm}$ ) occurred during the field campaigns but fortunately fell at night and did not affect the daytime flux measurements.

The microclimate within the Nkazana PSF was noticeably different to the adjacent SFW areas. The VPD within the Nkazana PSF canopy was consistently lower than the SFW where the automatic weather station was located approximately  $3 \text{ km}$  away, with the larger differences occurring from March to August, which is the winter period (Fig. 4). A difference in dawn  $T_{\text{air}}$  between the Nkazana PSF and the adjacent area was also noted. The difference was lowest in summer and highest in winter with the Nkazana PSF being up to  $6^\circ \text{C}$  warmer on some mornings in June 2010.

#### 3.2 Eddy covariance flux measurements

Despite the apparent consistency in the daily radiant density during August 2009 noted above (Table 1), the 30-minute net irradiance flux data showed that all field campaigns were affected by cloud during the daytime, as indicated by the standard error bars of the net irradiance (Figs. 5a, 5b and 5c). Even the August 2009 data, despite being in the middle of the dry season, was influenced by cloud during six out of the seven days of measurement (not shown). During the August 2009 and March 2010 field campaigns, there was a noticeable dip in the average  $R_n$  at approximately 11:00 a.m. LT. with large standard errors ( $> 90 \text{ W m}^{-2}$ ) due to cloud cover. In November, the dip occurred at approximately 1:00 p.m. LT., also accompanied by large standard errors ( $> 90 \text{ W m}^{-2}$ ). The cloud affected pattern of  $R_n$  was translated through to  $H$  and  $LE$ , which were positive during the day, and with largest standard errors coinciding with those of the  $R_n$  except for the early morning observed  $LE$  in August 2009, which was attributed to the evaporation of dew on some days. The maximum rates of  $LE$  were approximately  $400 \text{ W m}^{-2}$  in August 2009,  $600 \text{ W m}^{-2}$  in November 2009 and  $700 \text{ W m}^{-2}$  in March 2010 (not shown). The pattern of  $G$  fluctuated diurnally but due to attenuation (sensors were below the soil surface) the pattern was smoother than the other fluxes during the course of the day.

During the August 2009 field campaign the daily net radiant density, between  $10.2$  and  $11.8 \text{ MJ m}^{-2}$ , was reasonably consistent at a daily level (Fig. 6a), despite the irregularity observed from the 30-minute data. During the November 2009 ( $11.4$  to  $18.3 \text{ MJ m}^{-2}$ ) and the March 2010 ( $9.0$  to  $14.4 \text{ MJ m}^{-2}$ ) field campaigns, the daily net radiant density was more variable (Figs. 6b and 6c). This variability at a daily level was translated through to the  $H$  and  $LE$  results, which during August 2009 were fairly consistent, but irregular during November 2009 and March 2010. The average daily net radiant density was lowest in August 2009 ( $11.2 \text{ MJ m}^{-2}$ ), highest in November 2009 ( $15.1 \text{ MJ m}^{-2}$ ) and in-between during March 2010 ( $12.7 \text{ MJ m}^{-2}$ ). The average daily soil heat flux did not mirror the pattern of  $R_n$  and was highest in March 2010 at approximately  $11\%$  of  $R_n$  (up to  $1.8 \text{ MJ m}^{-2}$ ), lower in August 2009 at  $5\%$  of  $R_n$  ( $0.7 \text{ MJ m}^{-2}$ ) and lowest in November 2009 at  $1\%$  of  $R_n$  (up to  $0.3 \text{ MJ m}^{-2}$ ).

The daily total  $LE$  was higher than  $H$  in August 2009 (Fig. 6a), with a daily average  $\beta$  ratio of  $0.7$  ( $0.4$  to  $0.9$ ). In November 2009 (Fig. 6b) the daily average  $\beta$  ratio was higher with a daily average of  $0.9$  ( $0.5$  to  $1.3$ ) but in March (Fig. 6c) however,  $LE$  dominated the energy balance with an average  $\beta$  ratio of  $0.4$  ( $0.1$  to  $0.6$ ).

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Closure discrepancy was different for each field campaign. In August 2009 the  $D$  was 0.98 indicating exceedingly good closure. However, the second and third field campaigns produced  $D$ 's of 1.18 and 1.33 in November 2009 and March 2010, respectively, indicating (1) either an overestimation of  $LE$  and/or  $H$ , and/or an underestimation of the available energy ( $R_n - G$ ) and/or (2) unaccounted energy such as advection or storage in the canopy biomass.

### 3.3 *Measured actual total evaporation*

The mean daily  $ET_a$  over the three field campaigns was significantly different (based on their 95% confidence interval). The daily  $ET_a$  (Fig. 7) was lowest in the August 2009 (winter) and increased progressively through November 2009 (early summer) to March 2010 (late summer). The standard deviation (SD) for all field campaigns was similar (0.3 to 0.4 mm) but the coefficient of variation (not shown) differed with the highest in November 2009 (12.0) and August 2009 (11.0) and lowest in March 2010 (8.8).

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### 3.4 *Relationship between sapflow and actual total evaporation measured during two field campaigns*

The diurnal courses of the sapflow from the emergent and understory trees were surprisingly smooth in comparison to the  $ET_a$  results (Figs. 8a-d). The  $ET_a$  is an integrated measure of soil evaporation and transpiration from numerous plants at different levels within the canopy over the contributing area described by the footprint, whereas the transpiration measurements (assumed to equal sapflow) describe the physiology of a single tree. The  $R_n$ , frequently considered a significant driver of tree physiology, fluctuated due to cloud cover (Figs. 5a, 5b and 5c). These fluctuations were not translated into fluctuations in tree sapflow but are evident in the  $ET_a$  results particularly over the midday period. A similar pattern was observed in the March 2010  $ET_a$  data (Figs. 8c and 8d). It is recommended that  $G$  be measured at numerous positions under swamp forest canopies in order to capture the variability in  $G$  and a representative average.

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Despite the greater midday variability of the  $ET_a$  data, the polynomial regression (least squares) between hourly  $ET_a$  and tree sapflow showed a strong relationship in November 2009 for the emergent tree ( $RMSE=0.05 \text{ mm h}^{-1}$ ) as well as the understory tree ( $RMSE=0.06 \text{ mm h}^{-1}$ ). The polynomial regression was convex ( $R^2=0.89$ ) rather than linear ( $R^2=0.87$ ) in the case of the emergent tree (Fig. 9a) and concave ( $R^2=0.92$ ) rather than linear ( $R^2=0.90$ ) in the case of the understory tree (Fig. 9b). The increase in the rate of sapflow of the emergent tree was exponential for lower values of  $ET_a$  (morning and evening) but the rate of sapflow versus  $ET_a$  for higher values of  $ET_a$  slowed down as the tree reached its peak transpiration rate. In contrast the understory sapflow rate increased gradually per unit increase in  $ET_a$  at lower values but at higher values of  $ET_a$  the increase in sapflow was exponential. In March 2010 the results were similar with  $RMSE$ 's of  $0.07 \text{ mm h}^{-1}$  and  $0.08 \text{ mm h}^{-1}$  for the emergent and understory trees, respectively. Convex and concave trendlines again fitted the data best (Fig. 9c and 9d). Lagging the sapflow by one hour as suggested by Granier et al. (2000) did not improve the regression of sapflow on  $ET_a$ .

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### 3.5 *Comparison of the FAO Penman-Monteith reference evaporation versus the Priestley-Taylor potential evaporation during the three field campaigns*

The linear regression (least squares) of the hourly  $ET_o$  against hourly  $ET_a$ , explained 75%, 85% and 76% of the fluctuations in  $ET_a$  during the August 2009, November 2009 and March 2010 field campaigns, respectively (Table 2). The Priestley-Taylor model did not perform as well, accounting for 54%, 74% and 62% of the variation in  $ET_a$  during the August 2009, November 2009 and March 2010 field campaigns, respectively (Table 2).

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The slope of the linear regression ( $K_c$ ) varied between field campaigns (Table 2) and was highest in March (1.3), and lower in November 2009 (1.1) and August 2009 (0.8). The  $\alpha$ , also estimated by the

slope of the linear regression, was similar during the August (1.0) and November 2009 (1.0) field campaigns (Table 2) while during March 2010,  $\alpha$  was slightly higher (1.1). The standard deviations and root mean square errors of  $\alpha$  were higher than those of the  $K_c$  (Table 2). Therefore, the FAO Penman-Monteith  $ET_o$  model was adopted as most suitable for use over the Nkazana PSF in this study.

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The time interval (hourly and daily) at which the FAO Penman-Monteith  $ET_o$  and Priestley-Taylor models were computed resulted in different  $K_c$  and  $\alpha$  estimates. Daily computations used average daytime  $T_{air}$ , typically derived from an average of maximum and minimum daily  $T_{air}$ . In this research the models were run hourly and the average  $T_{air}$  derived from 10 s measurements of  $T_{air}$  (while  $R_n > 0$ ) accurately representing that hour. However, using hourly data produced outliers in the calculation of  $K_c$  and  $\alpha$  at the beginning or end of a day where the measured or modelled results are very small numbers, producing, from division, erroneous estimates of  $K_c$  and  $\alpha$  (Eqs. 5 and 6). These typically occurred near sunset or sunrise and were filtered out of the data as they represented outliers. In addition, due to the vastly different canopy structures and heights within the Mfabeni Mire, of the SFW (~0.8 m) and Nkazana PSF (~20 m), climatic data from above the forest was used as an input to the models to determine whether the SDs of  $K_c$  and  $\alpha$  could be minimised, but no significant improvement was found. This indicated that the nearby weather station data (from within the SFW) was a suitable input for both models supporting the application of these models using the standard FAO Penman-Monteith  $ET_o$  weather station sensor heights of two meters (Allen et al., 2006).

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### 3.6 Modelling long-term actual total evaporation and monthly crop factors

The long-term  $ET_a$  (October 2009 to September 2010) was modelled through the relationship between the observed  $ET_a$  and observed sapflow over the November 2009 and March 2010 field campaigns. In regressions of the emergent tree sapflow with  $ET_a$  over the two field campaigns (Figs. 9a and 9c), it was found that there was little gain in using separate linear models for the two periods ( $R^2 = 0.92$  and  $0.89$ ;  $RMSE = 0.05 \text{ mm h}^{-1}$  and  $0.06 \text{ mm h}^{-1}$ ) as a single, combined model, described  $ET_a$  equally well ( $R^2 = 0.90$ ;  $RMSE = 0.07 \text{ mm h}^{-1}$ ). A similar result was found for the understory tree, indicating that for both trees a single relationship between  $ET_a$  and sapflow represented both field campaigns.

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In addition, a multiple regression, including the emergent and understory trees as predictors of  $ET_a$  ( $R^2 = 0.91$ ;  $RMSE = 0.08 \text{ mm h}^{-1}$ ), provided insufficient benefit over the use of the single model based on only the emergent tree ( $R^2 = 0.90$ ;  $RMSE = 0.08 \text{ mm h}^{-1}$ ). The understory tree sapflow was considerably less (by 85%) than that of the emergent tree and the density of the understory trees within the Nkazana PSF is much lower than the emergent trees. These results support the omission of the understory tree from the prediction of  $ET_a$ , and the use of the following model to estimate the  $ET_a$  of the Nkazana PSF from hourly sapflow data:

$$ET_a = (0.16341 \cdot T_r + 0.06)^2 \quad (8)$$

where,  $ET_a$  is the actual total evaporation ( $\text{mm hr}^{-1}$ ) and  $T_r$  the emergent tree sapflow ( $\text{L hr}^{-1}$ ).

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The annual  $ET_a$  (October 2009 to September 2010) from the Nkazana PSF was 1125 mm, over which period the rainfall was 650 mm (well below the long-term average, reported to be between 844 and 1200  $\text{mm a}^{-1}$  for the area). Finally,  $K_c$  was calculated at a daily interval from the extended  $ET_a$  and  $ET_o$  (Eq. 5), and averaged for each month of the year (Fig. 10). These results equated well with the results of  $K_c$  calculated during the field campaigns (Table 2) which were 0.8, 1.0 and 1.3 in August, November and March, respectively. During a distinct period from February to May,  $K_c$  was between 1.2 and 1.4 while for the rest of the year it was 0.8 to 1.0. When  $K_c = 1$  the Nkazana PSF  $ET_a$  equals the evaporative demand, or in other words  $ET_o$ . However, a  $K_c$  of  $<1$  or  $>1$  indicates that the PSF  $ET_a$  is  $<$  than or  $>$  than the  $ET_o$ , respectively. Fig. 10 shows that the Nkazana PSF  $ET_a$  is at or just less than  $ET_o$  for eight

months of the year (June to January) and greater than  $ET_o$  for four months of the year (February to May).

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The derived crop factors were verified using independent measurements of  $ET_a$  over the Nkazana PSF collected during window periods at the same site from 8 to 12 August 2008 and 12 to 20 November 2008 in an experimental unpublished study conducted by the CSIR. The surface conditions during 2008 within the Nkazana PSF were much wetter as the water table was close to the surface with open water in low lying areas whereas in 2009 and 2010 the dry period had caused the water level to drop resulting in only a few areas of open water within the forest. Despite this difference in groundwater level, the  $K_c$  was 0.8 in August of 2008 and 0.9 during November 2008, validating the results derived for  $K_c$  (from the extended record of  $ET_a$  modelled from sapflow of the emergent tree), thus confirming that the  $K_c$  derived was applicable across wetter and drier years.

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### 3.7 Response of sapflow to climatic variables

Equation 8 enabled the derivation of  $ET_a$  over the period during which there were sapflow measurements (October 2009 to September 2010). The purpose for this was to better understand the relationship between important climatic variables and  $ET_a$ . Three statistical approaches were used to determine these relationships with sapflow, which were directly related to  $ET_a$  and the climatic variables. The simple linear regressions of daily sapflow were considered with radiant flux density and VPD and it was found that these were poor, with coefficients of determination of only 0.51 and 0.52 respectively (not shown). Clearly the relationship between climatic conditions and sapflow is more complex. By applying multiple regression analysis  $I_s$ , RH,  $T_{air}$  and  $\theta$  at 0.075 m were found to be significant ( $p < 0.001$ ) with up to four-way interactions. Finally a regression tree analysis was applied of hourly log-transformed sapflow with the meteorological variables  $I_s$ , RH,  $T_{air}$  and  $\theta$  (Fig. 11). This showed again that the relationships are complex but that  $T_{air}$  and  $\theta$  were not required for the optimal split for the Nkazana PSF emergent tree sapflow. The most important split was between data with  $I_s$  of less than  $55.7 \text{ W m}^{-2}$  and data with  $I_s$  greater than  $55.7 \text{ W m}^{-2}$ . Solar irradiance was clearly a key variable to include and the first split observed, essentially separates day and night-time data. Solar irradiance was also highly correlated with  $T_{air}$ , which may be the reason  $T_{air}$  was not found to be an additionally required variable. The next important splits were for RH above and below 93.2% for the night time data (essentially when it is raining and when it is not) and an additional split for  $I_s$  above and below  $279.2 \text{ W m}^{-2}$  for the day time data; therefore splitting day time data during high and low irradiance periods. At night the logged sapflow was found to be negative, with the greatest negative average logged sapflow when the RH was less than 96.4%. The greatest average positive logged sapflow was found to be when  $I_s$  was greater than  $279.2 \text{ W m}^{-2}$ , and this occurred 28% percent of the time.

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## 4 Discussion

The EC method is recognised internationally to be a suitable and accurate technique for estimating  $ET_a$  over vegetated surfaces and long-term EC measurements over the Nkazana PSF could provide the data required to understand the annual cycles of  $ET_a$ . However, EC systems have relatively high power requirements and need careful and frequent attendance as well as data checking, correction and analysis for complete records. The remote location of the Nkazana PSF, with no road access and difficult access on foot, high wind speeds and dangerous wild animals such as buffalo, rhinoceros, hippopotamus and crocodiles, prompted a research strategy to characterise the  $ET_a$  of the Nkazana PSF during field campaigns conducted in representative seasons, as it was impractical to maintain a full EC system over an extended period of time (such as a year). There was a risk that a period of unusual weather could have coincided with the window periods (between seven and nine consecutive days at a time). However the weather conditions during the field campaigns showed that a range of climatic conditions were captured that were representative of the seasons (Table 1). With this approach, field campaigns could be extended should unusual weather conditions be encountered over the planned measurement period.

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The challenge remained in interpolating and extrapolating the  $ET_a$  results from the EC system to annual  $ET_a$ . In long-term evaporation studies where gaps occur or where window periods have been used, and interpolation of the  $ET_a$  record is required, meteorological models are typically used. Total evaporation has been estimated using models that are computationally simple such as the Priestley-Taylor model (Priestley and Taylor, 1972; Shuttleworth and Calder, 1979) to more complex models using multi-layer approaches within the canopy, but still based on the Penman-Monteith approach (Roberts et al., 1993; Harding et al., 1992), with significant deviations between measurements and modelled results. These meteorological models are, however, uncoupled from the transpiring vegetation and therefore the pattern of actual tree sapflow was considered in this study as a predictor of  $ET_a$ .

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External regulation of sapflow has been described by numerous variables including the readily available soil water of the rooting area (Oren and Pataki, 2001), the micrometeorological conditions of the atmosphere (Lundblad and Lindroth, 2002), leaf area (Granier et al., 2000), canopy conductance (Granier et al., 2000), aerodynamic resistance (Jacobs and De Bruin, 1992; Hall, 2002), shading of lower leaves (Cienciala et al., 2000) and wind stress (Kim et al., 2014). However, it has been found that trees can have several mechanisms of internal regulation related to species specific morphology and physiology that is partially uncoupled from the external conditions (Zweifel et al., 2005). Nevertheless, in most trees with actively transpiring leaves and some readily available soil water, a diurnal pattern of sapflow results from a combination of internal and external conditions, which determines how a tree contributes to the  $ET_a$  of a forest stand.

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With advances in sapflow measurement techniques, long-term forest  $ET_a$  has been estimated by up-scaling from tree transpiration to forest  $ET_a$  using various techniques generally based on sapwood area (Čermák et al., 2004). However, the large majority of these studies, especially where tree transpiration has been up-scaled, have been conducted in uniform forest stands (Oren et al., 1999; Wilson et al., 2001) and much of the work has taken place in temperate boreal stands (Lundblad and Lindroth, 2002; Launiainen et al., 2011) and their applicability to other climatic zones needs consideration. In addition, it has also been recognised that transpiration often varies amongst species (Oren and Pataki, 2001; Ewers et al., 2002; Bowden and Bauerle, 2008) and up-scaling to forest transpiration in species-rich indigenous forests is complex.

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The results from this study showed that the hourly sapflow of a single emergent tree, selected as a dominant species, correlated well with the hourly  $ET_a$  measured over two window periods. In species rich forests, measuring the sapflow of the different vegetation types (including the ferns, vines, understory and emergent trees) would be challenging, and up-scaling questionable, due to the variety of plant structures within the canopy and our lack of information on the plant physiologies. Therefore, the empirical relationship between the single tree and  $ET_a$  provided an ideal opportunity to derive the annual  $ET_a$  of a vegetation type for which there is no information of the water-use characteristics. This relationship indicated that the emergent canopy trees are the main contributors to  $ET_a$ . The other contributors to  $ET_a$ , including open water, peat, ferns, vines and understory trees were either (1) insignificant contributors due to the low irradiance and VPD below the emergent tree canopy (supported by the low measured sapflow rate of the understory tree), or (2) follow similar diurnal trends in evaporation and sapflow as the emergent tree (also supported by the diurnal trend in the sapflow rate of the understory tree) and are therefore captured in the empirical model of the emergent tree.

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Variation of the energy balance closure discrepancy ( $D$ ) occurred between field campaigns, despite replication of the same instrumentation at the same site and with the same data processing procedures. Only the placement of the soil heat flux sensors changed slightly within the vicinity of the site between field campaigns. However, the soil heat fluxes (as a percent of net irradiance) fluctuated from 1% to 11%, likely due to the specific placement of the sensors within the Nkazana PSF in a predominantly

shaded area in contrast to a sunlit location due to gaps in the canopy. During August 2009 when  $D = 1$  (i.e. perfect closure of the energy balance), the soil heat flux was approximately 5% of  $R_n$  and was likely to be the most representative result for  $G$  for a forested area, so agreeing with Dye et al. (2008). In March,  $G$  was 11% of  $R_n$  and may have contributed to the poorest result of  $D = 1.33$ . Wilson et al. (2002) found that energy balance closure, especially over forests, is seldom achieved. However, in most cases the magnitude of the long-term turbulent fluxes is lower than the available energy (Twine et al., 2000; Oliphant et al., 2004), which was not the case in the Nkazana PSF study where  $D$  increased with increasing  $ET_a$  from August 2009 through November 2009 to March 2010.

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An important observation, made over the three field campaigns, was that the average  $ET_a$  measured during March 2010 ( $4.4 \text{ mm day}^{-1}$ ) did not correspond to the period of highest  $R_n$  (November 2009), which is commonly accepted to be one of the main driving variables in the process of  $ET_a$  (Albaugh et al., 2013). This may indicate a lag in the  $ET_a$  of the Nkazana PSF in relation to the maximum  $R_n$ , possibly explaining the poor relationships observed between tree sapflow and climatic variables (such as  $R_n$ ). This lag was also observed in the high  $K_c$  values from February to May, where the  $ET_a$  of the PSF was higher relative to  $ET_o$ . Typically,  $K_c$  is higher while vegetation is more actively transpiring and is associated with higher  $I_s$  and water availability, which in the Nkazana PSF would coincide with the summer period (October to March). However, the period of higher  $K_c$  values in the Nkazana PSF occurred quite late (February to May) in the summer season (Fig. 10). Clulow et al. (2013) showed the Nkazana PSF sapflow to be relatively consistent between seasons but that  $ET_o$  rapidly decreased from February to May ( $4.2 \text{ mm day}^{-1}$  to  $2.4 \text{ mm day}^{-1}$ ). The high  $K_c$  is therefore likely a result of decreasing  $ET_o$  measured at the meteorological station, while transpiration rates in the Nkazana PSF were maintained into the late autumn period. A number of reasons may be attributed to this including the microclimate of the Nkazana PSF. For example, the lower energy loss at night from the ground and within the canopy, due to the combined effect of high water vapour levels (a greenhouse gas) and reduced infrared emission as a result of canopy absorbance, reflectance and re-emission downwards, compared to areas outside the PSF with shorter canopies, resulted in higher minimum daily temperatures (Fig. 4). The area adjacent to the Nkazana PSF where the automatic weather station was located (with a shorter canopy of approximately 1 m in height) experienced lower daily minimum temperatures (Fig. 4). The importance of this result is that  $T_{air}$  affects biochemical processes such as photosynthesis and senescence. This  $T_{air}$  difference, although greatest in winter, starts to build in January and could play a role in influencing the  $ET_a$  in relation to the summer season as well as the period of higher  $K_c$  values in the latter half of summer.

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Two important points regarding the weather station data and model calculations were noted. Firstly, where possible, hourly model time intervals should be used, which concurs with Irmak et al. (2005). However, this frequently resulted in outliers in  $K_c$  and  $\alpha$  at the beginning or end of a day where the measured or modelled results were small numbers, producing, through division, erroneous estimates. It was therefore favourable to sum the hourly  $ET_o$  and  $ET_a$  data for each day (while  $R_n > 0$ ) and calculate the daily  $K_c$  (which was then averaged for each month). Secondly, when calculating the  $K_c$  and  $\alpha$  coefficient's, there was no benefit in using the climatic data from above the tree canopy rather than the climatic data from the adjacent SFW of the Mfabeni Mire, which sufficiently represented the microclimate for the model calculations. This showed that data from nearby weather stations can be used with the  $K_c$  to estimate the  $ET_a$  although this may only hold in humid environments where there is little difference in the VPD of the boundary layer conditions over the Nkazana PSF and the surrounding wetland areas, which are likely to all be at, or near, equilibrium evaporation.

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The shape of the regressions of hourly  $ET_a$  versus hourly sapflow (Fig. 9) during the window periods showed that sapflow of the emergent tree responded rapidly for low conditions of  $ET_a$ . These conditions occurred most frequently in the early morning and late afternoon when the angle of the  $I_s$  was low but still incident upon the emergent tree leaves. At higher rates of  $ET_a$  the sapflow peaked as the physiology



of the tree limited the sapflow rates. In contrast, the understory tree sapflow rate increased slowly relative to  $ET_a$ , while  $ET_a$  was low, and exponentially for higher values of  $ET_a$ . This is likely due to shading of the understory trees for low sun angles (early morning and late afternoon) with  $I_s$  limiting transpiration (together with the low VPD discussed above) with maximum rates occurring when shading by the emergent trees was at a minimum (noon) and  $ET_a$  was at a maximum. These different responses of the trees indicated that a model to derive  $ET_a$  from sapflow would require the inclusion of both emergent and understory trees. However, the sapflow and density of the understory trees was much lower than the emergent trees and therefore its inclusion in the empirical model was not found to significantly improve the relationship between entire canopy  $ET_a$  and sapflow. This conclusion applies specifically to the Nkazana PSF. Some models such as the WAVES model permits two canopy simulations due to the importance of the understory canopy in some forest sites (Dye et al., 2008).

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Within South Africa, the study by Dye et al. (2008) measured daily  $ET_a$  of between 2 mm and 6 mm on clear days over three field campaigns during February, June and October 2004, which are comparable with the results from the Nkazana PSF of between 2.2 mm (August 2009) and 5.1 mm (March 2010). Internationally, no results of  $ET_a$  or modelling guidelines for peat swamp forests were found, signifying the unique contribution of this study.

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The comparison of meteorological variables with sapflow revealed that it is unlikely that a single climatic variable is able to determine sapflow, and in turn  $ET_a$ . The relationships were revealed to be non-linear and that to model sapflow accurately, data needs to be sub-set into different periods; at least into day and night.

## 5 Conclusions and opportunities for further research

This study portrayed the difficulties of using the most advanced systems available to measure  $ET_a$ , such as EC, in remote and difficult-to-access areas. It showed that intensive window period measurements using high maintenance EC systems provide reliable and continuous measurements of  $ET_a$  but require a method to determine the  $ET_a$  during the in-between periods to be able to estimate long-term  $ET_a$ . This was overcome by measuring the long-term sapflow of an emergent canopy tree and deriving a qualitative model for  $ET_a$  based on sapflow measurements. Further research on the benefit of measuring multiple emergent trees and the possible variability of transpiration within different species and the extent to which this could improve the long-term estimate of forest  $ET_a$  together with window periods of EC data would be beneficial.

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Energy balance closure discrepancy ( $D$ ) remains an unresolved matter which affects flux measurements such as  $ET_a$  and  $CO_2$ . Corrections suggested in research studies can be applied but without conclusively identifying the source of the error in the observations. In contrast to most studies reported, the closure discrepancy of the energy balance over the Nkazana PSF was greater than 1 for two of the field campaigns. Although attributed in part to unrepresentative  $G$  measurements,  $D$  increased as  $ET_a$  increased.

The model used to derive the annual  $ET_a$  from sapflow (Eq. 8), and then monthly crop factors was verified with data from two independent field campaigns in 2008, when conditions were much wetter and there were larger areas of open water within the forest. The much wetter conditions in 2008 did not alter the  $K_c$  thus indicating that the relationship between  $ET_a$  and  $ET_o$  remained constant and that the  $K_c$  derived can be applied over a range of climatic conditions. In addition, it indicates that the humid, low VPD environment within the forest canopy minimises the contribution of open water evaporation within the forest to  $ET_a$ . However, the general dearth of information on the  $ET_a$  of subtropical indigenous forests internationally allows little comparison of the results obtained from the Nkazana PSF and similar

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forest types and knowledge of the extent to which these crop factors can be extrapolated geographically and to similar forests would benefit from further comparisons.

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The Mfabeni Mire is actively managed by the iSimangaliso Wetland Park. These results provide the basis for improved estimates of the  $ET_a$  component of the Nkazana PSF water balance and the environmental water requirements. Water is critical to the functioning of this ecosystem for biotic and abiotic life, the sequestration or release of carbon from the Mire and also to the spread of fires. The annual  $ET_a$  estimated in this study (1125 mm) was even higher than the range (844 to 1200 mm  $yr^{-1}$ ) of reported estimates of mean annual precipitation for the area (Lynch, 2004; Taylor et al., 2006; ARC-ISCW, 2011).

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**Commented [AD93]:** Reworded.

The difference between  $ET_a$  and rainfall highlights the importance of the groundwater contributions and the critical role it plays in assuring the survival of this groundwater dependant ecosystem. The groundwater available to the Mfabeni Mire is in part determined by the management of the upstream catchments and the groundwater levels of the greater Zululand Coastal Aquifer, emphasising the need for an integrated catchment management approach to the area.

*Acknowledgements.* This research was funded by Key Strategic Area 2 (i.e. Water-Linked Ecosystems) of the Water Research Commission (WRC) of South Africa and the Council for Scientific and Industrial Research and forms part of an unsolicited research project (Evapotranspiration from the Nkazana Swamp Forest and Mfabeni Mire). The iSimangaliso Wetland Park are acknowledged for their support in providing access to the research sites. Craig Morris provided invaluable statistical analysis and support. Assistance in the field by Piet-Louis Grundling, Sipiwe Mfeka, Scott Ketcheson, David Clulow, Lelethu Sinuka and the late Joshua Xaba is much appreciated.

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**Table 1.** Summary of weather conditions during the August 2009, November 2009 and March 2010 field campaigns

**Commented [AD106]:** Three tables combined into one

Date	Solar radiant density (MJ m <sup>-2</sup> )	Wind speed (m s <sup>-1</sup> )	Wind direction (°)	VPD (kPa)	Air temperature (°C)		RH (%)		Rain (mm)
					Max	Min	Max	Min	
13/8/2009	14.2	4.6	199	1.5	21.9	13.0	88.7	33.7	0.8
14/8/2009	15.4	2.4	194	1.2	21.8	9.8	95.5	43.3	
15/8/2009	15.3	1.9	83	1.1	22.4	7.0	98.9	50.7	
16/8/2009	14.9	2.5	74	1.1	23.3	11.2	97.0	46.5	
17/8/2009	15.9	3.2	38	1.0	22.6	10.4	98.1	48.9	
18/8/2009	14.8	4.3	33	1.0	23.0	14.1	95.0	52.5	
19/8/2009	15.5	5.5	28	1.2	24.5	13.2	96.3	45.8	
<b>Average</b>	15.1	3.5		1.2	22.8	11.1	95.6	45.9	
4/11/2009	22.0	2.1	115	0.9	23.8	13.2	96.4	51.9	5.3
5/11/2009	16.7	4.2	40	0.6	25.2	17.7	93.3	66.7	
6/11/2009	18.1	5.3	37	0.6	25.8	19.9	93.3	73.0	
7/11/2009	19.0	6.9	36	0.6	25.9	21.6	93.2	70.5	
8/11/2009	25.3	7.4	37	0.7	26.4	21.3	90.5	69.0	
9/11/2009	21.1	6.2	34	0.7	25.3	21.0	94.7	69.2	
10/11/2009	16.2	4.4	223	0.6	24.7	19.4	95.6	61.6	
11/11/2009	21.2	2.3	47	0.5	26.1	15.5	97.1	64.6	0.3
<b>Average</b>	22.8	3.1		0.8	28.3	18.4	94.9	58.2	
16/3/2010	19.6	3.5	66	1.0	27.9	20.0	92.8	65.2	
17/3/2010	14.6	2.3	245	0.8	28.7	18.4	96.0	60.3	
18/3/2010	17.2	2.2	214	0.8	26.4	17.7	94.1	65.5	
19/3/2010	20.2	3.0	58	0.8	28.6	16.1	96.8	62.6	
20/3/2010	20.6	3.8	66	1.0	30.0	22.1	93.2	59.0	
21/3/2010	16.2	1.9	90	1.0	28.6	21.9	92.8	59.9	0.3
22/3/2010	22.5	1.7	97	0.8	28.9	16.4	96.7	59.6	
23/3/2010	19.9	2.3	234	1.0	28.8	16.8	97.3	63.9	
24/3/2010	21.2	2.1	79	1.0	30.2	18.6	96.7	56.6	
<b>Average</b>	19.1	2.5		1.1	28.7	18.7	95.2	61.4	

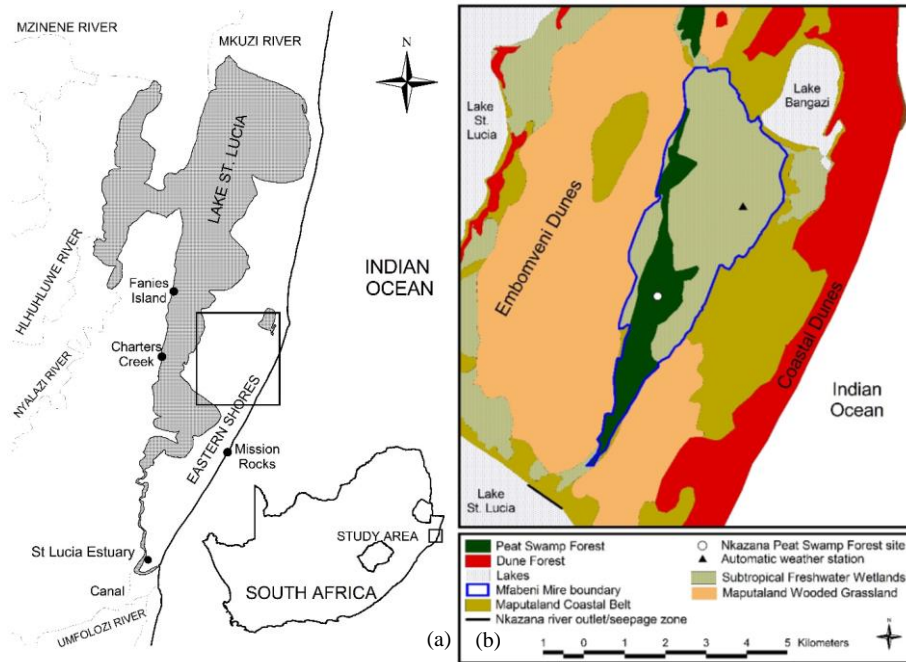
**Table 2.** Summary of the hourly crop co-efficient  $K_c$  and advective term  $\alpha$  with standard deviation and root mean square error (RMSE) for each of the three field campaigns.

	$K_c$	$K_c$			$\alpha$	$\alpha$		
		Coefficient of determination	Standard deviation	RMSE		Coefficient of determination	Standard deviation	RMSE
Aug 2009	0.8	0.75	0.22	0.07	1.0	0.54	0.35	0.08
Nov 2009	1.0	0.85	0.17	0.07	1.0	0.74	0.34	0.11
Mar 2010	1.3	0.76	0.39	0.11	1.1	0.62	0.46	0.13

**Commented [AD107]:** Table title reworted and corrected







**Fig. 2.** (a) Location of the Eastern Shores within South Africa, (b) the Nkazana Peat Swamp Forest site (where the EC and sapflow systems were located) and the automatic weather station within the Mfabeni Mire on the Eastern Shores (data from Mucina and Rutherford, 2006).

**Commented [AD109]:** Additional place names added to maps



Fig. 3. (a) Telescopic mast (21.3 m) erected in the swamp forest to raise the eddy covariance instruments above the forest canopy, (b) the computer installed at the swamp forest, housed in a temperature controlled enclosure and (c) the instruments attached to the head of the mast.

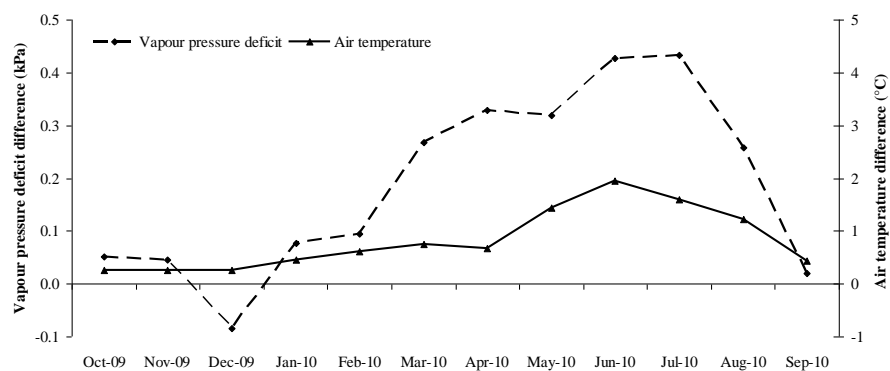


Fig. 4. The difference in the monthly daytime (9am to 3pm) vapour pressure deficit and difference between the monthly average dawn air temperatures measured in the subtropical freshwater wetland area of the Mfabeni Mire (reeds, sedges and grasses) and within the canopy of the Nkazana Peat Swamp Forest site.

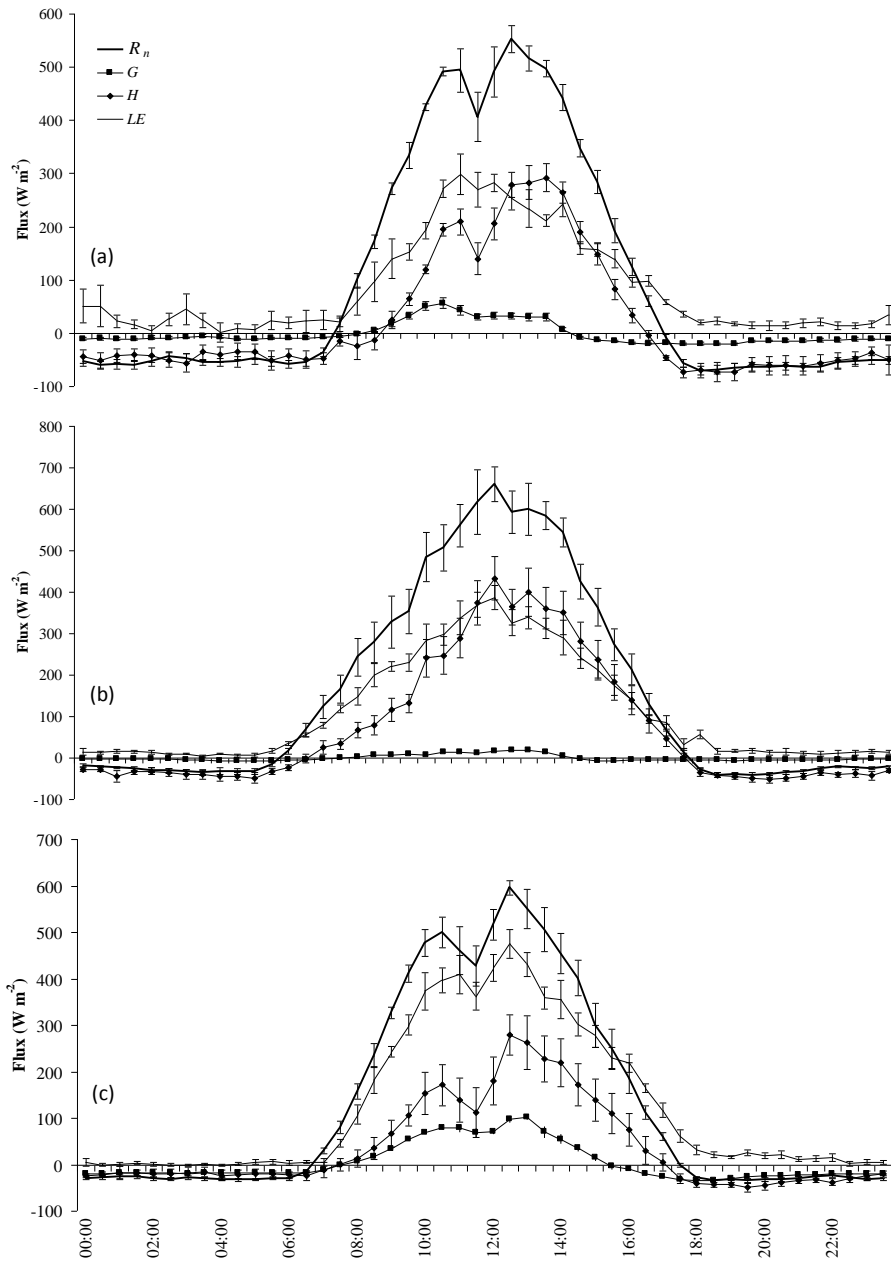


Fig. 5. The average of the half-hourly energy fluxes, with error bars indicating the standard error, measured at the Nkazana Swamp Forest in (a) August 2009, (b) November 2009 and (c) March 2010.

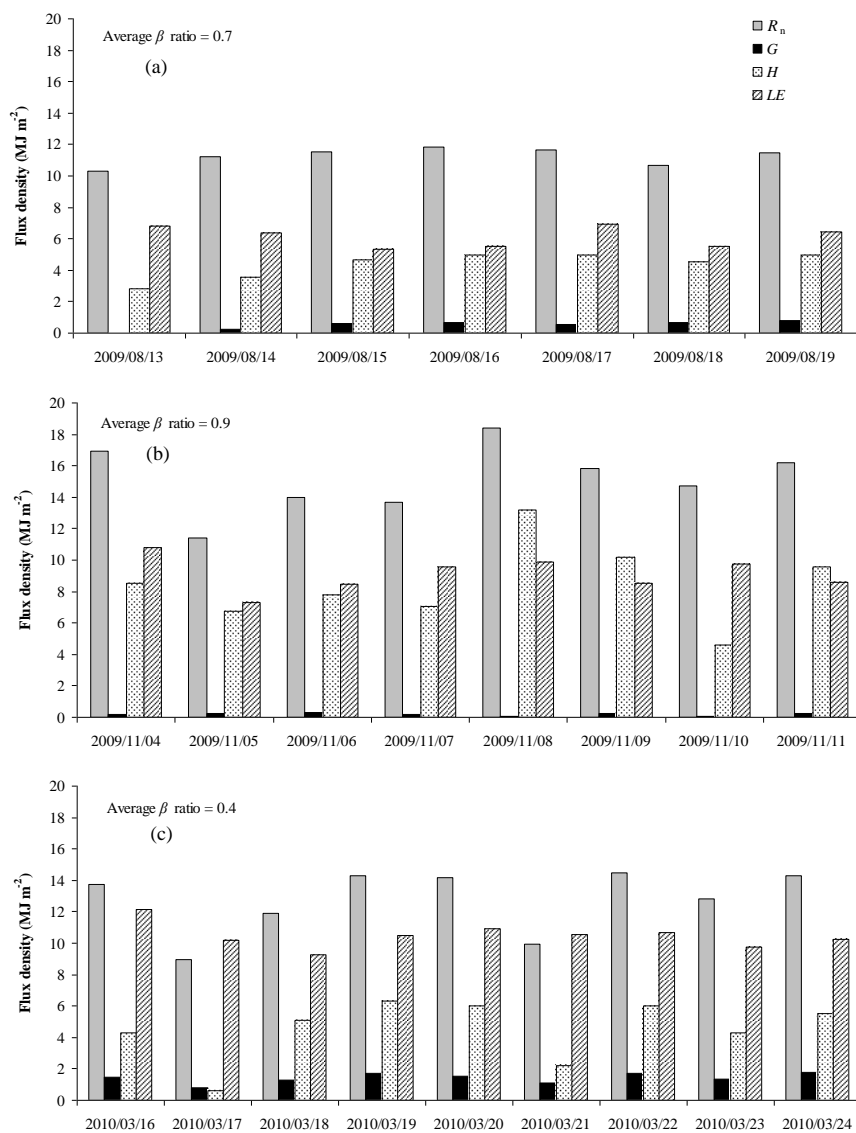


Fig. 6. Daily total energy densities (while  $R_n > 0$ ) measured at the Nkazana Swamp Forest in (a) August 2009, (b) November 2009 and (c) March 2010.

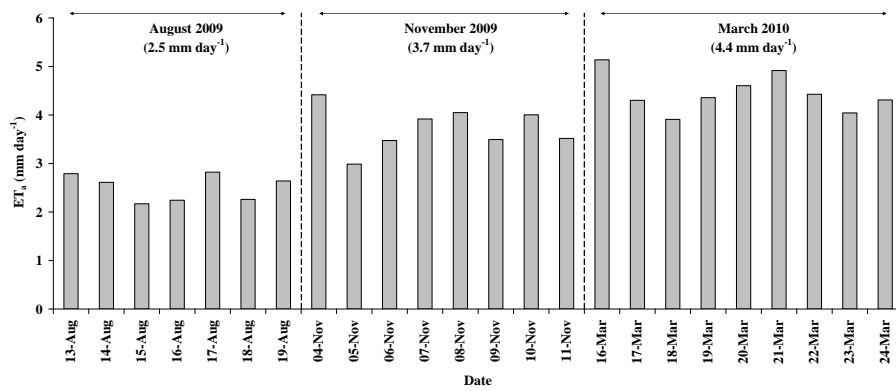


Fig. 7. Daily actual total evaporation (ET<sub>a</sub>) measured over the Nkazana Swamp Forest during three representative periods.

Commented [AD110]: Y axis label and caption corrected

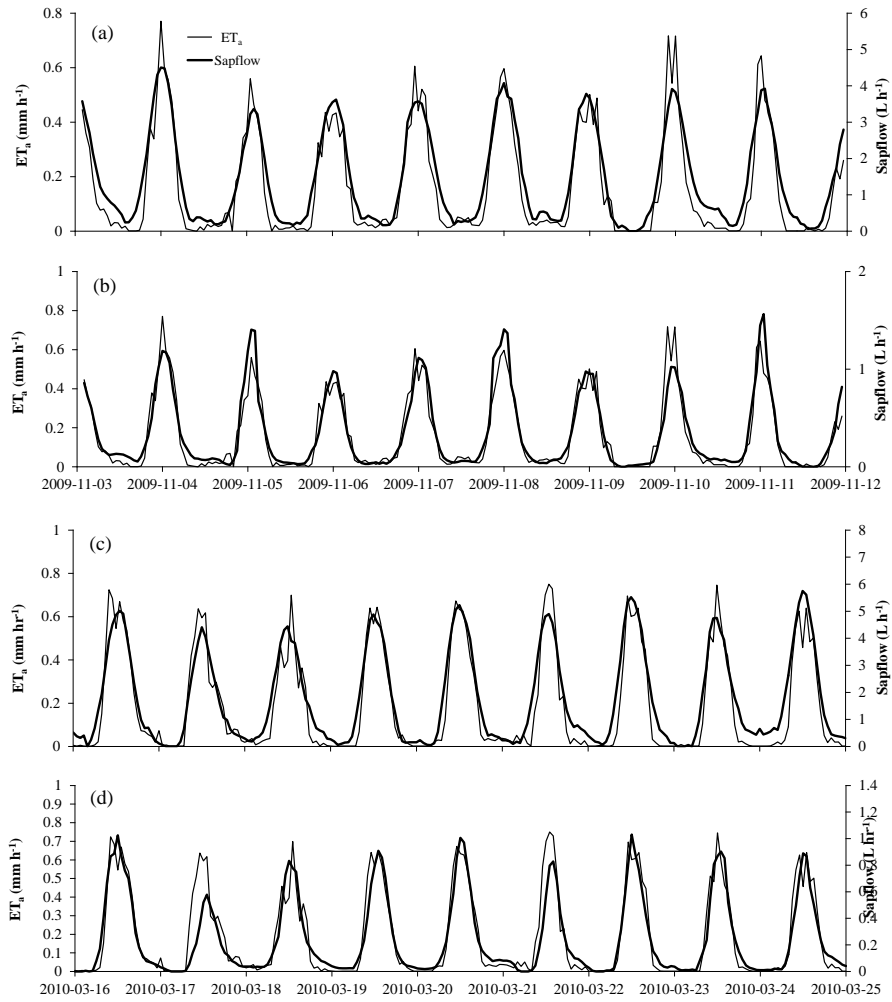


Fig. 8. Diurnal course of the hourly actual total evaporation ( $ET_a$ ) and sapflow in November 2009 (a and b) and March 2010 (c and d) for the emergent and understory trees, respectively.

Commented [AD111]: Previously two Figs now combined.



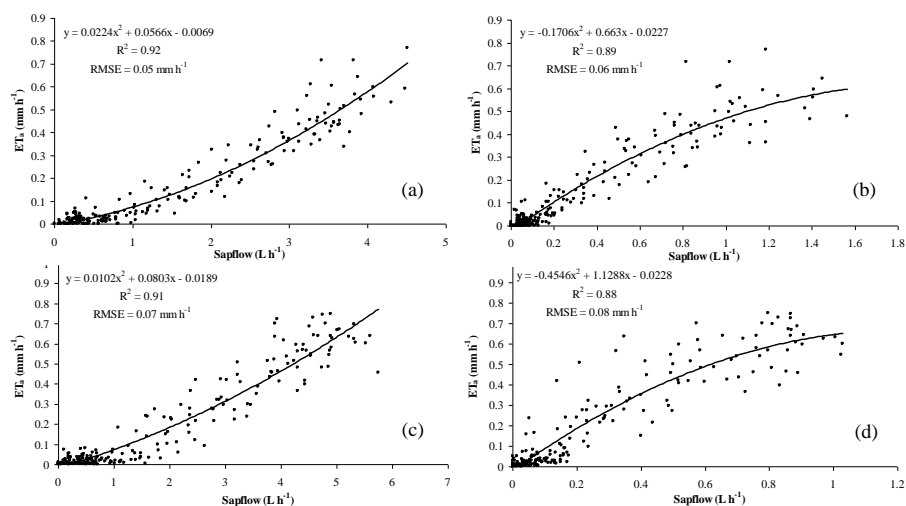


Fig. 9. Polynomial regressions of actual total evaporation ( $ET_a$ ) against the hourly sapflow for the (a) emergent and (b) understory trees during November 2009, and the (c) emergent and (d) understory trees in March 2010.

Commented [AD112]: Units of RMSE corrected

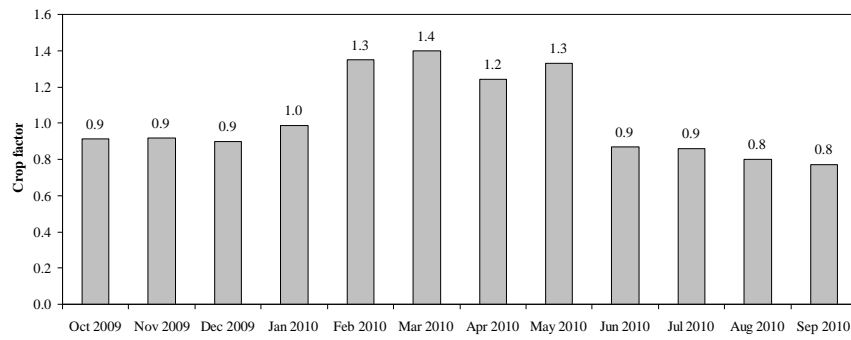


Fig. 10. Monthly crop factors  $K_c$  for the Nkazana Peat Swamp Forest.

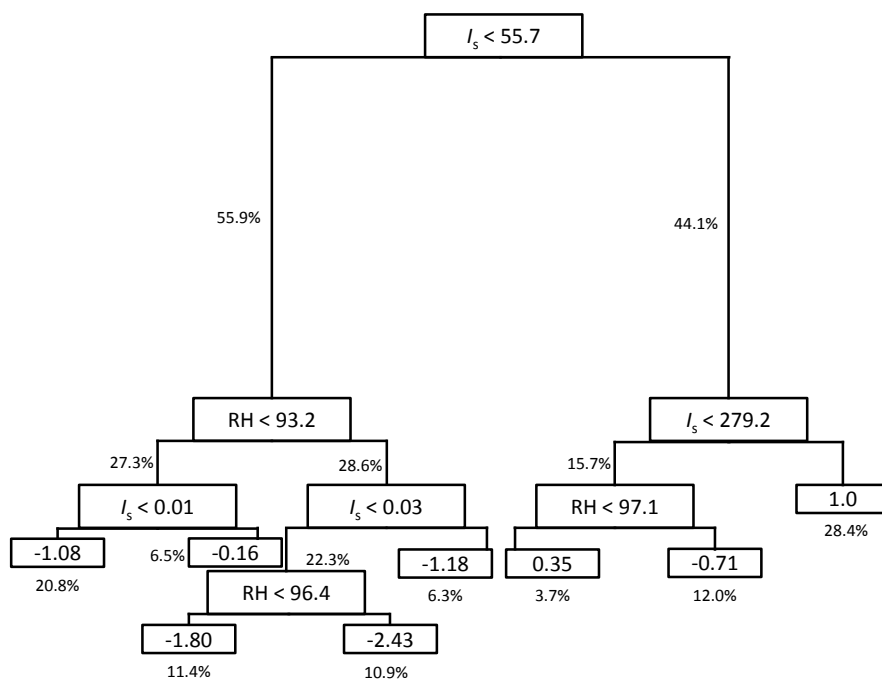


Fig. 11. A regression tree analysis for sapflow showing the optimal splits of solar irradiance ( $\text{W m}^{-2}$ ) and relative humidity (%). Air temperature and volumetric water content were included, but these variables were not required for the optimal splits. The percentage of the total data at each split is also shown.

Commented [AD113]: *I<sub>s</sub>* was italicised in regression tree