Evapotranspiration model comparison and an estimate of field scale *Miscanthus* canopy precipitation interception

AMANDA J. HOLDER[1] (iD), JON P. MCCALMONT[1], NIALL P. MCNAMARA[2],
REBECCA ROWE[2] and IAIN S. DONNISON[1]

[1]Institute of Biological, Environmental and Rural Sciences (IBERS), Aberystwyth University, Gogerddan, Aberystwyth, Wales SY23 3EQ, UK, [2]Centre for Ecology & Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster LA1 4AP, UK

Abstract

The bioenergy crop *Miscanthus* × *giganteus* has a high water demand to quickly increase biomass with rapid canopy closure and effective rainfall interception, traits that are likely to impact on hydrology in land use change. Evapotranspiration (ET, the combination of plant and ground surface transpiration and evaporation) forms an important part of the water balance, and few ET models have been tested with *Miscanthus*. Therefore, this study uses field measurements to determine the most accurate ET model and to establish the interception of precipitation by the canopy (C_i). Daily ET estimates from 2012 to 2016 using the Hargreaves–Samani, Priestley–Taylor, Granger–Gray, and Penman–Monteith (short grass) models were calculated using data from a weather station situated in a 6 ha *Miscanthus* crop. Results from these models were compared to data from on-site eddy covariance (EC) instrumentation to determine accuracy and calculate the crop coefficient (K_c) model parameter. C_i was measured from June 2016 to March 2017 using stem-flow and through-flow gauges within the crop and rain gauges outside the crop. The closest estimated ET to the EC data was the Penman-Monteith (short grass) model. The K_c values proposed are 0.63 for the early season (March and April), 0.85 for the main growing season (May to September), 1.57 for the late growing season (October and November), and 1.12 over the winter (December to February). These more accurate K_c values will enable better ET estimates with the use of the Penman-Monteith (short grass) model improving estimates of potential yields and hydrological impacts of land use change. C_i was 24% and remained high during the autumn and winter thereby sustaining significant levels of canopy evaporation and suggesting benefits for winter flood mitigation.

Abbreviations

C_i = interception of precipitation by the plant canopy
EC = eddy covariance
ET_a = actual evapotranspiration
ET_c = evapotranspiration for a specific crop type
ET_{EC} = evapotranspiration calculated from eddy covariance data
ET = evapotranspiration
ET_o = evapotranspiration for a reference crop type
ET_P = potential evapotranspiration
GG = Granger–Gray evapotranspiration model
HS.adj = HS adjusted with a soil moisture coefficient
HS = Hargreaves–Samani evapotranspiration model
K_c = crop coefficient
LE = latent heat flux

PAR = Photosynthetically Active Radiation
PMgrass = simplified Penman–Monteith short grass reference evapotranspiration model
PMK_c = PMgrass adjusted with K_c values calculated for *Miscanthus*
PMsugarcane.adj = PMsugarcane adjusted with a soil moisture coefficient
PMsugarcane = PMgrass adjusted with K_c values for sugarcane
PT.adj = PT evapotranspiration model adjusted with a soil moisture coefficient
PT = Priestley-Taylor evapotranspiration model
Rh = relative humidity
Rs = solar/global radiation
SRC = short rotation coppice
Ta = air temperature.

Introduction

The planting of perennial bioenergy crops is expected to grow following an increased focus on renewable energy generation in order to meet global greenhouse gas

Correspondence: Amanda J. Holder, tel. +44 1970 823197,
fax +44 1970 622350, e-mail: amh21@aber.ac.uk

emission targets (IPCC, 2014; Energy Technologies Institute, 2015). Adaptations to changes in climate are also being considered as it is now anticipated that some of the predicted impacts of climate change are unavoidable (IPCC, 2007, 2014). In the UK, repeated flooding events have stimulated interest in identifying mitigation strategies and have highlighted the potential role for farmland and upland areas for buffering against high rainfall (Marshall *et al.*, 2009; Christen & Dalgaard, 2013; Wynne-Jones, 2016). This need is leading to an interest in finding commercially viable climate change resilient crops (Environment Agency, 2015) that can be located within these landscapes to provide wide-ranging environmental benefits. *Miscanthus × giganteus* Greef et Deu (Greef & Deuter, 1993) is a low input biomass feedstock that, beyond simply burning in power stations, is also marketable in the biorefining industry (producing liquid fuels and chemicals) and as animal bedding (Brosse *et al.*, 2012; Van Weyenberg *et al.*, 2015).

The current commercial clone, *Miscanthus × giganteus* (hereafter *Miscanthus*), is a tall-growing (up to ~3 m) sterile perennial grass hybrid with an efficient C_4 photosynthetic pathway. Requiring few agricultural inputs, it has the potential to grow on poorer soils (Lewandowski *et al.*, 2000; Hastings *et al.*, 2008; Lovett *et al.*, 2009; Cadoux *et al.*, 2012). *Miscanthus* has limited stomatal control, a high water demand used to quickly increase biomass, and rapid canopy closure with a large leaf area index providing effective rainfall interception (Clifton-Brown *et al.*, 2002; Joo *et al.*, 2017). The site-specific impacts of land use change to *Miscanthus* on water balances vary depending on factors including altitude, climate, and stage of crop maturity (Dunkerley, 2000; Stephens *et al.*, 2001a). Increased planting of *Miscanthus* could potentially increase evapotranspiration (ET) and affect ecosystem water dynamics through impacts on boundary layer temperatures, humidity, and solar radiation to the ground (Hickman *et al.*, 2010; Milner *et al.*, 2016). However, these traits may also reduce flooding, soil erosion, and nutrient run-off. Information regarding these potential impacts is vital for accurate modelling of land use change scenarios to fully inform policymakers.

ET is mainly estimated using models due to the cost of equipment and time-consuming nature of field studies. A number of models can be used to calculate estimates of actual ET (ET_a, evaporation from all surfaces under natural conditions), potential ET (ET_p, the ET rate where there is no shortfall in soil water for vegetation use), and reference crop ET (ET_o, ET_p from a specific reference crop type (e.g. short grass) with no water shortage) (Allen *et al.*, 1998; Xu & Chen, 2005; McMahon *et al.*, 2013).

Different models require varying levels of data and have different approaches to the basis of the calculations, and the impacts of these differences for the prediction of ET rates for a novel crop like *Miscanthus* are not clear. The Hargreaves–Samani (HS, Hargreaves & Samani, 1985) model is based on air temperature, Priestley–Taylor (PT, Priestley & Taylor, 1972) on solar radiation, and the Granger–Gray (GG, Granger & Gray, 1989) model uses a complementary relationship where land and atmosphere feedbacks lead to a mutual dependency between ET_a and ET_p (Bouchet, 1963; Morton, 1965). The simplified Penman–Monteith model (PMgrass, Allen *et al.*, 1998) uses net incoming radiation and atmospheric and surface resistance terms to provide an estimate of ET_o for a reference short green crop. PMgrass results can be further adapted to provide estimates of ET for a specific crop type (ET_c) with the use of a crop coefficient value (K_c) (Allen *et al.*, 1998).

To our knowledge, there are no published studies comparing different ET models with a *Miscanthus* crop. The PMgrass model in conjunction with K_c values has been used for *Miscanthus* plants by Beale *et al.* (1999) in a water use efficiency study, and by Triana *et al.* (2015) and Liu *et al.* (2014) in water balance studies. K_c values reported for *Miscanthus* range from 0.31 to 1.20 (Beale *et al.*, 1999; Stephens *et al.*, 2001b; Triana *et al.*, 2015), based on data obtained from locations with different climates, and do not always include the full *Miscanthus* growing season. Hydrology models incorporating ET have also been used to model land use change to *Miscanthus*: Stephens *et al.* (2001b) and Borek *et al.* (2010) used the WaSim model (calculating ET using PMgrass with the option of K_c values); Finch *et al.* (2004) the Met. Office Surface Energy Scheme (MOSES) model; Vanloocke *et al.* (2010) the Agro-IBIS model; and Cibin *et al.* (2015) the Soil & Water Assessment Tool (SWAT) model. The SWAT model can calculate ET_p via the Penman–Monteith equation (Monteith, 1965), PT, or HS methods (SWAT, n.d.). Only Stephens *et al.* (2001a,b) and Finch *et al.* (2004) model hydrology for *Miscanthus* in a UK climate type. Simulations by Stephens *et al.* (2001a) show reductions in run-off and groundwater recharge under *Miscanthus* compared to grass, whereas simulations by Finch *et al.* (2004) show *Miscanthus* having lower water use than grass, whilst pointing out that measurements over a full year are required to confirm this. More crop-specific measurements for energy grasses are required to provide accurate estimates of ET and validate model predictions (Stephens *et al.*, 2001a; Finch *et al.*, 2004; Vanloocke *et al.*, 2010; McCalmont *et al.*, 2017a). Of the few studies that have measured ET for *Miscanthus*, Finch *et al.* (2004) recorded growing season highs of ~5 mm day^{-1} with eddy covariance (EC) equipment, Hickman *et al.* (2010) measured highs of

~7 mm day^{-1} using a residual energy balance approach and Triana *et al.* (2015) report a maximum 11 mm day^{-1} using lysimeters.

Knowledge of the accuracy of commonly used ET formulae is not only of use in modelling the hydrological impacts of land use change but will also be of benefit in the modelling of potential yields and other environmental impacts such as greenhouse gas emissions where models require ET$_P$ as an input (Richter *et al.*, 2008; Hastings *et al.*, 2009; Dondini *et al.*, 2016).

In addition to ET, canopy precipitation interception (C$_i$) is an important metric in understanding winter evaporation and soil moisture recharge. To date, there have been few studies relating to tall grass energy crops and interception, with only one UK *Miscanthus* study. Finch & Riche (2010) reported measured *Miscanthus* C$_i$ of 24%. However, measurements took place in small trial plots and the effect cannot be assumed to be the same at field scale as surface resistance becomes a smaller factor in water vapour diffusion to the atmosphere with increasing canopy cover forming a uniform layer (Monteith & Unsworth, 2008; Finch & Riche, 2010).

This study aims to:

- Determine the most accurate ET model compared to EC ET data (ET$_{EC}$) for use with *Miscanthus*.
- Establish C$_i$ in a commercial-scale *Miscanthus* plantation under the UK climate conditions.

To achieve this, four base ET models, with further adjustments taking account of soil moisture status, were used to compare to ET$_{EC}$ at a commercial-scale mature *Miscanthus* plantation in Wales, UK, where *in situ*

weather station and EC equipment have been recording since land use conversion from grassland in 2012. A field study was set up in the plantation to record C$_i$ from June 2016 to March 2017.

Materials and methods

Site description

Field experiments, EC measurements, and weather data collection took place at a 6 ha plantation of *Miscanthus* located in Aberystwyth, Wales (52°25′17″ N 4°04′14″ W) (Fig. 1). The site elevation is ~110 m a.s.l. with coastal cliffs ~0.5 miles west of the field boundary. It is predominantly flat with a slight slope (7°) to the south. The soil, a mixture of clay loam and sandy/silty clay loam, is formed over Denbigh series bedrock. The field capacity is 0.38 m^3 m^{-3}, as shown in Saxton & Rawls (2006) and confirmed from *in situ* soil moisture probes (2× CS616 Campbell Scientific (CSI), Logan, UT, USA, soil water content reflectometer installed at 25 cm depth). Permanent wilting point is 0.22 m^3 m^{-3} (Saxton & Rawls, 2006). The field was converted from semi-improved grass pasture to *Miscanthus* in April 2012.

Meteorological data

EC data were recorded by two open-path systems (EC150/CSAT3A OPEC system, CSI, Logan, UT, USA) located at two towers (Fig. 1) covering the central and most level 3.9 ha portion of the cropped area. Sensors were raised during the growing season to maintain a height of 2 m above the canopy. The systems included a sonic anemometer (CSAT-3A, CSI), infrared gas analyser (EC150, CSI), and air temperature (Ta, °C) and relative humidity (Rh, %) probes (HMP155A, CSI) recording to
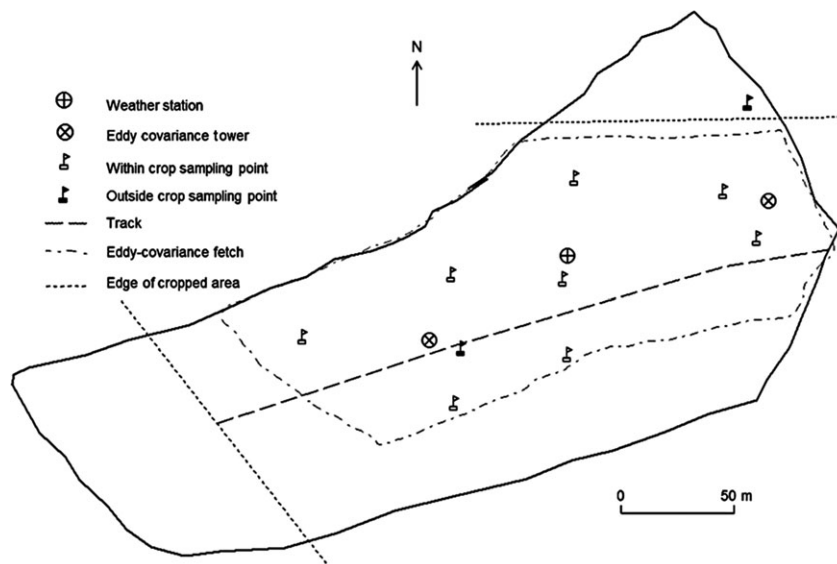

Fig. 1 Map showing the outline of the 6 ha (approx.) *Miscanthus* field with the cropped area, sampling points, and meteorological and atmospheric measuring equipment locations marked.

data loggers (CR3000, CSI) at 20 Hz and processed to 30 min averages using EddyPro software (EddyPro version 4.2.0, LI-COR bioscience, Lincoln, NE, USA). Data were quality controlled and gap-filled as described in McCalmont *et al.* (2017b). Latent heat flux (LE) values surrounding gap-filled values were further checked for abnormally high figures caused by wet instrumentation and were replaced using averages of nearby nongap-filled values. ET figures were determined from LE using Eqn (1) and were converted to mm day^{-1}.

$$ET_{EC} = \frac{LE}{\lambda} \qquad (1)$$

where ET_{EC} is the ET flux (mm h^{-1}), LE is the 30 min latent heat flux after corrections and gap filling (Wm^2), and λ is the latent heat of vaporization constant. The value used for the hourly rate constant was 690.42 Wm^2 (2.4855 MJ m^{-2}), as determined by the EddyPro software.

Excepting Rh and Ta (measured at each eddy covariance tower) meteorological data were collected from a station located in the centre of the field (Fig. 1) and logged in 30 minute intervals using a CR1000 (CSI) data logger. Precipitation (mm) was recorded using a tipping bucket rain gauge (52203, R.M. Young, Ann Arbor, MI, USA). Photosynthetic photon flux density (μmol m^{-2} s^{-1}) was measured with a SKP215 Photosynthetically Active Radiation (PAR) Quantum sensor (Skye systems, Llandrindod Wells, UK). Wind speed (ms^{-1}) and direction (from north) were collected using a 05013 wind monitor (R.M. Young). Small gaps in the weather data (<1% overall) were filled from a nearby weather station.

ET models

Four ET models were calculated using Eqns (2–10) with the R (R Core Team, 2015) package 'Evapotranspiration' (Guo & Westra, 2016). Results were output on a daily (24 h) time step.

The Granger–Gray (GG) formula (McMahon *et al.*, 2013) calculates actual ET Eqn (2).

$$GG = \frac{\Delta G_g}{\Delta G_{g+\gamma}} \frac{R_n - G}{\lambda} + \frac{\gamma G_g}{\Delta G_{g+\gamma}} E_a \qquad (2)$$

where GG is the Granger–Gray ET model (mm day^{-1}), G_g is based on Eqns (3) and (4), G is the soil heat flux (MJ m^{-2} day^{-1}), γ the psychrometric constant (kPa °C^{-1}), R_n the net daily radiation (MJ m^{-2} day^{-1}), λ the latent heat of vaporization (MJ Kg^{-1}), and Ea the drying power of the air calculated from Eqn (5).

$$G_g = \frac{1}{0.793 + 0.20 e^{4.902 Dp}} + 0.006\, Dp \qquad (3)$$

where Dp is calculated using Eqn (4).

$$Dp = \frac{E_a}{E_a + \frac{R_n - G}{\lambda}} \qquad (4)$$

where Ea is calculated using Eqn (5).

$$E_a = f(u)\,(v^*a - va) \qquad (5)$$

where $f(u)$ is the wind function shown in Eqn (6), v^*a the daily saturation vapour pressure (kPa) and va the mean daily actual vapour pressure (kPa).

$$f(u) = 1.313 + 1.381\, u_2 \qquad (6)$$

where u_2 is the average daily wind speed (m s^{-1}) at 2 m.

The Priestley–Taylor (PT) formula (McMahon *et al.*, 2013) calculates potential ET (Eqn 7).

$$PT = \alpha PT \left[\frac{\Delta}{\Delta + \gamma} \frac{R_n}{\lambda} - \frac{G}{\lambda} \right] \qquad (7)$$

where PT is the Priestley–Taylor ET model (mm day^{-1}), αPT is a constant of 1.26 for advection-free saturated surfaces, Δ is the slope of vapour pressure curve (kPa °C^{-1}), γ the psychrometric constant (kPa °C^{-1}), R_n the net daily radiation (MJ m^{-2} day^{-1}), λ the latent heat of vaporization (MJ Kg^{-1}), and G the soil heat flux (MJ m^{-2} day^{-1}).

The Hargreaves–Samani (HS) formula (McMahon *et al.*, 2013) calculates reference ET for a short grass crop with no water shortage (Eqn 8).

$$HS = 0.0135 C_{HS} \frac{R_a}{\lambda} (T_{max} - T_{min})^{0.5} (T_a + 7.8) \qquad (8)$$

where HS is the Hargreaves–Samani ET model (mm day^{-1}), C_{HS} is a coefficient based on Eqn (9), R_a is extraterrestrial radiation (MJ m^{-2} day^{-1}), λ the latent heat of vaporization (MJ Kg^{-1}), T_{max} and T_{min} the maximum and minimum daily temperatures (°C), and T_a the average daily temperature (°C).

$$C_{HS} = 0.00185(T_{max} - T_{min})^2 - 0.0433(T_{max} - T_{min}) \qquad (9)$$

where C_{HS} is the Hargreaves–Samani coefficient and T_{max} and T_{min} are the maximum and minimum daily temperatures (°C).

The Penman–Monteith (PMgrass) formula (Allen *et al.*, 1998) calculates reference ET for a short grass crop with no water shortage (Eqn 10)

$$\frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a + 273} u_2 (v_a^* - v_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad (10)$$

where Δ is the slope of the vapour pressure curve (kPa °C^{-1}), R_n the net radiation (MJ m^{-2} day^{-1}), G the soil heat flux (MJ m^{-2} day^{-1}), γ the psychrometric constant (kPa °C^{-1}), T_a the mean daily air temperature (°C), u_2 the average daily wind speed (at 2 m) (m s^{-1}), v^*a the daily saturation vapour pressure (kPa), and va the mean daily actual vapour pressure (kPa).

The inputs required for the models along with the values used for the constants are shown in Table 1. Global radiation, also known as solar radiation (Rs) (Allen *et al.*, 1998), was calculated as 2× PAR (Monteith & Unsworth, 2008) and converted to MJ m^2 day^{-1}.

Adjustment from ET_p to ET_a

The PT and HS models were adjusted daily to provide a prediction of ET_a via the use of a soil moisture function (Mintz & Walker, 1993; Dingman, 2002; Xu & Chen, 2005) which reduces ET estimates as soil water becomes depleted to critical levels. The relationship between ET_p, precipitation, the soil moisture function (F), and ET_a is as follows:

    if ET_p > precipitation then $ET_a = ET_p \times F$
    if ET_p = precipitation then $ET_a = ET_p$
    if ET_p < precipitation then $ET_a = ET_p$

Table 1 Data input requirements for the Hargreaves–Samani (HS), Priestley–Taylor (PT), Granger–Gray (GG), and Penman–Monteith (short grass) (PMgrass) evapotranspiration models. The options and values for the constants used in this study are shown in italics

Inputs	HS	PT	GG	PMgrass
Date, time, and day of the year of each record	✔	✔	✔	✔
Air temperature, Ta (°c)	✔	✔	✔	✔
Relative humidity, Rh (%)	✔	✔	✔	✔
Wind speed at 2 m height, u_2 (m s^{-1})			✔	✔
Solar radiation, Rs (MJ m^{-2} day^{-1})	✔	✔	✔	✔
Precipitation (mm)	✔	✔	✔	✔
Alpha (*0.23*)			✔	✔
Alpha PT (*1.26*)		✔		
1948 Penman wind function version Short crop				✔
				✔
Elevation (*115 m*)	✔	✔	✔	✔
Latent heat of vaporization, Lambda (*2.45 MJ Kg^{-1} at 20 °C*)	✔	✔	✔	✔
Latitude (*0.914902 radians*)	✔	✔	✔	✔
Solar constant, Gsc, (*0.082 MJ m^{-2} min^{-1}*)	✔	✔	✔	✔
Stefan-Boltzmann constant, Sigma (*4.903 10^9 MJ K^{-4} m^{-2} day^{-1}*)		✔	✔	✔
Soil heat flux, G (*0, negligible for daily time step*)		✔	✔	✔
Height of wind instrument, Z (2 m)			✔	✔

The soil moisture function is calculated from a basic soil water balance using Eqns (11–13).

$$F [0 - 1] = \frac{W}{W^*} \quad (11)$$

where F is the soil moisture function restricted to between 0 and 1, W the soil moisture estimated from Eqn (12), and W^* the soil storage capacity calculated from Eqn (13).

$$W_t [0 - 96] = W_{t-1} + (P_t - ET_{pt}) \quad (12)$$

where W_t is the soil moisture (mm) restricted to between 0 and the field capacity (96 mm, from Eqn 13), W_{t-1} the soil moisture (mm) from the previous day, P_t the precipitation (mm), and ET_{pt} the calculated ET_P (mm).

$$W^* = 1000(0.38 - 0.22)0.60 \quad (13)$$

where W^* is the site-specific soil moisture storage capacity (mm), 1000 the conversion to mm, 0.38 the site-specific field capacity (m^3 m^{-2}), 0.22 the site-specific wilting point (m^3 m^{-2}), and 0.60 the site-specific approximate soil/rooting depth (m).

Following the method in Allen *et al.* (1998), the PMgrass results were adjusted with a water stress coefficient (K_s) and a crop coefficient (K_c) to provide an estimate of ET_a, as shown in Eqn (14). The K_c values for sugarcane, also a C$_4$ plant with tall stems and a large leaf area index, were used. Sugarcane published K_c values are 0.40 for the early growth stage, 1.25 for the

main growing season, and 0.75 for the late season (Allen *et al.*, 1998). 0.75 was also used for the winter season.

$$ET_a = K_s K_c \, ET_o \quad (14)$$

where ET_a is the PMgrass results adjusted for the soil moisture depletion and crop type, K_s the water stress coefficient calculated from Eqns (15–17), K_c the crop-specific coefficient, and ET_o the PMgrass result.

$$K_s [0 - 1] = \frac{TAW - Dr}{TAW - RAW} \quad (15)$$

where K_s is the water stress coefficient (between 0 and 1), TAW the total available water (mm) calculated in the same way as W* (Eqn 13), Dr the root zone moisture depletion calculated from Eqn (16), and RAW the readily available water (mm) calculated from Eqn (17).

$$Dr_t = Dr_{t-1}, -P_t + ET_{ct} \quad (16)$$

where Dr is the root zone depletion (mm), Dr_{t-1} the water content in the root zone on the previous day (mm), P_t the precipitation (mm), and ET_{ct} the crop evapotranspiration (mm).

$$RAW = pTAW \quad (17)$$

where RAW is the readily available water (mm), TAW the total available water (mm) calculated in Eqn (13), and p the fraction of TAW that the plant can extract without suffering water stress applied on a seasonal basis [values of p used were 0.76 for the early and late season, 0.67 for the main season, and 0.77 for the winter – based on the values and adjustments given for sugarcane in Allen *et al.* (1998)].

Miscanthus crop coefficient (K_c)

To calculate the *Miscanthus*-specific K_c, ET_{EC} and PMgrass daily ET rates were divided to approximately correspond to the relevant stages of plant growth (Table 2).

The K_c value for each season was calculated using Eqn (18), and the value multiplied by the results of PMgrass to provide the Penman–Monteith K_c (PMK$_c$) estimated ET.

$$K_c = \frac{ET_{EC}}{PM} \quad (18)$$

where K_c is the crop coefficient, ET_{EC} the mean daily EC calculated evapotranspiration for the season, and PM the mean daily evapotranspiration calculated by the Penman–Monteith (short grass) model.

Table 2 Months allocated to each seasonal stage of *Miscanthus* plant growth for calculation of the crop coefficient (K_c)

Season	Month
Early	March and April
Main	May, June, July, August, and September
Late	October and November
Winter	December, January, and February

Canopy precipitation interception

Measurements took place from 23rd June 2016 until 13th March 2017 using methods similar to those used by Riche & Christian (2001). Eight sampling locations (2 m^2) within the cropped area (Fig. 1) were selected by stratified random sampling using a preconversion topsoil moisture map to take account of wetter and drier areas. Three stem-flow and three through-fall gauges (Fig. 2a–c) were randomly placed within each sampling location.

Two further sampling areas to collect gross precipitation were located outside the crop canopy – one to the north and the other in a clearing along the centre track (Fig. 1). A monthly count of the number of mature stems in 1 m^2 along with the average stem thickness was carried out in an area immediately adjoining the sampling locations. Gauges were checked approximately twice weekly with measurements taken in dry weather when water levels were high enough in the gauges for accurate measurement with the use of a graduated cylinder. After the first few weeks of data collection, an error level of less than or equal to 4.75% was calculated from the sums of squares and coefficient of variation using the means of the eight zones within the crop (Raghunath, 2006).

The C$_i$ was taken to be the difference between the gross precipitation recorded outside the crop and the net precipitation recorded within the crop (Eqn 19).

$$C_i = GP - (TF + SF) \quad (19)$$

where C$_i$ is the interception (mm), GP the measured gross precipitation (mm), TF the measured through-fall (mm), and SF the measured stem-flow (mm).

For each recording event, the amount of precipitation collected in the through-fall bottles was converted into a depth measurement based on the area of the funnel. Gross rainfall was collected and converted to a depth measurement in the same way as the through-fall using the four gauges located in each of the two locations outside the crop. For each recording event, stem-flow amounts were adjusted for the average size of the stem and reduced by the amount collected by the closest through-fall bottle to account for through-fall that would also have been collected by the funnel (Eqn 20). Total stem-flow was then calculated as a mean depth measurement (Eqn 21). During measurement, 19 samples of a total of 2856 (2.62%) were rejected as a result of broken stems or damage to the collecting system.

$$SFA = SFC - (TFC - SP) \quad (20)$$

where SFA is the stem-flow amount (ml), SFC the amount collected in the stem-flow bottle (ml), TFC the amount collected in the closest through-fall bottle (ml), and SP the percentage of the funnel/overflow bottle area taken up by the stem (%).

$$SFD = \frac{(SFA \times S) * 1000}{SA} \quad (21)$$

where SFD is the total stem-flow depth (mm), SFA the mean stem-flow amount (calculated from the mean stem-flow amount in each sampling area) (ml), S the mean number of stems in 1 m^2, 1000 the conversion to mm^3, and SA the surface area of the stem count (mm^2).

Statistics

Statistics were carried out using R version 3.2.3 (R Core Team, 2015). Model residual plots were checked for the appropriateness of linear regression, and the linear model function was used to obtain the R^2 values (with ET$_{EC}$ as the independent variable). The seasonal daily means, standard deviation, and standard error of the mean were calculated for all the daily ET results. The HydroGof (Zambrano-Bigiarini, 2017) R package was used to calculate the mean absolute error (MAE), Root Mean Square Error (RMSE), modified Index of Agreement (md) (return of between 0 and 1 where 1 = a perfect match), and the modified Nash Sutcliffe Efficiency (mNSE) (return of between –infinity and 1 where 1 = a perfect match and
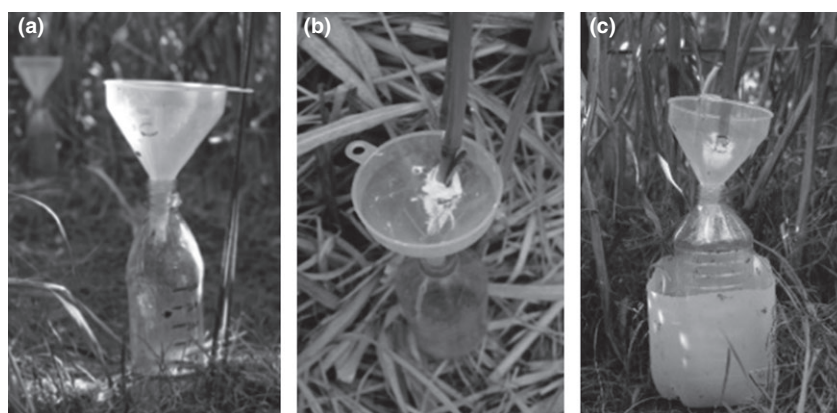

Fig. 2 (a) Through-fall within the crop and precipitation outside the crop canopy was measured using 500 ml plastic bottles with 95 mm diameter funnels. The funnel and bottle were attached to a garden stake and secured with an elastic band and tent peg. (b) Stem-flow was measured using 750 ml plastic bottles (of the same height as the 500 ml bottles) with a 95 mm diameter funnel adapted to fit around the stem and sealed with silicon sealant. (c) As a precaution against overflowing the stem-flow bottle was placed inside a plastic container.

0 = predictions as accurate as the mean of the observed data) as described in Legates & McCabe (2005).

Results

Experimental data

Meteorological data from the weather station and eddy covariance instrumentation are shown in Fig. 3. Wind direction at the site is predominantly from the west with mean wind speeds and annual precipitation of 2.45 ms^{-1} and 871 mm for the period 2012 to 2016. Over the C$_i$ study period (23rd June 2016 to 13th March 2017), the total precipitation was 776 mm. Conditions at the site during the C$_i$ sampling period were generally within the five year average with the exception of short periods of high wind speeds due to seasonal storms, and particularly high rainfall during the summer of 2016 caused by shifts in the gulf stream (Fig. 3a, Met Office, 2016a). Most precipitation was received during the winter with the exception of 2012 and 2016 where high rainfall was also received during the summer. 2012 was the wettest of the 5 years reflecting national conditions with 2012 being one of the wettest years on record (Met Office, 2016b). Ta was similar across the years with 2013 and 2016 having the highest summer and winter temperatures (Fig. 3b). Rh was mostly above 80% for all of the 5 years (Fig. 3d). Soil moisture only dropped below the wilting point from 24th July 2014 to 20th October 2014 (Fig. 3e). Rs levels and LE and sensible heat (H) fluxes were comparable across each of the 5 years (Fig. 3f–h).

ET results

The mean annual ET rates (mm yr^{-1}) from 2013 to 2016 (excluding the conversion year) were ET$_{EC}$ 483, GG 432, PMgrass 545, PMsugarcane 552, PMsugarcane.adj 408, HS 698, HS.adj 327, PT 547, PT.adj 295, and PMK$_c$ (*Miscanthus*) 494. The highest daily ET$_{EC}$ was 4.65 (mm day^{-1}) in the main 2015 growing season.

Monthly trends in ET$_{EC}$ (Fig. 4) were similar over the five year study period with 2014 and 2015 showing the highest summer peaks, and the winters of 2012/2013 and 2014/2015 showing the lowest drops. ET$_{EC}$ was higher in the winter than predicted by all the models. There was no drop in ET$_{EC}$ during the period when the soil moisture was below wilting point, although there was a drop over the following late and winter seasons. GG, PMgrass, and PT.adj correspond well to the summer peak of 2012 which was the conversion year, but all
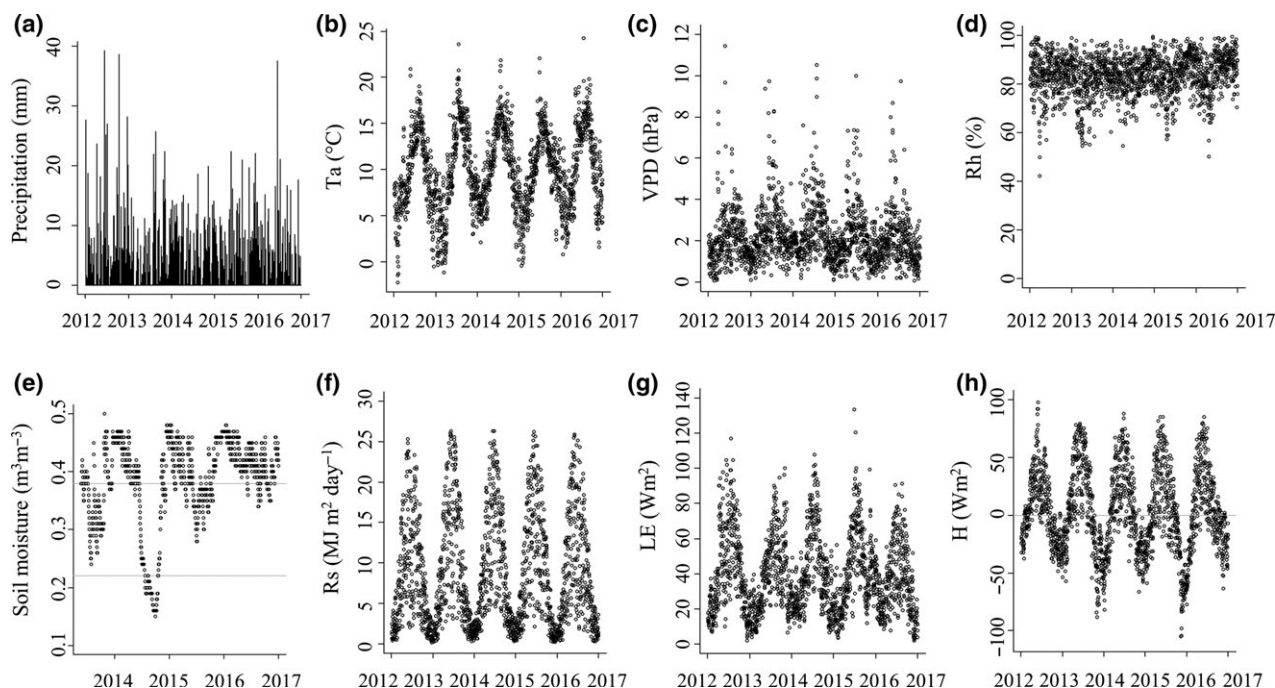

Fig. 3 Daily (24 h) data for the period 2012 to 2016: (a) total daily precipitation (mm); (b) mean daily air temperature (°C); (c) mean daily vapour pressure deficit (hPa); (d) mean daily relative humidity (%); (e) mean daily soil moisture (m^3 m^{-3}) at 25 cm depth (available data are from 22/05/2013 to end 2016) with the grey lines showing the field capacity (0.38) and wilting point (0.22); (f) mean daily solar radiation (calculated as 2× Photosynthetically Active Radiation) (MJ m^2 day^{-1}); (g) mean daily latent heat flux (Wm^2), and (h) mean daily sensible heat flux (Wm^2).
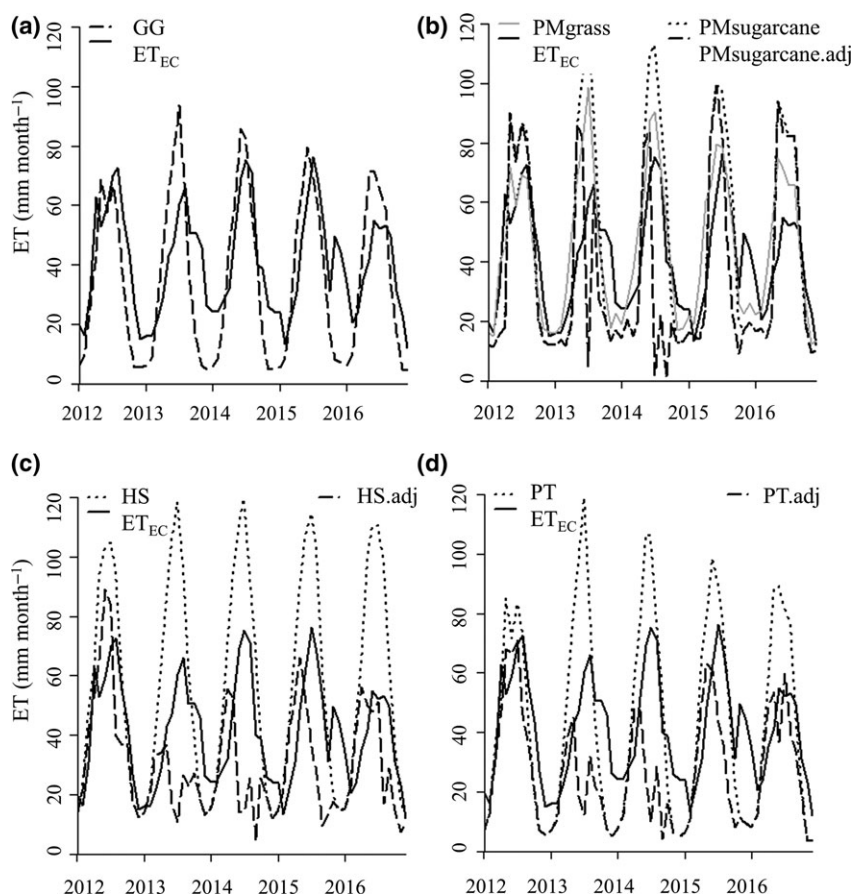
Fig. 4 Results of the daily evapotranspiration (ET) model predictions and eddy covariance ET (ET$_{EC}$) summed to provide monthly values: (a) Granger–Gray (GG) actual ET model predictions and ET$_{EC}$; (b) Penman–Monteith short grass reference ET (PMgrass), Penman–Monteith sugarcane crop ET (PMsugarcane), Penman–Monteith sugarcane crop ET adjusted with a water stress coefficient (K_s) (PMsugarcane.adj) and ET$_{EC}$; (c) Hargreaves–Samani grass reference ET (HS), Hargreaves–Samani grass reference ET adjusted with a soil moisture function (F) (HS.adj) and ET$_{EC}$; (d) Priestley–Taylor potential ET (PT), Priestley–Taylor potential ET adjusted with a soil moisture function (F) (PT.adj) and ET$_{EC}$.

the potential ET models overestimate the summer peaks. Adjustments for soil moisture with HS.adj and PT.adj reduce the main growing season levels too much compared to ET$_{EC}$, but PMsugarcane.adj overestimates them. Whilst HS results are considerably higher in the summer, the model performs better over the winter. PMgrass and PMsugarcane results are also close to ET$_{EC}$ over the winter, although the late growing season higher values are not captured by any of the models.

Statistics carried out for the early season (Table 3) show low R^2 values for all the models compared with ET$_{EC}$. The seasonal daily mean of the GG results is the closest to ET$_{EC}$ and is followed by PT.adj. All the model predictions overestimate with the exception of PMsugarcane. HS is shown to be the worst model for the early season with the most unfavourable outcomes of all the statistical tests performed compared to the other models. Adjustments for soil moisture during the early

season improved PT and HS results (mean F values for the early season for PT and HS were 0.89 and 0.84, respectively) but made no difference to PMsugarcane (mean K_s for the early season was 1). PT.adj, GG, PMsugarcane, and PMsugarcane.adj show a moderate fit using the modified Index of Agreement (md); however, the modified Nash Sutcliffe Efficiency (mNSE) test results in below zero values for all the models, with PT.adj being closest to it at −0.04. Overall for the early season, PT.adj performs the best, closely followed by GG. Comparing the potential ET models shows the PT results to be closest to PMgrass.

The mean values and statistics for the main season (Table 4) show PMgrass to be the best model compared to ET$_{EC}$, followed by GG. All the model means (except HS.adj and PT.adj) show an overestimation for the season, but GG and PMsugarcane.adj show the smallest difference to ET$_{EC}$. However, PMsugarcane.adj has a

Table 3 Mean daily evapotranspiration for the early season (2012–2013, number of observations 305) with the standard deviation (SD), standard error of the mean (SEM), R^2, mean absolute error (MAE), root mean square error (RMSE), modified Index of Agreement (md), and modified Nash Sutcliffe Efficiency (mNSE)

	EC	GG	PMsugarcane.adj	PMsugarcane	PMgrass	HS	HS.adj	PT	PT.adj
Mean (mm day^{-1})	1.03	1.17	0.57	0.57	1.43	1.78	1.48	1.44	1.26
SD (mm day^{-1})	0.52	0.54	0.23	0.23	0.57	0.48	0.38	0.64	0.47
SEM (mm day^{-1})	0.03	0.03	0.01	0.01	0.03	0.03	0.02	0.04	0.03
R^2 [0-1]		0.27	0.21	0.21	0.21	0.19	0.22	0.28	0.37
MAE (mm day^{-1})		0.43	0.47	0.47	0.55	0.81	0.57	0.56	0.40
RMSE (mm day^{-1})		0.54	0.65	0.65	0.69	0.92	0.66	0.71	0.50
md [0-1]		0.48	0.45	0.45	0.38	0.29	0.34	0.41	0.49
mNSE [-INF - 1]		−0.12	−0.22	−0.22	−0.44	−1.12	−0.47	−0.45	−0.04

The models are as follows: GG, Granger–Gray; PMsugarcane.adj, PMgrass adjusted with a water stress coefficient and the crop coefficient for sugarcane; PMsugarcane, PMgrass adjusted with the crop coefficient for sugarcane; PMgrass, Penman–Monteith (short grass); HS, Hargreaves–Samani; HS.adj, HS adjusted with a soil moisture function; PT, Priestley–Taylor; PT.adj, PT adjusted with a soil moisture function. Model results are compared to eddy covariance (EC).

Table 4 Mean daily evapotranspiration for the main season (2012–2013, number of observations 765) with the standard deviation (SD), standard error of the mean (SEM), R^2, mean absolute error (MAE), root mean square error (RMSE), modified Index of Agreement (md) and modified Nash Sutcliffe Efficiency (mNSE)

	EC	GG	PMsugarcane.adj	PMsugarcane	PMgrass	HS	HS.adj	PT	PT.adj
Mean (mm day^{-1})	1.89	2.03	2.05	2.79	2.23	3.11	1.21	2.58	1.27
SD (mm day^{-1})	0.68	0.87	1.36	1.06	0.85	0.67	1.23	1.07	0.93
SEM (mm day^{-1})	0.02	0.03	0.05	0.04	0.03	0.02	0.04	0.04	0.03
R^2 [0-1]		0.40	0.12	0.49	0.49	0.11	0.02	0.43	0.05
MAE (mm day^{-1})		0.54	1.04	0.93	0.51	1.25	1.41	0.81	0.92
RMSE (mm day^{-1})		0.70	1.31	1.18	0.71	1.45	1.63	1.06	1.19
md [0-1]		0.58	0.39	0.44	0.60	0.30	0.23	0.48	0.39
mNSE [-INF - 1]		−0.03	−0.87	−0.67	0.08	−1.25	−1.53	−0.45	−0.65

The models are as follows: GG, Granger–Gray; PMsugarcane.adj, PMgrass adjusted with a water stress coefficient and the crop coefficient for sugarcane; PMsugarcane, PMgrass adjusted with the crop coefficient for sugarcane; PMgrass, Penman–Monteith (short grass) model; HS, Hargreaves–Samani; HS.adj, HS adjusted with a soil moisture function; PT, Priestley–Taylor; PT.adj, PT adjusted with a soil moisture function. Model results are compared to eddy covariance (EC).

high MAE and low mNSE compared with the other models. PMgrass is the only model to have a mNSE value above zero (0.08). The impact of soil moisture across the adjusted models is not the same with the mean F values for the season for HS and PT as 0.25 and 0.42, respectively, whereas the seasonal mean K_s value is 0.74. Comparing the potential ET models to PMgrass again shows the PT results to be closest. The model with the worst fit to ET_{EC} for the main season is the HS model.

During the late season, the means for all the models underestimate ET_{EC}, including the potential ET formulae (Table 5). Only the Penman–Monteith-derived models have mediocre R^2 values, whereas the values for the other models are low. Results of the md test for all the models are in a similar range, although PMgrass shows the best fit at 0.49. All of the results of the mNSE test are below zero, although PMgrass and HS are slightly better than the other models with values of −0.06 and

−0.09, respectively. Of the potential ET models, PMgrass performs better than HS and PT, but HS is closest to the PMgrass results. The means of the models adjusted for soil moisture were further away from the mean ET_{EC} than their unadjusted potential ET base models. Overall for the late season, PMgrass shows the best fit, followed by HS. GG is the worst fit for the season.

During the winter season, as in the late season, all the models' means were less than the ET_{EC} mean (Table 6). PMgrass was closest mean to ET_{EC} and also had the most favourable md result of 0.51. PMsugarcane and PMsugarcane.adj were similar to PMgrass with md values of 0.48. PMgrass was the only model with a mNSE result above zero (0.10). Both the PMsugarcane models mNSE results were zero. Adjustments for moisture were minimal for this season with only HS being adjusted (the winter seasonal mean F value for HS was 0.97 and for PT was 1, and the mean K_s value for adjusting

Table 5 Mean daily evapotranspiration for the late season (2012–2013, number of observations 305) with the standard deviation (SD), standard error of the mean (SEM), R^2, mean absolute error (MAE), root mean square error (RMSE), modified Index of Agreement (md) and modified Nash Sutcliffe Efficiency (mNSE)

	EC	GG	PMsugarcane.adj	PMsugarcane	PMgrass	HS	HS.adj	PT	PT.adj
Mean (mm day^{-1})	1.21	0.36	0.52	0.58	0.77	0.95	0.65	0.48	0.38
SD (mm day^{-1})	0.59	0.22	0.27	0.27	0.36	0.37	0.42	0.33	0.30
SEM (mm day^{-1})	0.03	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
R^2 [0-1]		0.02	0.41	0.37	0.37	0.03	0.12	0.06	0.12
MAE (mm day^{-1})		0.85	0.69	0.64	0.48	0.49	0.63	0.74	0.83
RMSE (mm day^{-1})		1.04	0.83	0.79	0.64	0.69	0.82	0.94	1.00
md [0-1]		0.34	0.39	0.42	0.49	0.41	0.41	0.37	0.35
mNSE [-INF - 1]		−0.88	−0.53	−0.40	−0.06	−0.09	−0.39	−0.63	−0.83

The models are as follows: GG, Granger–Gray; PMsugarcane.adj, PMgrass adjusted with a water stress coefficient and the crop coefficient for sugarcane; PMsugarcane, PMgrass adjusted with the crop coefficient for sugarcane; PMgrass, Penman–Monteith (short grass) model; HS, Hargreaves–Samani; HS.adj, HS adjusted with a soil moisture function; PT, Priestley–Taylor; PT.adj, PT adjusted with a soil moisture function. Model results are compared to eddy covariance (EC).

Table 6 Mean daily evapotranspiration for the winter season (2012–2013, number of observations 449) with the standard deviation (SD), standard error of the mean (SEM), R^2, mean absolute error (MAE), root mean square error (RMSE), modified Index of Agreement (md) and modified Nash Sutcliffe Efficiency (mNSE)

	EC	GG	PMsugarcane.adj	PMsugarcane	PMgrass	HS	HS.adj	PT	PT.adj
Mean (mm day^{-1})	0.74	0.23	0.49	0.49	0.66	0.56	0.54	0.27	0.27
SD (mm day^{-1})	0.39	0.14	0.23	0.23	0.31	0.19	0.19	0.23	0.23
SEM (mm day^{-1})	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
R^2 [0-1]		0.00	0.23	0.23	0.23	0.00	0.00	0.00	0.00
MAE (mm day^{-1})		0.53	0.31	0.31	0.28	0.36	0.36	0.51	0.51
RMSE (mm day^{-1})		0.66	0.43	0.43	0.37	0.48	0.48	0.65	0.65
md [0-1]		0.35	0.48	0.48	0.51	0.34	0.35	0.35	0.35
mNSE [-INF - 1]		−0.71	0.00	0.00	0.10	−0.18	−0.16	−0.64	−0.63

The models are as follows: GG, Granger–Gray; PMsugarcane.adj, PMgrass adjusted with a water stress coefficient and the crop coefficient for sugarcane; PMsugarcane, PMgrass adjusted with the crop coefficient for sugarcane; PMgrass, Penman–Monteith (short grass) model; HS, Hargreaves–Samani; HS.adj, HS adjusted with a soil moisture function; PT, Priestley–Taylor; PT.adj, PT adjusted with a soil moisture function. Model results are compared to eddy covariance (EC).

PMsugarcane was also 1). Overall for the winter season, PMgrass showed the most favourable fit of the models tested, followed by PMsugarcane. The worst fit for the season was GG.

Miscanthus K_c value

In the early and main growing seasons, there is a difference in the *Miscanthus* K_c values (calculated from the eddy covariance data and the PMgrass results) when data are used from the whole 5 year period compared to just 2013 to 2016, but values are almost the same for the late and winter seasons (Table 7). The early season in 2012 represents an atypical period being the time of land conversion to *Miscanthus* with a dominance of bare soil during the crop's initial establishment. Figure 5 shows ET$_{EC}$ results in comparison with PMgrass adjusted with the calculated K_c values (PMK$_c$).

Canopy interception

Fifty-one recording events took place over the sampling period June 2016 to March 2017. Data were only removed from one of these occasions due to the high winds in November 2016 causing damage to the gauges. Measured C_i was 24% for the period. The total gross precipitation (outside of the crop) was 776 mm, and the net precipitation (a combination of stem-flow and through-fall) was 588 mm. The net precipitation was made up of 133 mm stem-flow and 455 mm through-fall. Gross precipitation was related to net precipitation with an R^2 value of 0.9 (Fig. 6a).

Interception is highest from July to September when the canopy is mature (Fig. 6b). The highest level of interception for a measuring occasion was 52% recorded during the period 15th – 18th July, and the highest mean monthly level of interception was 34% recorded

Table 7 K_c calculated using the Penman–Monteith (short grass) model and eddy covariance results for the seasons in the periods 2012 to 2016 and 2013 to 2016

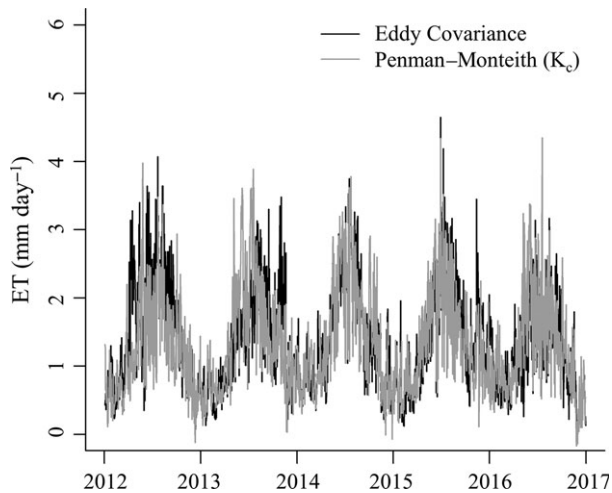| | K_c values | |
Season	2012–2016	2013–2016
Early	0.72	0.63
Main	0.85	0.81
Late	1.57	1.58
Winter	1.12	1.13

Fig. 5 Results of eddy covariance calculated evapotranspiration (ET) and the Penman–Monteith (short grass) model adjusted with *Miscanthus* calculated K_c values of 0.63 for the early season (March and April), 0.85 for the main season (May to September), 1.57 for the late season (October and November), and 1.12 over the winter (December to February).

for the month of August. Whilst the interception levels drop over the autumn and winter as leaves are dropped in senescence, the remaining canes continue to intercept rainfall until the harvest at the end of March. There are four instances where there was a higher net than gross precipitation (Fig. 6b). Examination of the data suggests these are related to occasions when wind direction may have caused gauges to record higher levels in the within-crop sampling due to the canopy intercepting rain being blown horizontally by the wind.

Discussion

ET models

The mean ET_{EC} of 483 mm yr^{-1} was over half of the mean annual rainfall demonstrating the importance of obtaining accurate estimates of ET in hydrological modelling. The maximum measured ET_{EC} value of 4.65 mm day^{-1} was considerably lower than the highs

of 7 and 11 mm day^{-1} found in the USA by Hickman *et al.* (2010) and in Italy by Triana *et al.* (2015). This is as expected for the very different climatic conditions of the studies. However, it was similar to the ET_{EC} of around 5 mm day^{-1} obtained in Hereford, UK, and within the range of the MOSES model predictions both shown in the study carried out by Finch *et al.* (2004).

The eddy covariance technique is a recognized method for obtaining field estimates of ET and is regarded as having a good level of accuracy – provided careful data processing and gap-filling strategies are employed (Aubinet *et al.*, 2012; Gebler *et al.*, 2015; Wagle *et al.*, 2016). The use of daily ET results has provided a detailed insight into the performance of the models within each season. Although none of the ET models provide a good fit compared to ET_{EC}, the highest modified Index of Agreement (md) results for each season were generally in the medium range (early 0.49, main 0.60, late 0.49 and winter 0.51).

A combination of factors in this study has allowed for reasonable comparisons of reference and potential ET models to ET_{EC} in this study. Whilst reference and potential ET models calculate ET on the basis of no crop water shortage, this was the case at the field site for the majority of the study period, with only a short time when the soil moisture status was below wilting point. Adjustments to the HS and PT base models to account for soil moisture stress generally resulted in ET rates less than ET_{EC} (Fig. 4). This *Miscanthus* genotype has also been shown to have a slower initial response to drought, with limited stomatal control (Clifton-Brown *et al.*, 2002; Joo *et al.*, 2017) and the ability to exploit the maximum soil depth and hence available water (Neukirchen *et al.*, 1999) enabling the maintenance of high ET rates compared to other crops. However, prolonged water stress is likely to reduce *Miscanthus* ET rates (Joo *et al.*, 2017).

PMgrass performed the best in all the seasons with the exception of the early season. This model had the highest md result for the main, late, and winter seasons and was the only model to achieve a mNSE score of above zero (main 0.08 and winter 0.10). *Miscanthus* emerges later than the start of the grass pasture growing season and can continue transpiring to the end of October (in favourable years). These are likely to be factors in differing early and late season ET rates of *Miscanthus* compared with grass.

GG was the second best model for both the early and main seasons (early: MAE 0.43, md 0.48, mNSE −0.12; main: MAE 0.54, md 0.58, mNSE −0.03), but it was the worst performing model for the late and winter seasons (late: MAE 0.85, md 0.34, mNSE −0.88; winter: MAE 0.53, md 0.35, mNSE −0.71). For the early season, GG
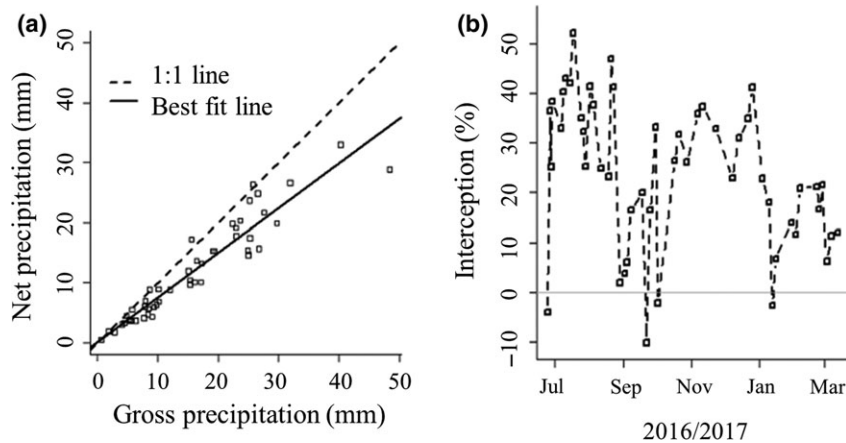
Fig. 6 Extent of canopy precipitation interception from June 2016 to March 2017 (a) Net precipitation recorded within the *Miscanthus* crop (a combination of stem-flow and through-flow) regressed against gross precipitation received outside of the crop; (b) percentage of interception loss on each measuring occasion.

closely followed the best-performing model which was PT.adj (MAE, 0.40, md 0.49, mNSE −0.04).

Both GG and PMgrass require wind speed data as an input, whereas this is not required by PT and HS. PT and HS models can also be used within the SWAT hydrology model to calculate ET in the absence of wind speed data (Arnold *et al.*, 2012) making them suitable for sites with more limited instrumentation. Comparing PT and HS to ET_{EC} has shown that PT performs better than HS over the early (PT, md 0.41; HS, md 0.29) and main growing seasons (PT, md 0.48; HS, md 0.30) but that over the late (PT, md 0.37; HS, md 0.41) and winter (PT, MAE 0.51, md 0.35, mNSE −0.64; HS, MAE 0.36, md 0.34, mNSE 0.36) seasons HS out performs PT. HS is more commonly used for warmer climates (Tabari, 2010) so was least suited to the UK climate type.

Winter ET_{EC} values were higher than all of the model predictions – an important point to consider when modelling the impacts on water balance and potential flood mitigation benefits. Winter precipitation interception by stalks and dead leaves in the field is not taken into account in PMgrass. Interception is an important factor in ET rates where differences of 30% between ET calculated with and without adjustment for the impact of C_i have been observed (Robinson *et al.*, 2017). The field site's coastal proximity and localized weather systems could also be impacting on lower model results compared with ET_{EC}. ET_a may be higher at times on site due to advection of sensible heat energy either from the sea or the presence of nearby hilly terrain causing localized wetter and drier air systems creating greater mixing in boundary layers (Van Dijk *et al.*, 2015).

Whilst the use of the more complex Penman–Monteith formulae (Monteith, 1965) may provide better results, the detailed data input requirements are not always available, and the simplified short grass equation (PMgrass) in conjunction with crop-specific K_c values has been used (Stephens *et al.*, 2001b; Borek *et al.*, 2010; Triana *et al.*, 2015). The use of K_c values for sugarcane did not perform as well as using the PMgrass base model (Fig. 4). Based on the data in this study, the following *Miscanthus*-specific K_c values are suggested: early season 0.63; main season 0.85; late season 1.57; and 1.12 over winter. The main growing season K_c value is the same as the 0.85 proposed by Beale *et al.* (1999) and within the wide range of 0.31 to 1.93 found by Triana *et al.* (2015). However, it is lower than the 1.20 suggested by Stephens *et al.* (2001b) and the 1.15 for maize and 1.25 for sugarcane given by Allen *et al.* (1998). Clearly, these measurements will to a degree be site specific and would benefit from testing at a wider number of sites; however, they do represent an improvement in our knowledge especially for the nongrowing season (Hay & Irmak, 2009).

Canopy precipitation interception

This study has shown that the *Miscanthus* crop is having a greater impact than short grass pasture on precipitation reaching the ground surface from the months of June (with the growth of leaves) through to the spring harvest date. High interception over July to September reflects the time when the canopy is at its fullest. However, it remains high into the autumn when the crop continues to intercept moisture after senescence due to stem density and some dead leaves remaining attached to stems until the end of January.

The measured interception of 24% from June to March is similar in value to the annual interception estimated for a mixed deciduous forest of 25% (Herbst

et al., 2008), 21% for short rotation coppice (SRC) poplar (Hall & Allen, 1982), and the model prediction for SRC willow of 20% (Stephens *et al.*, 2001a), suggesting benefits for flood alleviation by reducing soil moisture recharge (Marshall *et al.*, 2009). However, in contrast to forestry, the *Miscanthus* crop has a period after harvest each year when there is no, or very little, interception with only short stubble left in the field before spring regrowth. Nonetheless, interception by the *Miscanthus* canopy will play a role in reducing soil moisture, particularly in the late autumn and early winter when higher rainfalls can occur.

Data collected in this study compare well to the measured results in plots of *Miscanthus* found by Riche & Christian (2001) of 25% in 1997/1998, and 24% in 1998/1999. There was a longer period of interception in this study due to the late harvest date in March as opposed to the more typical harvest time of early February. When the interception is calculated over a shorter timescale of June to January, as in the study by Riche & Christian (2001), the result is slightly higher at 26%. The use of the Gash interception model by Finch & Riche (2010) suggested that interception might be reduced by as much as 6% in larger scale plantations, but the results of this study do not support this suggestion. This may be due to an estimated value for field scale wet canopy evaporation used in the Gash model and obtained from the full Penman–Monteith equation (Monteith, 1965). This component has a large influence in the result (Gash *et al.*, 1995, 1999), and therefore, the accuracy of the estimated evaporation rate will impact on the predicted interception. Higher measured interception than obtained via the Penman–Monteith equation has been noted before (Van Dijk *et al.*, 2015) and shows the importance of this field estimate for accurate hydrological modelling. Another possible reason for this higher interception (and therefore wet leaf evaporation) than modelled is the lower albedo of 0.21 (Miller *et al.*, 2016) for *Miscanthus* during October and November compared with 0.23 for grass (Allen *et al.*, 1998). This means the crop is reflecting less solar energy and retaining more heat energy.

This study shows the potential benefits for flood mitigation of *Miscanthus* compared to a short grass pasture with similar levels of interception to forestry and SRC, which are coupled with the crop's high water use and conversion efficiency and higher winter ET rates. The most accurate of the formulae considered to predict ET rates was the simplified Penman–Monteith (short grass) equation. The *Miscanthus*-specific K_c values suggested would benefit from being tested against other commercial-scale plantations where ET_{EC} or other field measurements of ET are available. However, information from this study can be used to increase accuracy of yield models and in determining suitable areas for planting.

References

Allen RG, Pereira LS, Raes D, Smith M, Ab W (1998) *Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements - FAO Irrigation and Drainage Paper 56.* FAO - Food and Agriculture Organization of the United Nations, Rome.

Arnold JG, Kiniry JR, Srinivasan R, Williams JR, Haney EB, Neitsch SL (2012) Input/Output documentation. *Soil and Water Assessment Tool*, Texas Water Resources Institute. Available at: http://swat.tamu.edu/documentation/2012-io/

Aubinet M, Vesala T, Papale D (eds) (2012) *Eddy Covariance A Practical Guide to Measurement and Data Analysis.* Springer, Dordrecht, Heidelberg, London, New York.

Beale CV, Morison JI, Long SP (1999) Water use efficiency of C4 perennial grasses in a temperate climate. *Agricultural and Forest Meteorology*, **96**, 103–115.

Borek R, Faber A, Kozyra J (2010) Water implications of selected energy crops cultivated on a field scale. *Journal of Food, Agriculture & Environment*, **8**, 1345–1351.

Bouchet RJ (1963) Evapotranspiration reelle et potentielle, signification climatique. *International Association of Hydrological Sciences Publication*, **62**, 134–142.

Brosse N, Dufour A, Meng X, Sun Q, Ragauskas A (2012) *Miscanthus*: a fast-growing crop for biofuels and chemicals production. *Biofuels, Bioproducts and Biorefining*, **6**, 580–598.

Cadoux S, Riche AB, Yates NE, Machet J (2012) Nutrient requirements of *Miscanthus* x *giganteus*: conclusions from a review of published studies. *Biomass and Bioenergy*, **38**, 14–22.

Christen B, Dalgaard T (2013) Buffers for biomass production in temperate European agriculture: a review and synthesis on function, ecosystem services and implementation. *Biomass and Bioenergy*, **55**, 53–67.

Cibin RAJ, Trybula E, Chaubey I, Brouder SM (2015) Watershed-scale impacts of bioenergy crops on hydrology and water quality using improved SWAT model. *GCB Bioenergy*, **8**, 837–848. https://doi.org/10.1111/gcbb.12307

Clifton-Brown JC, Lewandowski I, Bangerth F, Jones MB (2002) Comparative responses to water stress in stay-green, rapid and slow senescing genotypes of the biomass crop, *Miscanthus*. *New Phytologist*, **154**, 335–345.

Dingman SL (2002) *Physical Hydrology* (2nd edn). Prentice-Hall, Inc., Upper Saddle River, NJ.

Dondini M, Richards M, Pogson M *et al.* (2016) Evaluation of the ECOSSE model for simulating soil organic carbon under *Miscanthus* and short rotation coppice-willow crops in Britain. *GCB Bioenergy*, **8**, 790–804.

Dunkerley D (2000) Measuring interception loss and canopy storage in dryland vegetation: a brief review and evaluation of available research strategies. *Hydrological Processes*, **14**, 669–678.

Energy Technologies Institute (2015) *Bioenergy delivering greenhouse gas emission savings through UK bioenergy value chains.*

Environment Agency (EA) (2015) *Energy Crops and Floodplain Flows.* Environment Agency, Bristol.

Finch JW, Riche AB (2010) Interception losses from *Miscanthus* at a site in south-east England-an application of the Gash model. *Hydrological Processes*, **24**, 2594–2600.

Finch JW, Hall RL, Rosier PTW *et al.* (2004) The hydrological impacts of energy crop production in the UK. DTI/NERC.

Gash JHC, Lloyd CR, Lachaud G (1995) Estimating sparse forest rainfall interception with an analytical model. *Journal of Hydrology*, **170**, 79–86.

Gash JHC, Valente F, David JS (1999) Estimates and measurements of evaporation from wet, sparse pine forest in Portugal. *Agricultural and Forest Meteorology*, **94**, 149–158.

Gebler S, Hendricks Franssen HJ, Putz T, Post H, Schmidt M, Vereecken H (2015) Actual evapotranspiration and precipitation measured by lysimeters: a comparison with eddy covariance and tipping bucket. *Hydrology and Earth System Sciences*, **19**, 2145–2161.

Granger RJ, Gray DM (1989) Evaporation from natural nonsaturated surfaces. *Journal of Hydrology*, **111**, 21–29.

Greef JM, Deuter M (1993) Syntaxonomy of *Miscanthus* × giganteus GREEF et DEU. *Angewandte Botanik*, **67**, 87–90.

Guo D, Westra S (2016) *Evapotranspiration: modelling actual, potential and reference crop evapotranspiration*. R package. https://cran.r-project.org/package=Evapotranspiration

Hall RL, Allen SJ (1982) Water use of poplar clones grown as short-rotation coppice at two sites in the United Kingdom. *Aspects of Applied Biology*, **49**, 163–172.

Hargreaves GL, Samani ZA (1985) Evapotranspiration from temperature. *Applied Engineering in Agriculture*, **1**, 96–99.

Hastings A, Clifton-Brown J, Wattenbach M, Stampfl P, Mitchell CP, Smith P (2008) Potential of *Miscanthus* grasses to provide energy and hence reduce greenhouse gas emissions. *Agronomy for Sustainable Development*, **28**, 465–472.

Hastings A, Clifton-Brown J, Wattenbach M, Mitchell CP, Smith P (2009) The development of MISCANFOR, a new *Miscanthus* crop growth model : towards more robust yield predictions under different climatic and soil conditions. *GCB Bioenergy*, **1**, 154–170.

Hay CH, Irmak S (2009) Actual and reference evaporative losses and surface coefficients of a maize field during nongrowing (dormant) periods. *Journal of Irrigation and Drainage Engineering*, **135**, 313–322.

Herbst M, Rosier PTW, McNeil DD, Harding RJ, Gowing DJ (2008) Seasonal variability of interception evaporation from the canopy of a mixed deciduous forest. *Agricultural and Forest Meteorology*, **148**, 1655–1667.

Hickman GC, Vanloocke A, Dohleman FG, Bernacchi CJ (2010) A comparison of canopy evapotranspiration for maize and two perennial grasses identified as potential bioenergy crops. *GCB Bioenergy*, **2**, 157–168.

IPCC (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Pachauri RK, Reisinger A), 104 pp. IPCC, Geneva, Switzerland. Available at: https://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_full_report.pdf

IPCC (2014) Summary for policymakers. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Work- ing Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Zwickel T, Minx JC, Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, von Stechow C). Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/cbo9781107415324

Joo E, Zeri M, Hussain MZ, Delucia EH, Bernacchi CJ (2017) Enhanced evapotranspiration was observed during extreme drought from *Miscanthus*, opposite of other crops. *GCB Bioenergy*, **9**, 1306–1319. https://doi.org/10.1111/gcbb.12448

Legates DR, McCabe GJ Jr (2005) Evaluating the use of "goodness of fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research*, **35**, 233–241.

Lewandowski I, Clifton-Brown JC, Scurlock JMO, Huisman W (2000) *Miscanthus*: European experience with a novel energy crop. *Biomass and Bioenergy*, **19**, 209–227.

Liu W, Mi J, Song Z, Yan J, Li J, Sang T (2014) Long-term water balance and sustainable production of *Miscanthus* energy crops in the Loess Plateau of China. *Biomass and Bioenergy*, **62**, 47–57.

Lovett AA, Sunnenberg GM, Richter GM, Dailey AG, Riche AB, Karp A (2009) Land use implications of increased biomass production identified by gis-based suitability and yield mapping for *Miscanthus* in England. *Bioenergy Research*, **2**, 17–28.

Marshall MR, Francis OJ, Frogbrook ZL *et al.* (2009) The impact of upland land management on flooding: results from an improved pasture hillslope. *Hydrological Processes*, **23**, 464–475.

McCalmont JP, Hastings A, McNamara NP, Richter GM, Robson P, Donnison IS, Clifton-Brown J (2017a) Environmental costs and benefits of growing *Miscanthus* for bioenergy in the UK. *GCB Bioenergy*, **9**, 489–507.

McCalmont JP, McNamara NP, Donnison IS, Farrar K, Clifton-Brown JC (2017b) An interyear comparison of CO2 flux and carbon budget at a commercial-scale land-use transition from semi-improved grassland to *Miscanthus* x *giganteus*. *GCB Bioenergy*, **9**, 229–245.

McMahon TA, Peel MC, Lowe L, Srikanthan R, McVicar TR (2013) Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis. *Hydrology and Earth System Sciences*, **17**, 1331–1363.

Met Office (2016a) Climate summaries. Available at: http://www.metoffice.gov.uk/climate/uk/summaries (accessed 24 August 2017).

Met Office (2016b) Past weather events. Available at: http://www.metoffice.gov.uk/climate/uk/interesting (24 August 2017).

Miller JN, VanLoocke A, Gomez-Casanovas N, Bernacchi CJ (2016) Candidate perennial bioenergy grasses have a higher albedo than annual row crops. *GCB Bioenergy*, **8**, 818–825.

Milner S, Holland RA, Lovett A *et al.* (2016) Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB. *GCB Bioenergy*, **8**, 317–333.

Mintz Y, Walker GK (1993) Global fields of soil-moisture and land-surface evapotranspiration derived from observed precipitation and surface air-temperature. *Journal of Applied Meteorology*, **32**, 1305–1334. https://doi.org/10.1175/1520-0450(1993)032<1305:gfosma>2.0.co;2

Monteith JL (1965) Evaporation and environment. *Symposium of the Society for Experimental Biology*, **19**, 205–224.

Monteith JL, Unsworth MH (2008) *Principles of Environmental Physics* (3rd edn). Academic Press, London.

Morton FI (1965) Potential evaporation and river basin evaporation. *ASCE Journal of Hydraulic Engineering*, **102**, 275–291.

Neukirchen D, Himken M, Lammel J, Czypionka-Krause U, Olfs H-W (1999) Spatial and temporal distribution of the root system and root nutrient content of an established *Miscanthus* crop. *European Journal of Agronomy*, **11**, 301–309.

Priestley CHB, Taylor RJ (1972) On the assessment of surface heat flux and evaporation using large scale parameters. *Monthly Weather Review*, **100**, 81–92.

R Core Team (2015) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.

Raghunath HM (2006) *Hydrology* (2nd edn). New Age International (P) Ltd, New Delhi.

Riche AB, Christian DG (2001) Rainfall interception by mature *Miscanthus* grass in SE England. *Aspects of Applied Biology*, **65**, 143–146.

Richter GM, Riche AB, Dailey AG, Gezan SA, Powlson DS (2008) Is UK biofuel supply from *Miscanthus* water-limited? *Soil Use and Management*, **24**, 235–245.

Robinson EL, Blyth EM, Clark DB, Finch J, Rudd AC (2017) Trends in atmospheric evaporative demand in Great Britain using high-resolution meteorological data. *Hydrology and Earth System Sciences*, **21**, 1189–1224. https://doi.org/10.5194/hess-21-1189-2017

Saxton KE, Rawls WJ (2006) Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Science Society of America Journal*, **70**, 1569.

Stephens W, Hess T, Knox J (2001a) *Review of the effects of energy crops on hydrology*. Available at: https://dspace.lib.cranfield.ac.uk/handle/1826/3368

Stephens W, Hess TM, Knox JW (2001b) The effect of energy crops on hydrology. *Aspects of Applied Biology*, **65**, 101–108.

SWAT (n.d.) Soil & water assessment tool. Available at: http://swat.tamu.edu/ (14 December 2017).

Tabari H (2010) Evaluation of reference crop evapotranspiration equations in various climates. *Water Resources Management*, **24**, 2311–2337.

Triana F, Nassi o Di Nasso N, Ragaglini G, Roncucci N, Bonari E (2015) Evapotranspiration, crop coefficient and water use efficiency of giant reed (*Arundo donax* L.) and miscanthus (*Miscanthus* × *giganteus* Greef et Deu.) in a Mediterranean environment. *GCB Bioenergy*, **7**, 811–819.

Van Dijk AIJM, Gash JH, Van Gorsel E *et al.* (2015) Rainfall interception and the coupled surface water and energy balance. *Agricultural and Forest Meteorology*, **214–215**, 402–415.

Van Weyenberg S, Ulens T, De Reu K, Zwertvaegher I, Demeyer P, Pluym L (2015) Feasibility of *Miscanthus* as alternative bedding for dairy cows. *Veterinarni Medicina*, **60**, 121–132.

Vanloocke A, Bernacchi CJ, Twine TE (2010) The impacts of *Miscanthus* x *giganteus* production on the Midwest US hydrologic cycle. *Global Change Biology Bioenergy*, **2**, 180–191.

Wagle P, Kakani VG, Huhnke RL (2016) Evapotranspiration and ecosystem water use efficiency of switchgrass and high biomass sorghum. *Agronomy Journal*, **108**, 1007–1019.

Wynne-Jones S (2016) Flooding and media storms – controversies over farming and upland land-use in the UK. *Land Use Policy*, **58**, 533–536.

Xu CY, Chen D (2005) Comparison of seven models for estimation of evapotranspiration and groundwater recharge using lysimeter measurement data in Germany. *Hydrological Processes*, **19**, 3717–3734.

Zambrano-Bigiarini M (2017) hydroGOF: Goodness-of-fit functions for comparison of simulated and observed hydrological time series.