Predicting Bioretention Evapotranspiration from Meteorological, Mass-loss, and Moisture-loss data

Prédire l'évapotranspiration de la biorétention à partir des données météorologiques, de perte de masse et de perte d'humidité

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RÉSUMÉ

L'évapotranspiration (ET) est un mécanisme clé pour réduire les volumes d'eaux pluviales via des systèmes de drainage durables végétalisés (SuDS). Il existe de nombreuses méthodes pour prédire l'ET, dont beaucoup proviennent des disciplines de l'irrigation agricole. Pour donner confiance dans la transférabilité de ces méthodes aux microclimats urbains et aux SuDS, il est nécessaire de développer des ensembles de données de validation ET robustes. Cette étude a évalué le comportement ET de trois monocultures de plantes de biorétention courantes au Royaume-Uni sur une série de cinq périodes sèches de 14 jours à l'aide de données météorologiques, de perte de masse et de perte d'humidité. La méthode FAO-56 Penman-Monteith de calcul de l'ET potentielle (PET) à partir des données météorologiques a été comparée aux valeurs dérivées de l'ET réelle (AET) à partir des données de masse et de perte d'humidité. Il a été démontré que l'incorporation de coefficients de culture et de fonctions d'extraction de l'humidité du sol augmentait la qualité des prédictions de l'AET à partir du PET. Un coefficient de culture par défaut de 1,0 - équivalent à une culture de référence d'herbe courte - s'est avéré représenter adéquatement le comportement des trois monocultures de cette étude lorsqu'il est combiné avec une simple formulation SMEF.

ABSTRACT

Evapotranspiration (ET) is a key mechanism for reducing stormwater volumes via vegetated Sustainable Drainage Systems (SuDS). There are numerous methods for predicting ET, with many originating from agricultural irrigation disciplines. To provide confidence in the transferability of these methods to urban microclimates and SuDS, there is a need to develop robust ET validation data sets. This study evaluated the ET behaviour of three common UK bioretention plant monocultures over a series of five 14-day dry periods using meteorological, mass-loss, and moisture-loss data. The FAO-56 Penman-Monteith method of calculating Potential ET (PET) from meteorological data was compared with derived values of Actual ET (AET) from the mass and moisture-loss data. The incorporation of crop coefficients and soil moisture extraction functions were shown to increase the quality of AET predictions from PET. A default crop coefficient of 1.0—equivalent to a short grass reference crop—was found to adequately represent the behaviour of the three monocultures of this study when combined with a simple SMEF formulation.

KEYWORDS

Bioretention, Evapotranspiration, Sustainable Drainage Systems, Model Validation

1 INTRODUCTION

Evapotranspiration (ET), a combination of evaporation from exposed surfaces and transpiration from vegetation, is an important physical process of Urban Green Infrastructure (UGI) which reduces stormwater volumes and urban heat island effects. ET can be predicted from meteorological variables using well-established methods, such as FAO-56 Penman-Monteith (Allen et al., 1998). A common limitation of these techniques is the assumption of 'perfect' well-watered conditions for a reference crop (typically a mono-culture of short-cropped grass). In practice, soil water availability heavily influences the actual ET (AET) rates that occur within SuDS (Berretta et al., 2014). Values of AET can be determined from PET through the application of a soil moisture extraction function (SMEF). To account for variability arising from the water use behaviour of specific plant species, these moisture-corrected estimates of AET can be scaled using crop coefficients:

$$AET = K_c \times PET \times f\left(\theta, \theta_{fc}\right) \quad (1)$$

where Kc is the crop coefficient and f(θ,θfc) represents the SMEF as a function of soil moisture content, θ, and soil field capacity, θfc. The aim of this study is to determine the suitability of the above approach for calculating the AET of three common bioretention plant monocultures under UK climatic conditions.

2 METHODS

Twelve Bioretention Columns were constructed with a 160 mm internal diameter and an 1100 mm depth. Each column comprised (from bottom to top): a 180 mm drainage layer, a 120 mm transition layer, a 700 mm layer of growing media, and a 100 mm ponding zone (Figure 1a). The growing media for this study was sourced locally within Sheffield, UK, and comprised 100% recycled waste components (De-Ville et al., 2021). Four vegetation treatments were trialled (in triplicate) across the 12 columns. These were: an un-vegetated control, an amenity grass mix, a tufted hair-grass (*Deschampsia cespitosa* 'Goldtau') and an iris (*Iris sibirica* 'Ruffled Velvet', Figure 1b).

ET observation trials took place within a climate-regulated growth chamber at The University of Sheffield's Arthur Willis Environment Centre (Sheffield, UK). There were three distinct data collection periods: April—May 2021, September—October 2021, and April—May 2022. These are henceforth referred to as Trial A, Trial B and Trial C respectively. Within each trial, there were either one or two 14-day observation periods. Column mass losses and growing media moisture content were continuously evaluated via individual load cells and a vertical array of moisture content probes (in select columns). The moisture content probes were positioned vertically at depths of 100, 300 and 500 mm (Figure 1a).

During each ET trial, columns were first placed on to individual load cells (Figure 1c). The column outlet control valves were closed and the columns were then saturated and left for 24-hours. The outlet control values were then opened for 2-hours. After which time, the outlet control valves were closed and the columns were then left for 14-days without irrigation or maintenance. Column mass, moisture content and meteorological variables used in the determination of FAO-56 Penman-Monteith estimates of potential ET (PET) were monitored at an hourly resolution across these 14-day periods. Vegetation specific SMEF and crop coefficients were identified for each vegetation configuration to relate predicted PET data to observed estimates of ET from the mass and moisture loss data.

Figure 1. a) Column schematic diagram. b) The four vegetation configurations. c) Assembled columns on load cells.

3 RESULTS & DISCUSSION

Figure 2 presents the complete data record for Trial A. Figure 2a presents the meteorological data at an hourly resolution, where diurnal cycles are clearly visible in all variables. Figure 2b presents the cumulative ET derived from the mass loss ($AET_{\Delta M}$) and moisture loss ($AET_{\Delta\theta}$) methods. Each data point represents a mean value from three replicate columns, with the surrounding shaded region indicating the observed range across replicates. Finally, Figure 2c presents the ET data from three specific 48-hour periods during the early (day 3-4), mid (day 8-9), and late (day 13-14) periods of each trial. Daily values of PET are also included.

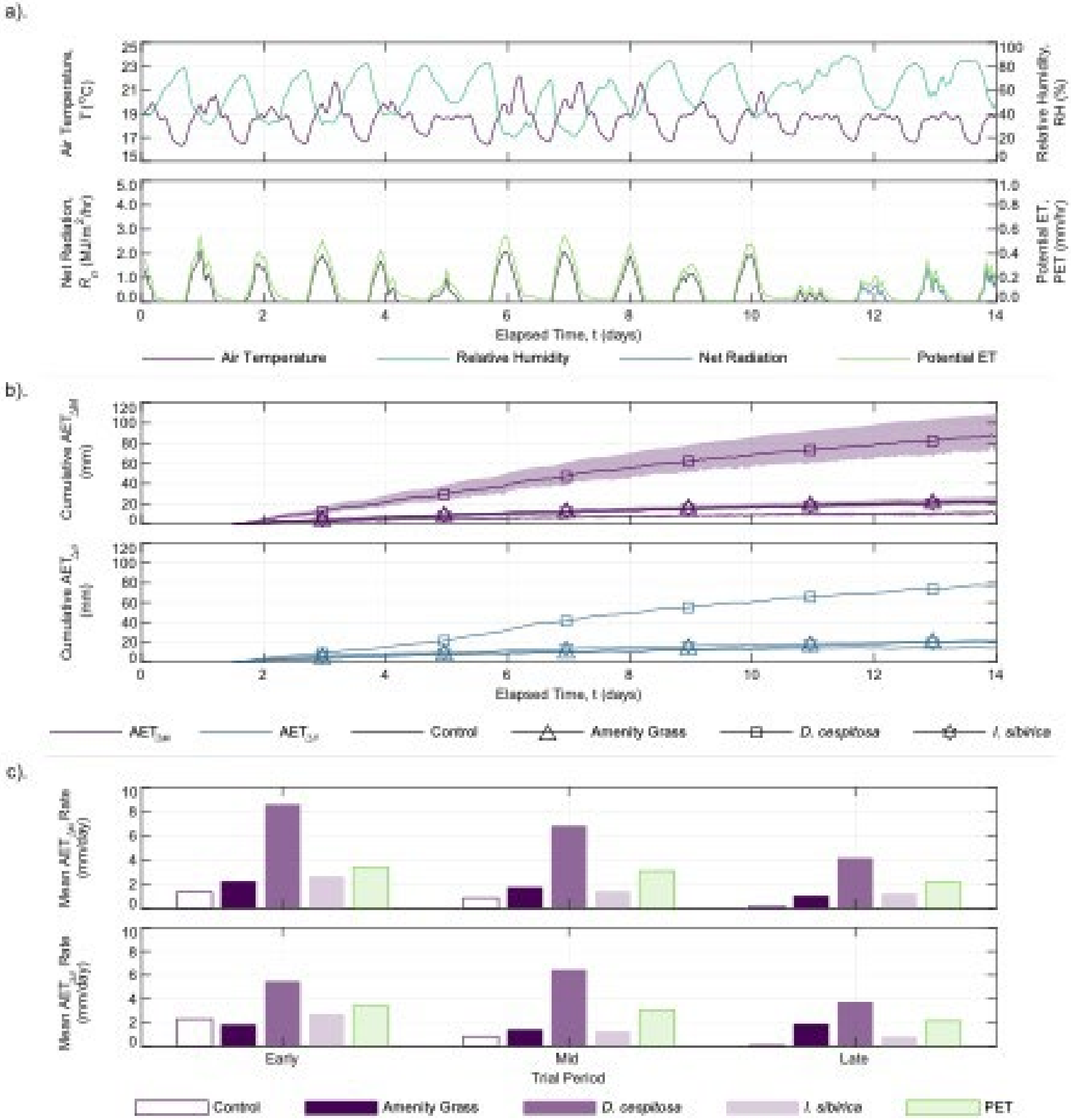

Figure 2. Complete data record for Trial A. a). Collected meteorological data. b). Cumulative ET derived from the mass loss ($AET_{\Delta M}$) and moisture loss ($AET_{\Delta\vartheta}$)) methods, shaded regions represent range of observed values. c). Comparison of mass loss ($AET_{\Delta M}$) and moisture loss ($AET_{\Delta\vartheta}$)) derived ET rates with PET in the early (day 3-4), mid (day 8-9) and late (day 13-14) period of the trial [vertical shaded regions in a). and b).].

The optimised crop coefficients are presented in Figure 3a. A horizontal line at K_c = 1.0 is approximately equal to the mean value of all observed crop coefficients. This value is equal to that of an FAO-56 Penman-Monteith short reference crop, and indicates that AET is equal to PET. There is no observable difference in the optimised crop coefficient by season (spring of Trial A and C, and summer of Trial B) suggesting a single crop coefficient value may be used throughout the growing season. Figure 3b demonstrates how the inclusion of a SMEF within Equation 1 leads to a better fit to observed data compared to the application of a crop coefficient only. The SMEF acts to reduce ET in the latter days of the trial as moisture becomes restricted.

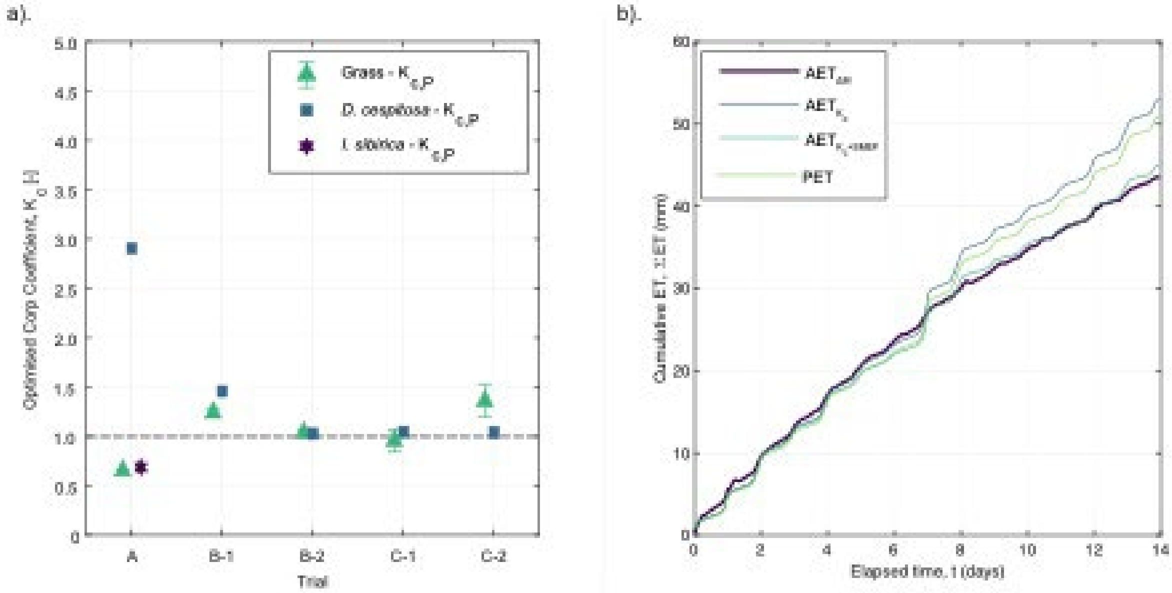

Figure 3. a). Identified Crop Coefficients. *I. sibirica* data is not available beyond Trial A due to sensor failure. Dashed horizontal line at 1.0 is the proposed engineering estimate. b). Example fit of predicted AET using crop coefficient only (AET_{Kc}) and a crop coefficient coupled with a SMEF ($AET_{Kc+SMEF}$) for a *D. cespitosa* column during Trial C-2.

4 CONCLUSIONS

Predicting actual evapotranspiration in SuDS can be challenging given current uncertainties about the transferability of existing agricultural models to urban microclimates. This study produced a robust ET model validation dataset used to evaluate the performance of FAO-56 Penman-Monteith for three common vegetation mixes used within bioretention systems in the UK. FAO-56 Penman-Monteith was found to predict ET well when combined with a crop coefficient and a soil moisture extraction function. This work has highlighted that a fixed crop coefficient of 1.0 may be used in the absence of empirical crop coefficient data.

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