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Rainfall interception modelling: is the wet bulb approach adequate to estimate mean evaporation rate from wet/saturated canopies in all forest types?

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Abstract

The Penman-Monteith equation has been widely used to estimate the maximum evaporation rate (E) from wet/saturated forest canopies, regardless of canopy cover fraction. Forests are then represented as a big leaf and interception loss considered essentially as a one-dimensional process. With increasing forest sparseness the assumptions behind this big leaf approach become questionable. In sparse forests it might be better to model E and interception loss at the tree level assuming that the individual tree crowns behave as wet bulbs ("wet bulb approach"). In this study, and for five different forest types and climate conditions, interception loss measurements were compared to modelled values (Gash's interception model) based on estimates of E by the Penman-Monteith and the wet bulb approaches. Results show that the wet bulb approach is a good, and less data demanding, alternative to estimate E when the forest canopy is fully ventilated (very sparse forests with a narrow canopy depth). When the canopy is not fully ventilated, the wet bulb approach requires a reduction of leaf area index to the upper, more ventilated parts of the canopy, needing data on the vertical leaf area distribution, which is seldom-available. In such cases, the Penman-Monteith approach seems preferable. Our data also show that canopy cover does not *per se* allow us to identify if a forest canopy is fully ventilated or not. New methodologies of sensitivity analyses applied to Gash's model showed that a correct estimate of E is critical for the proper modelling of interception loss.

Keywords: interception loss; surface temperature; Gash model; sparse forest; Penman-Monteith

1. Introduction

A proportion of the rain falling on to a forest canopy is intercepted and evaporates back to the atmosphere (David et al., 2005). Several models of the process have been developed (see the review by Muzylo et al., 2009) and these have contributed to a good understanding of the underlying mechanisms of interception loss. Interception models are also important as a component of hydrological catchment models or continental-scale water balance models (e.g. Wallace et al., 2013), to assess global evaporation (e.g., Miralles et al., 2010; Zhang et al., 2016), and in the land surface schemes of Global Circulation Models (see Carlyle-Moses and Gash, 2011).

The most widely used interception models are those developed by Rutter (Rutter et al., 1972; Rutter et al., 1975) and Gash (Gash, 1979). The former was the first with a physically-based background where interception loss was explicitly driven by the rate of evaporation from the wet canopy. To calculate the dynamic water balance of the forest canopy and trunks, during each rainfall event, the Rutter model requires a continuous evaluation of the maximum evaporation rate under wet conditions. Based on the Rutter model, Gash (1979) proposed a simpler, storm-based analytical model to estimate interception loss, which needs only the average rainfall and evaporation rates ($\bar{R}$, $\bar{E}$) under fully saturated canopy conditions for the entire period of simulation.

In their original formulations, these models assume that forest canopy uniformly covers the entire ground area. Based on this assumption, they were successfully applied to closed canopy forests, but their application to sparse forests proved to be problematic, with interception loss being overestimated (Gash et al., 1995). To overcome this limitation, both the Rutter and Gash models have been reformulated to adapt to sparse forests (Gash et al., 1995; Valente et al., 1997) by treating the open and the covered areas separately. In these revised model versions, the rate of evaporation is partitioned between the open area, where it is considered zero, and the covered area where it is modelled as a closed forest under the same environmental conditions.

Usually, the Penman-Monteith equation is adopted to estimate the maximum evaporation rate from the wet/saturated canopy (Carlyle-Moses and Gash, 2011), setting canopy resistance to zero. With the Penman-Monteith model the tree canopy is considered as a big leaf, and evaporation is treated as a one-dimensional vertical process, with the aerodynamic conductance estimated assuming a vertical logarithmic wind profile between the canopy level and some reference height above it (van Dijk et al., 2015). However, this assumption does not take into account the possible effect of forest sparseness on the enhancement of turbulence and evaporation rate – becoming increasingly questionable as the forest becomes more and more sparse.

Pereira et al. (2009b) suggested that, for very sparse stands, an approach based on the rate of evaporation from the individual, isolated wet (non-overlapping) tree-crowns would be more appropriate. These authors showed that the saturated crowns of isolated trees behave like wet bulbs, allowing the estimation of their evaporation rate through a simple diffusion equation. Knowing the tree density, the whole-stand evaporation could then be derived in this case as the sum of the contribution of the individual trees.

Like the Penman-Monteith model, this "wet bulb approach" is also physically based but, compared to the former, requires less data to estimate the maximum evaporation rate from saturated tree canopies.

By combining this approach with the Gash analytical model, Pereira et al. (2009a) estimated the interception loss from two savanna-type Mediterranean oak woodlands with a good accuracy (normalized mean error less than ±10%).

Being simpler and less data demanding than the Penman-Monteith equation, the wet bulb approach seems an attractive option. However, the need to check whether the assumption that tree crowns behave as fully ventilated wet bulbs remains. We need to answer the question: is the wet bulb approach applicable or adaptable to more-closed forests? For instance, Roberts et al. (1990; 1993) showed that the canopy of a closed Amazonian rainforest was much better ventilated in the upper crown strata (roughly the upper half of the canopy), where wind speed was higher and air temperature relatively uniform compared to the lower canopy layers. Furthermore, the results reported by Gash et al. (1999) show that better estimates of evaporation rate from a fully wet, sparse pine forest based on use of the Penman-Monteith model were obtained when the aerodynamic conductance for vapour flux was set equal to the measured conductance to momentum flux. This may be taken as an additional indication that in saturated canopies the lower boundary of the main source of water vapour flux is located at the same height where momentum is (apparently) absorbed.

Many forest structural characteristics may affect its aerodynamic behaviour, such as the canopy cover fraction, tree density, tree height, canopy depth and forest composition (type and number of species). Our aim is to determine how these structural features may interact, trying to distinguish in which types of forests interception loss can be best modelled using a one (Penman-Monteith) or a three-dimensional (wet bulb) approach.

The present study reanalyses data from several forest types and climate conditions where the measurement and modelling of interception loss has already been done previously: a eucalyptus plantation in central Portugal, two maritime pine stands (one in Portugal and another in Les Landes, France), an agroforestry system in Kenya and an Amazonian terra firme rainforest (see Table 1 for references).

The objectives of the work were: (1) to use the micrometeorological datasets obtained in the course of previous research to derive new estimates of the maximum evaporation rate from fully wet canopies using the wet bulb approach (E_{WB}); (2) to compare interception loss measurements with modelling results using these E_{WB} estimates, attempting to check the adequacy of the wet bulb approach in forests of different sparseness; (3) to quantify the impact of the method used to estimate E (Penman-Monteith or wet bulb) on the performance of Gash's interception model.

2. Methods

2.1. Sites

Two main criteria were used to select the forest sites: (1) they should cover a wide range of forest structure; and (2) availability of the necessary datasets. Four distinct forest types at five different locations were selected: two maritime pine stands with canopy covers of 45% and 64%; a *Eucalyptus globulus* Labill. plantation with a canopy cover of 60%; an Amazonian tropical rainforest with a canopy cover of 92%; and an African agroforestry plantation consisting of a tree stratum of *Grevillea robusta* with a tree crown cover varying from 2 to 54 %. Details of forest stands are given in Table 1. Besides differences in canopy cover, these forests also contrast in climate type and rainfall regime (maritime, Mediterranean, and tropical wet and semi-arid/sub-humid). Total annual rainfall and potential evapotranspiration varies between sites from 600 to 2400 mm and 741 to 1396 mm, respectively, while the ratio between them varies from 0.5 (in the Portuguese and Kenya sites) to 1.8 (in the Amazonian rainforest) (Table 1).

All the listed structural parameters (namely canopy cover, leaf area index, number of species, plant density, tree height and age) are liable to influence the rainfall interception process (Llorens and Domingo, 2007), either directly or indirectly.

As with most rainfall interception modelling studies, the contribution of undergrowth or of lower vegetation strata to interception loss was not considered in the original studies. Likewise, it is not considered in this study.

2.2. Mean evaporation rate

In all sites used in this study, the revised version of Gash's model has previously been applied to predict interception loss, using the Penman-Monteith equation to estimate the average maximum evaporation rate ($\bar{E}_{PM}$) from the wet canopies assuming a one-dimensional representation of the forests (see Table 2). The good modelling results obtained in all cases (good fit between measured and modelled interception loss) suggest that those evaporation rates were adequately estimated.

As an alternative and for comparison purposes, the wet bulb approach suggested by Pereira et al. (2009b) is now used to estimate the average maximum evaporation rate ($\bar{E}_{WB}$). According to Pereira et al. (2009b), evaporation (E, kg m^{-2} s^{-1}) from a fully wet, isolated tree crown can be estimated as:

$$\lambda E = \frac{\rho_a\, c_p}{\gamma} g_{bV} [e_s(T_s) - e_a] \quad (1)$$

and the surface temperature T_s (°C) of a saturated tree crown as:

$$T_s = \frac{1}{\rho_a\, c_p} \frac{\gamma}{\Delta + \gamma} \frac{A}{g_{bV}} + T_w \quad (2)$$

where λ (J kg^{-1}) is the latent heat of vaporization, ρ_a (kg m^{-3}) is air density, c_p (J kg^{-1} °C^{-1}) is air specific heat at constant pressure, γ (Pa °C^{-1}) represents the psychrometric constant, g_{bV}

(m s^{-1}) is the tree bulk aerodynamic conductance for water vapour, $e_s(T_s)$ (Pa) is the saturation vapour pressure at surface temperature T_s, e_a (Pa) represents the actual vapour pressure of the surrounding air, Δ (Pa °C^{-1}) is the slope of the saturation vapour pressure *vs*. temperature curve, A (W m^{-2}) is the available energy per unit tree crown projected area and T_w (°C) is the wet bulb temperature of the air.

Since under typical rainfall conditions available energy tends to zero (e.g., Stewart, 1977; Teklehaimanot and Jarvis, 1991; Pereira et al., 2009b), it becomes apparent from Eq. (2) that the surface temperature of a wet tree crown should approach the wet bulb temperature of the surrounding air. Therefore, Eq. (1) was used to estimate evaporation from wet tree canopies considering $T_s = T_w$, an assumption consistent with the analysis made by van Dijk et al. (2015). The mean evaporation rate from a wet tree crown with a surface temperature identical to the air wet bulb temperature ($\bar{E}_{WB}$), was then estimated, following Gash (1979), as the average evaporation rate for all hours when gross rainfall rate equalled or exceeded 0.4 mm hr^{-1} (two raingauge bucket tips for Gash's original study).

Although both the Penman-Monteith and the wet bulb approaches estimate the maximum evaporation rate at which intercepted rain may evaporate back to the atmosphere, hereafter we will refer to it simply as "evaporation rate".

2.3. Aerodynamic conductance

The use of Eq. (1) only requires the measurement of the air wet and dry bulb temperatures (T_w and T_d, respectively) and knowledge of the bulk tree crown aerodynamic conductance.

In all forest sites used here, both air temperatures (dry and wet bulb) were measured in the original studies by aspirated psychrometers with an accuracy of 0.2ºC.

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Since those studies did not include any component dedicated to the evaluation of the bulk aerodynamic conductance (g_{bV}) for a tree crown, we had to estimate it for all forest sites as a function of mean leaf dimensions, and leaf area index (L*) (Pereira et al., 2009b):

$$g_{bV} = \overline{g_{lV}}\, L^*/c \qquad (3)$$

where $\overline{g_{lV}}$ (m s^{-1}) is the mean leaf boundary layer conductance for water vapour, c (dimensionless) the canopy cover fraction and L^* (dimensionless) the leaf area index expressed on a total ground area basis (according to the original measurements). The correct calculation of g_{bV} is critical for a proper application of the wet bulb approach (Eq. 1), but requires some somewhat subjective assumptions in the estimation of both g_{lV} and L*.

In all cases except for the Amazonian rain forest, $\overline{g_{lV}}$ was derived using the so-called engineering formulae dependent upon average leaf characteristic dimensions and wind speed. For each forest type, the formulae used were derived from those given by Monteith and Unsworth (2008), assuming that eucalyptus and *Grevilea robusta* leaves could be represented as flat plates and pine needles as cylinders.

The characteristic dimension of the leaves (l) was taken as the average leaf dimension (length or diameter) parallel to the direction of air flow (Grace, 1983). For *Eucalyptus globulus* leaves and from measurements made by J. Tomé (personal comm., 1994) l was taken as 18 mm (most leaves are vertical). *G. robusta* has highly divided, bipinnate leaves, which cannot be easily represented by any typical geometric shape. Moreover, their orientation in the tree canopy is also variable. Hence, we assumed a characteristic dimension for these leaves given by the average of the length and width of the main leaflets (l = 28.2 mm). In the case of *Pinus pinaster* needles, l was considered as 1.5 mm, corresponding to the mean value of the range of variation of needle diameters in this species (Castroviejo et al., 1993).

It has been noted that the values usually obtained by engineering formulae differ from the actual (experimentally measured) conductances, depending on the leaf type, i.e., leaves or needles. For broadleaf species, the engineering formulae tend to underestimate g_{lV}, with the ratio between observed and estimated conductance usually varying between 1.25 and 1.5 (Schuepp, 1993) - although values as high as 2.5 have been reported (Monteith and Unsworth, 2008). The opposite happens with needles, which are grouped in clusters that create a "shelter effect" (Monteith and Unsworth, 2008). Mutual sheltering between needles reduces needle conductance so that they tend to be lower than those estimated by the engineering formula. This reduction has been observed to be in the range of 0.33 to 0.50 (Tibbals et al., 1964; Monteith and Unsworth, 2008). As a result of these effects we need either an enhancement factor in conductance in the case of leaves, or a reduction factor in the case of needles. For both cases, we have assumed here values for these factors that represent the midpoints of the above reported intervals of variation, i.e., 1.38 and 0.40 for leaves and needles, respectively. These values can be used whenever no specific information is available.

The formulae derived to estimate $\overline{g_{lV}}$ as well as the enhancement/reduction factors adopted for each forest are presented in Table 3.

The estimates of $\overline{g_{lV}}$ were then combined with the leaf area index (expressed on a tree crown projected area basis, L^*/c) to determine the bulk tree crown aerodynamic conductance according to Eq. (3).

2.4. Evaporation rate and leaf area index

In the modelling of interception loss by the Gash model the Penman-Monteith equation has been widely and successfully used in canopies with variable cover fraction as was the case for all forests considered in the present study. On the other hand, the wet bulb approach was, so far, only tested (successfully) in the modelling of interception loss from a savannah-type forest (Pereira et al., 2009a) and from a traditional olive grove - pasture system (Nóbrega et al., 2015). Therefore and to evaluate the adequacy of the wet bulb approach, the new $\bar{E}_{WB}$ estimates (Eq. 1) were compared to the already tested $\bar{E}_{PM}$ ones and results were analysed considering that:

a) the matching of estimates of E by both methods could be taken as an indication that the tree canopies are fully ventilated and any of the approaches can be used to model interception loss with equally good accuracy;

b) whenever the two estimates failed to match ($\bar{E}_{WB} > \bar{E}_{PM}$), this could be seen as indicative that the whole canopy is not fully ventilated. In those cases we hypothesized that the upper and more ventilated parts of the canopy were the main contributors to interception loss. Accordingly, when $\bar{E}_{WB} > \bar{E}_{PM}$, we reduced the canopy leaf area to that of the top layers to test if $\bar{E}_{WB}$ converged to $\bar{E}_{PM}$ and if it was still possible to model interception loss with a good accuracy through the wet bulb approach.

2.5. Rainfall interception - Gash's analytical model

Although the Gash analytical model was used to estimate interception loss in all of these forests, the versions adopted in each case were not the same and, thus, the meaning of the canopy structure parameters differs from case to case. Table 2 shows the values of those parameters for each forest as derived in the original studies and indicates, as well, the model version used. For further details on the model structure and formulation, Table 2 also includes the references to the papers where the different versions are described.

The model version proposed by Valente et al. (1997) was adopted in this study at the stand level since it has been shown to improve the estimation of total interception loss in sparse forests, while retaining the ability to accurately predict interception loss from closed canopies.

2.6. Sensitivity analysis

Considering that the objective of this paper was to test the impact of a different method of calculating the mean evaporation rate under wet/saturated conditions ($\bar{E}$) on interception loss modelling results, a sensitivity analysis was done on the performance of Gash's model (considering $\bar{E}$ and the other model parameters). Two different approaches were selected: the first consists of a local analysis on the impact of evaporation rate on model output; the second is a global analysis whereby the combined and simultaneous influence of the various model parameters is accounted for. Although local sensitivity analyses of Gash model parameters have been conducted previously (e.g., Limousin et al., 2008), it has never been done simultaneously for multiple datasets. The overall/combined sensitivity analysis technique used here has never been applied before in rainfall interception modelling.

2.6.1. Local approach

The local sensitivity analysis was performed for the $\bar{E}$ parameter. As this type of analysis is data-dependent, only results from a set of studies can give a broad view on the influence of a given parameter on model performance. Therefore, the effect of the variation of $\bar{E}$ when all the other parameters were kept constant at their derived value (Table 2) was assessed for the five forests under study. For the Kenya agroforestry stand, S and c were set to their maximum observed values, 0.93 mm and 0.54, respectively.

2.6.2. Morris screening

The global sensitivity analysis allows the evaluation of the combined and simultaneous effects of the various model parameters. The Morris method (Morris, 1991) is a global sensitivity analysis technique that aims to identify the parameters that have: negligible effects, linear or additive effects, non-linear effects and interaction with each other. The parameter space is divided into p levels, transforming the experimental region (Ω) in a k-dimensional p-level grid, where k is the number of parameters. Within Ω a starting value for the parameter vector $\boldsymbol{X}$ is randomly selected. A succession of (k + 1) sampling points, called a trajectory, is created varying one parameter at time by a quantity δ, multiple of 1/(p – 1). Each sampling point differs from the previous one in only one factor. Once a trajectory is constructed an incremental ratio, called Elementary Effect (EE), can be computed for each parameter. For a given value $\boldsymbol{x} = (x_1, x_2, \ldots, x_\mathrm{k})$ of $\boldsymbol{X}$, the EE of the ith input factor is defined as

$$EE_i(\boldsymbol{x}) = \frac{[y(x_1, \ldots, x_{\mathrm{i}-1}, x_\mathrm{i}+\delta, x_{\mathrm{i}+1}, \ldots, x_\mathrm{k}) - y(\boldsymbol{x})]}{\delta}. \quad (4)$$

The experimental design consists of r trajectories independently generated, with each trajectory having a different starting point randomly selected. Since each succession provides one EE for each parameter, k finite distributions of r elementary effects are created. The mean (μ) and the standard deviation (σ), from the distributions represent the sensitivity measures: μ gives the overall importance of an input parameter, while σ describes non-linear effects and interactions between parameters. Campolongo et al. (2007) enhanced the Morris method by improving the sampling strategy and proposed calculating the mean of the distribution of the absolute values of the elementary effects (μ*). μ* was introduced because the effects of opposite signs of EE could mask the importance of a parameter. For instance, if δ variations of a ith parameter can cause positive as well as negative effects on EE, μ will assume lower values than μ*. Therefore, μ* better expresses the importance of the parameters and is more reliable in ranking them.

Campolongo et al. (2007) also suggested assigning even values to the number of levels p, while making δ equal to p/[2(p-1)]. The number of trajectories, r, has to be large enough so that if two subsequent Morris analyses are performed with the same r, similar values of μ, μ*

and σ must be obtained for each parameter. In other words, the number of trajectories must ensure that the results are general and not sample-specific.

The Morris method was applied, for the first time, to the sparse version of the Gash analytical model with r = 1000 different input trajectories. Each of the seven parameters of the model (c, S, S_t, p_d, e, $\bar{R}$ and $\bar{E}$) varied between minimum and maximum values pre-defined for each site. The ranges taken for parameter variation (Table 4) were based on published literature, trying to reflect the characteristics of the forests studied.

3. Results

3.1. Estimation of average evaporation rates from wet canopies

The estimates of $\bar{E}$ obtained according to the wet bulb approach ($\bar{E}_{WB}$) for the forests under analysis are presented in Table 5, along with the values derived in the original studies through the Penman-Monteith equation ($\bar{E}_{PM}$). In two of the studied forests (the Carrasqueira pine stand and the Kenya agroforestry system), $\bar{E}_{WB}$ was almost identical to $\bar{E}_{PM}$, when considering the contribution of the whole canopy (full L*) to interception loss. In the other cases, $\bar{E}_{WB}$ using the whole canopy L* overestimated $\bar{E}_{PM}$, suggesting that the canopy was not entirely and fully ventilated. Therefore, L* was reduced to the upper canopy layers to test if $\bar{E}_{WB}$ would reach a value that could still allow a reasonably good interception loss modelling (see Section 2.4.). In the end, the estimated $\bar{E}_{WB}$ was closer to $\bar{E}_{PM}$ for all studied forests. Table 5 presents the estimates of $\bar{E}_{WB}$ considering both the full and reduced L* values. Table 5 also presents interception loss results: the originally measured and modelled values and new simulations through the revised version of Gash's analytical model (Valente et al., 1997), based on the $\bar{E}_{WB}$ estimates. For all interception loss estimates, the normalized mean errors are also provided in Table 5.

3.2. Impact of evaporation rate on interception loss modelling

Although Table 5 gives a perception of the impact of the different $\bar{E}$ estimates ($\bar{E}_{PM}$ and $\bar{E}_{WB}$) on interception loss, a deeper insight can be obtained by performing sensitivity analyses on the sparse version of Gash's analytical model. Two approaches were followed: a local one to assess the effect of variations in $\bar{E}$, while keeping all the other parameters constant; and a global approach – Morris screening – to identify the importance and nature of the influence of all model parameters on interception loss estimates. Results of the two sensitivity analyses are presented in Figs. 1 and 2, respectively. According to Fig. 1, the two Portuguese forests, the Espirra eucalyptus plantation and the Carrasqueira pine stand, show the most sensitivity of the sparse version of Gash's analytical model to the mean evaporation rate: a relative change of +50% in $\bar{E}$ results in an increase of nearly 30% in the estimated interception loss. Though to a lesser extent, modelled interception loss in the other three forests is also still quite sensitive to the mean evaporation rate. The global sensitivity analysis by Morris screening (Fig. 2) confirmed the importance of $\bar{E}$, independently of the different values the other model parameters may take: for all datasets except the Kenyan one, $\bar{E}$ has high values of mean (μ*) and standard deviation (σ).

4. Discussion

4.1. Estimation of average evaporation rates from wet canopies

The estimates of $\bar{E}$ obtained according to the wet bulb approach ($\bar{E}_{WB}$), considering the contribution of the whole canopy, and those derived in the original studies using the Penman-Monteith equation ($\bar{E}_{PM}$), matched very well in the Carrasqueira pine stand and the Kenya agroforestry system. These two forests have highly sparse canopies and narrow crown depths which favours air circulation within the canopy, allowing the surface temperature of saturated tree crowns to approach the air wet bulb temperature under rainy conditions. In these cases both methods (Penman-Monteith or wet bulb) can be used - the choice depending on data availability. However, the wet bulb method may be preferable since it is less data demanding and it lacks the questionable underlying assumptions in applying the Penman-Monteith equation in sparse forests (Monteith, 1965; Pereira et al., 2009b).

In all the other forests, $\bar{E}_{WB}$ overestimated the evaporation rate when L* of the entire canopy was considered, limiting the chances of good interception loss modelling if these $\bar{E}_{WB}$ estimates were used directly. The evaporation estimates by the wet bulb approach were then recalculated only accounting for the contribution of the upper and better ventilated parts of the canopy. However, the scope of this analysis was somewhat constrained by the limited information available on the vertical leaf area distribution in these forests.

For the eucalyptus forest, the mean evaporation rate estimates given by the Penman-Monteith model and the wet bulb approach, when L* of the upper third of the canopy is considered, are nearly identical (leaf area index in the eucalyptus stand was 0.83, 1.40 and 0.94, for the upper, middle and lower thirds of the canopy, respectively; J. Tomé, personal comm., 1994). This eucalyptus forest plantation is relatively sparse, but the canopy depth represents about 61% of the mean tree height (Valente, 1999). Therefore, the ventilation of the lower part of the canopy may be attenuated leading to a reduction in evaporation from this canopy region.

These results seem to suggest that the upper third of the canopy constitutes the main effective source of evaporation during rainfall, when tree crowns are saturated.

In Les Landes pine forest, the whole canopy L* (2.3) referred to by Gash et al. (1995) was estimated using remote sensing techniques during a special observation period, from May to July 1986 (André et al., 1990). Here, the leaf area and L* for the top crown layers were estimated based on the leaf area vertical distribution models derived by Porté et al. (2000) for three Les Landes maritime pine stands. Besides other identical characteristics, one of these stands (Bray 95) had a total leaf area index very similar to that of the forest studied by Gash et al. (1995) and, thus, its vertical leaf area distribution was used. When only accounting for the contribution of the higher canopy layers, corresponding to the top fourth or third of crown depth, the mean wet bulb evaporation rate was 0.142 or 0.223 mm hr^{-1}, respectively, which is not much different from the rate originally reported by Gash et al. (1995) (see Table 5). By using $\bar{E}_{WB}$ associated with the top third of crown depth, interception loss could be modelled as efficiently as in the original study, suggesting that the wet bulb approach can also be used in these conditions as long as only upper and well exposed parts of the canopy are considered. In the Amazonian rainforest, Roberts et al. (1993) divided the whole forest canopy in five strata, assigning to each of them the respective $L*$ and an average leaf boundary layer conductance. This allowed the evaporation rate to be modelled considering the contribution of the different strata, especially of the top three layers. According to Roberts et al. (1990; 1993), and in relation to the lower strata, these top layers were characterized by a more homogeneous air temperature profile and higher values of leaf conductance, probably a consequence of higher wind speed and more effective turbulent mixing. The average evaporation rate estimated by the wet bulb approach considering the contribution of these upper three layers of the canopy was 0.178 mm hr^{-1} which is about 15% less than the original Penman-Monteith estimate obtained by Lloyd et al. (1988). The difference between both estimates may be related with the more or less arbitrary choice of the canopy depth and with the use of constant values for leaf aerodynamic conductance irrespective of wind speed. Indeed, in a forest like this, with high species diversity and a complex spatial pattern of leaf area distribution, it is not simple to derive g_{lV} wind-dependent functions using engineering formulae which must then also be combined with $L*$ to estimate a bulk aerodynamic conductance.

412 In three of our sites where it was necessary to reduce L^* to the upper canopy layers (Les
413 Landes, Amazonia and eucalyptus) it is questionable whether the wet bulb approach should be
414 adopted, because it would require seldom-available information on the leaf area vertical
415 distribution. This may be particularly problematic in mixed forests with a complex 3-D
416 structure. In all these cases the application of the Penman-Monteith equation seems more
417 appropriate, as long as its underlying assumptions remain valid (Monteith, 1965).
418 Results also show that the canopy cover fraction (c) is not, *per se*, an adequate sparseness
419 indicator to define when the wet bulb is a good alternative to Penman-Monteith. The Espirra
420 eucalyptus plantation and the Carrasqueira pine stand are an example of this: both have
421 approximately the same c but the wet bulb approach can only be successfully used without
422 further assumptions in the pine site, probably because canopy depth is smaller in the pine
423 forest compared to that of eucalyptus. We believe that in moderately sparse forests their
424 structure (e.g., tree density, tree crown height and radius) also play an important role in
425 determining the depth of the fully ventilated part of the canopy. Les Landes pine forest is
426 another example: it has a canopy cover which is about 20% lower than that of Carrasqueira
427 forest but its tree density is 50% higher. This means that the structure of the stand and the
428 characteristics of individual tree crowns should differ. For instance, Les Landes forest with
429 smaller and younger trees is more likely to have a larger relative canopy depth with leaf area
430 distributed predominantly in its lower half (e.g., Porte et al., 2000). With deeper tree crowns
431 and smaller distances between trees than in the Carrasqueira stand, Les Landes pine forest
432 may behave more like the closed canopy rainforest, with mainly the upper part of the crowns
433 contributing to the evaporation from the saturated canopy. Thus, it is not surprising that, when
434 using the whole canopy L^*, the wet bulb approach overestimates $\bar{E}$ by a value that doubles the
435 original Penman-Monteith estimate in Les Landes pine forest.

The previous discussion evidences that a wider application/validation of the wet bulb approach is limited by the lack of easily obtainable information on foliage profile, canopy structure and forest sparseness. Recent studies suggest that some remote sensing techniques such as LiDAR and InSAR (e.g. Lefsky et al., 2002; Treuhaft et al., 2009; Tang et al., 2015) may be extremely useful to get that information.

Furthermore, in all situations, the use of the wet bulb approach also depends on the possibility of deriving wind functions for tree bulk aerodynamic conductance using engineering formulae. This will certainly be easier when there is only one tree species and leaves have a simple morphology.

4.2. Impact of evaporation rate on interception loss modelling

For a better evaluation of the impact of $\bar{E}$ ($\bar{E}_{PM}$ and $\bar{E}_{WB}$) on interception loss estimates, a sensitivity analysis was performed for the sparse version of Gash's analytical model.

In the context of rainfall interception modelling, sensitivity analysis is typically applied as a local measure of the effect of each parameter on the model output (usually the interception loss) (e.g., Llorens, 1997; Valente et al., 1997; Limousin et al., 2008). Commonly, the relative importance of the uncertainty of a parameter on the output of a model is computed numerically by perturbing each parameter around a base value, while holding all the other parameters constant: the so-called "one-factor-at-a-time" sensitivity analysis (Saltelli and Annoni, 2010). As shown by previous authors (Llorens, 1997; Limousin et al., 2008), the interception loss predicted by Gash's analytical model is positively and linearly related to $\bar{E}$. However, its sensitivity to errors in this parameter depends on the values taken by data inputs and other parameters (Fig. 1). According to the analysis presented in Fig. 1, interception loss estimated by the sparse version of Gash's analytical model was quite sensitive to the mean evaporation rate in all studied forests, particularly in the Portuguese eucalyptus and pine plantations where a +50% change in $\bar{E}$ results in a nearly 30% increase in interception loss.

Although in the present study, the main concern is on the average evaporation rate during saturation conditions, the other parameters of the model are also subject to errors and uncertainties. The previous one-factor-at-a-time sensitivity analysis cannot detect interaction among parameters and does not answer relevant questions like "which of the uncertain input parameters is driving most of the uncertainty in the output of the model?" (Saltelli et al., 2004). What is the importance of $\bar{E}$ in this context?

To address these issues a global sensitivity analysis (Morris screening) was performed to evaluate the effect of a factor while all the others are also varying and interacting. Fig. 2 shows how model output, affected by changes in the parameters, depends on the dataset used to run the model. Except for results obtained with the Kenya dataset, $\bar{E}$ is an important parameter (high values of μ^* and σ). On the other hand, factors that parameterize stemflow (S_t, p_d, and e) have a much smaller effect and, in general, $\bar{R}$ has a moderate influence on the output. In Kenya as in the two pine forests and the eucalyptus plantation, the model is also highly sensitive to the ground cover fraction (c) showing the importance of correctly assessing this parameter in sparse forests. In general, parameters with a high value for μ^* are also associated with a high value for σ, indicating that these parameters have also relevant non-linear/interaction effects, i.e., none of them has a purely linear effect on the modelled output. The exception is the canopy storage capacity (S), that in four of the sites (Les Landes, Espirra, Carrasqueira and Amazonia) has a high overall effect on the output of the model (high μ^*) but a low σ, indicating that the effect of S is almost independent of the values of the other parameters. Overall, Morris screening has shown that $\bar{E}$ has a large influence on the interception loss modelled by the sparse version of the Gash analytical model but its relative importance to the other parameters can depend on the dataset used to run the model.

5. Conclusion

In two of the studied forests (Portuguese pine stand and Kenya agroforestry system), the wet bulb approach provided very good estimates of $\bar{E}$ under canopy saturation using L* of the whole canopy. These results together with the structural features of the forests (low canopy cover and a narrow canopy depth) suggest that in both these cases the whole canopy can be considered as fully ventilated. Under these circumstances either the wet bulb or the Penman-Monteith approach can be used to estimate $\bar{E}$, but the wet bulb approach is simpler and less data demanding. Furthermore and in contrast with the Penman-Monteith approach, it makes no assumptions about horizontal homogeneity, which becomes problematic when forest sparseness increases.

In the other three forests (Les Landes pine stand, eucalyptus plantation and Amazonian rainforest) the wet bulb approach required a reduction of L* to the upper, more ventilated parts of the canopy, needing seldom-available data on the vertical leaf area distribution. In those cases, the Penman-Monteith approach seems preferable.

Therefore, the logical follow up to the present study would be the development of a way to identify whether, or not, the forest tree crowns are exposed to the same air temperature and humidity conditions, i.e., whether the canopy is fully ventilated. The data used here suggest that the aerodynamic canopy conductance and the wind speed vertical profiles may depend on several forest structural parameters, such as canopy cover fraction, canopy depth, tree height, crown radius, tree density and forest composition and heterogeneity. It would be interesting to find simple, easily applicable parameters and/or relationships between the structural and aerodynamic features of forests that might help to identify if the canopy is fully ventilated or not. Additionally, this research could bring some new insights into the processes underlying the evaporation from wet forest canopies.

The sensitivity analysis on Gash's interception model confirmed that it is particularly sensitive to wet canopy evaporation rate and, therefore, choosing the correct estimation method is of critical importance. Developing techniques that might help make that choice is essential if we are to correctly represent interception loss across the range of sparseness encountered in real forests.

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Table 1 Location and main characteristics of the forests and experimental sites considered in this study

Site name	Les Landes	Espirra	Carrasqueira	Amazonia	Kenya
Local	Les Landes, France	Herdade da Espirra, Portugal	Pinhal da Carrasqueira, Portugal	Reserva Florestal Ducke, Manaus, Brazil	Machakos , Kenya
	44° 5'' N, 0° 5' W	38° 38' N, 8° 36' W	38° 50' N, 8° 51' W	2° 57' S, 59° 57' W	1° 33' S, 37° 8' E
Forest type	Maritime pine forest	Eucalyptus plantation	Maritime pine forest	Amazonian rain forest	Agroforestry plantation
Tree species	Maritime pine (*Pinus pinaster* Aiton)	Eucalyptus (*Eucalyptus globulus* Labill.)	Maritime pine (*Pinus pinaster* Aiton)	Many tree species (see Cuartas et al. (2007))	*Grevillea robusta* A. Cunn.
Elevation (m)	146	85	20	----	1560
Study period	Feb/1986 - Jan/1987	Jan/1992 - Jul/1994	Jan/1992 - Jul/1994	Sep/1983 - Aug/1985	Nov/1994 - Jun/1997
Age (year)	37	7 (1993; first rotation)	60 (1993)	----	3
Forest density (trees ha^{-1})	430	1010	312	3000	833
Canopy cover (c, %)	45.0	60.0	64.0	92.0	2.0 - 54.0
LAI (L^*)	2.30	3.20	2.70	6.60 (Roberts et al., 1993)	0.25 - 2.75
Mean tree height (m)	20.3	16.5	23.9	35.0 aprox.	from 0.5 to 9.5
Climate	Maritime	Mediterranean	Mediterranean	Tropical wet	Semi-arid/sub-humid
Mean annual rainfall (mm)	942 (André et al., 1986)	600 aprox.	600 aprox.	2391	782
Total rainfall in the study period (mm)	613	1546	1366	4804	1583
Mean potential annual evaporation (mm)	741 (Habets et al., 1999)	aprox. 1300	aprox. 1300	aprox.1319 (Shuttleworth, 1988)	1450 (Ong et al., 2000)
Original study	(Gash et al., 1995)	(Valente et al., 1997)	(Valente et al., 1997)	(Lloyd et al., 1988; Lloyd and Marques, 1988)	(Jackson, 2000)

Table 2 Parameters of the Gash analytical model derived for each forest in the original studies

		Site				
		Les Landes	Espirra	Carrasqueira	Amazonia	Kenya
Gash's analytical model (version adopted)		Revised (Gash et al., 1995)	Revised (Valente et al., 1997)	Revised (Valente et al., 1997)	Original (Gash, 1979)	Revised (Gash et al., 1995)
Average rainfall rate (mm hr^{-1})	$\bar{R}$	1.650	1.814	1.743	5.150	2.280 (monthly rates in the range 0.5 - 3.2)
Average evaporation rate (mm hr^{-1})	$\bar{E}_{PM}$	0.170	0.200	0.315	0.210	0.230
Canopy storage capacity (mm)	S	0.250	0.210	0.410	0.740	0.710 - 0.930
Trunk storage capacity (mm)	S_t	0.170	0.016	0.017	0.150	0.185
Drainage partitioning coefficient	p_d		0.0324	0.0076		
Stemflow partitioning coefficient	p_t	0.0275			0.0360	0.0260

Table 3 Engineering formulae used to estimate mean leaf boundary layer conductance and values of the empirical "correction" factor adopted for each forest.

Site	Geometric shapes representing leaves	Leaf characteristic dimension (mm)	Leaf boundary layer conductance model (m s^{-1})	Enhancement / reduction factor
Les Landes	cylinder	1.5	$\overline{g_{lV}} = 0.0778u^{0.47}$	0.40
Espirra	flat plate	18.0	$\overline{g_{lV}} = 0.0502u^{0.5}$	1.38
Carrasqueira	cylinder	1.5	$\overline{g_{lV}} = 0.0778u^{0.47}$	0.40
Kenya	flat plate	28.2	$\overline{g_{lV}} = 0.0623u^{0.5}$	1.38

Table 4 Minimum and maximum values for Gash's analytical model parameters used in Morris screening for the different sites.

	Site					
	Les Landes Espirra Carrasqueira	Amazonia	Kenya	Les Landes Espirra Carrasqueira	Amazonia	Kenya
Parameter	Minimum values			Maximum values		
c	0.4	0.9	0.02	0.8	1	0.6
S	0.15	0.7	0.7	0.5	1	1
$\bar{R}$	1.5	4	0.5	2.2	6	3.2
	Minimum values common to all sites			Maximum values common to all sites		
$\bar{E}$	0.15			0.33		
S_t	0.01			0.2		
p_d	0.005			0.04		
e	0.01			0.03		

Table 5 Mean evaporation rates determined in the original studies ($\bar{E}_{PM}$) and using the wet bulb approach ($\bar{E}_{WB}$). For the forests where the estimates are different, interception loss results are also presented (originally measured and modelled interception loss and new simulations based on $\bar{E}_{WB}$ estimates through the revised version of Gash's analytical model (Valente et al., 1997)). For all the estimates of interception loss the respective normalized mean errors are between brackets.

		Site				
		Les Landes	Espirra	Carrasqueira	Amazonia	Kenya
Original studies	$\bar{E}_{PM}$ (mm hr^{-1})	0.170	0.200	0.315	0.210	0.230
	I (mm) observed	73	101	154	428	161
	I (mm) modelled	70 (-0.041)	98 (-0.03)	157 (0.019)	543 (0.269)	128 (-0.205) (a) 154 (-0.043) (b)
Actual study	$\bar{E}_{WB}$ (mm hr^{-1})	0.383	0.774	0.315	0.316	0.232
		L^* value for the whole canopy at each site used for estimating $\bar{E}_{WB}$				
		2.3	3.2	2.7	6.6	variable
	$\bar{E}_{WB}$ (mm hr^{-1})	0.223	0.203	0.315	0.178	0.232
		L^* value for the canopy layer considered at each site for estimating $\bar{E}_{WB}$				
		1.34	0.83	2.7	2.52	variable
	Canopy layer	1/3 top	1/3 top	whole canopy	1/2 top	whole canopy
	I (mm) modelled	76 (0.041) (c)			491 (0.147)	

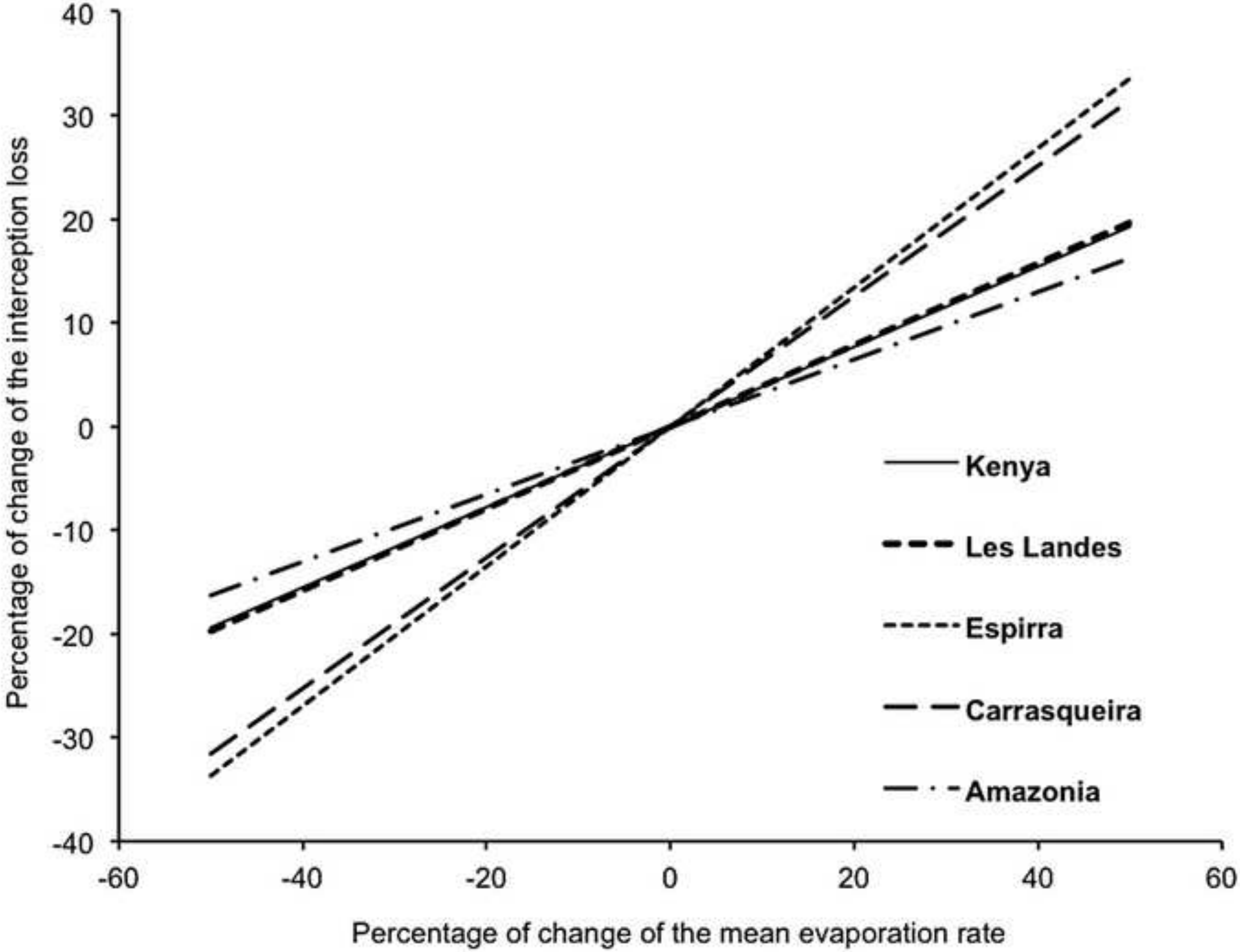
(a) estimate obtained using the global $\bar{R}$ and (b) estimate based on monthly $\bar{R}$ values; (c) simulation for a slightly different (higher) gross rainfall total of 613 mm corresponding to the period 09 February 1986 – 03 January 1987, excluding the period of 13 March – 14 April 1986 when some data loss occurred.

Rainfall interception modelling: is the wet bulb approach adequate to estimate mean evaporation rate from wet/saturated canopies in all forest types?

Figure Captions

Figure 1 Local sensitivity analysis for $\bar{E}$ measured by the influence of the percentage change in this parameter on the percentage change in the interception loss simulated by the sparse version of Gash's analytical model, using the data sets of the five experiments.

Figure 2 Plots of Morris sensitivity measures μ* and σ for the seven parameters of the sparse version of Gash's analytical model: mean rainfall rate ($\bar{R}$), mean evaporation rate ($\bar{E}$), canopy cover (*c*), canopy storage capacity (*S*), trunk storage capacity (S_t), drainage portioning coefficient (p_d) and ratio between the evaporation rates from the saturated trunk and canopy (*e*) Each graph was obtained with a different data set: (a) Les Landes (pine), (b) Espirra (eucalyptus), (c) Carrasqueira (pine), (d) Amazonia (rainforest) and (e) Kenya (agroforestry).



40
30
20
10
0
-10
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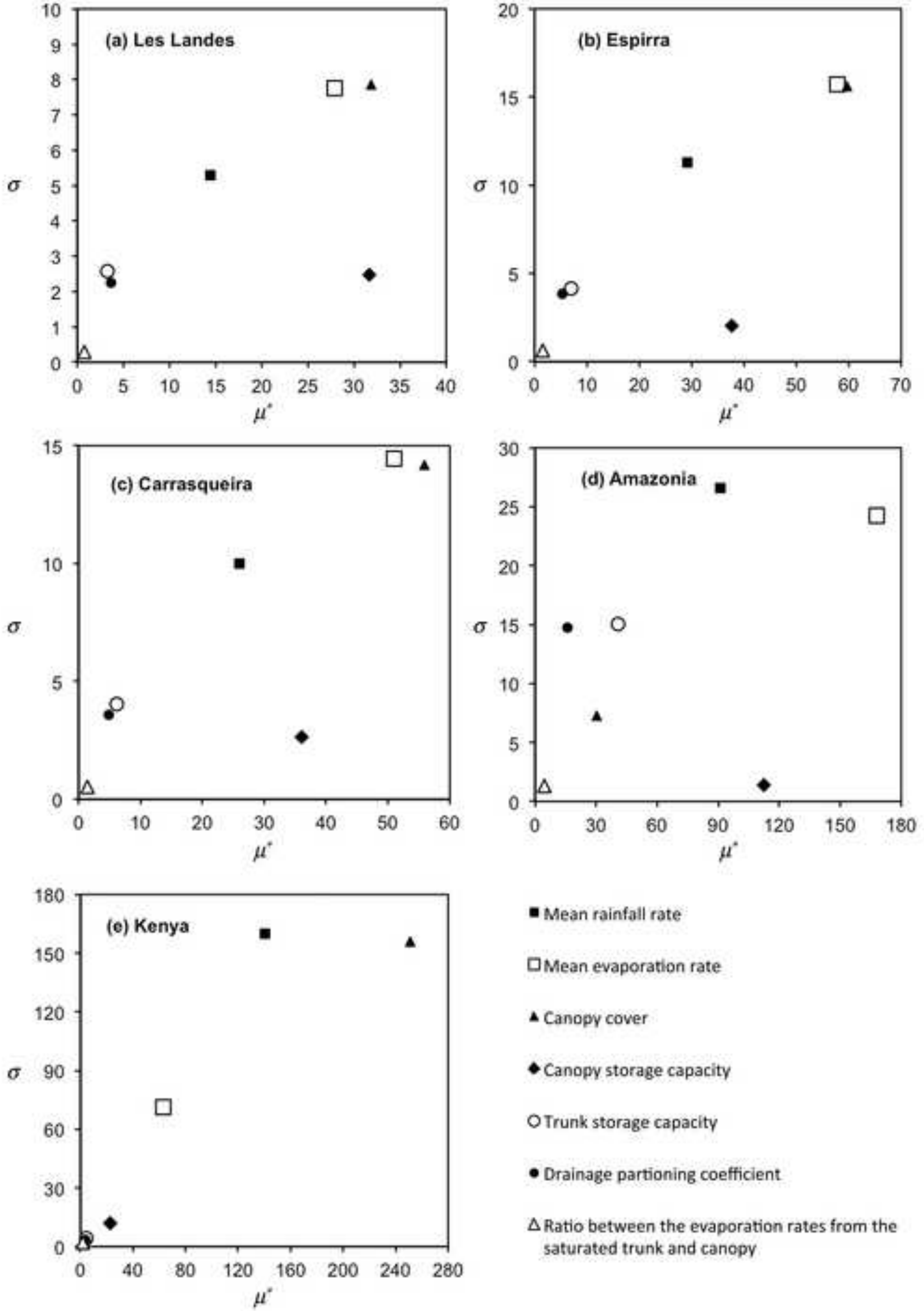
-40
Percentage of change of the interception loss
-60
-40
-20
0
20
40
60
Percentage of change of the mean evaporation rate
Kenya
Les Landes
Espirra
Carrasqueira
Amazonia


(a) Les Landes
(b) Espirra
(c) Carrasqueira
(d) Amazonia
(e) Kenya
σ
μ*
Mean rainfall rate
Mean evaporation rate
Canopy cover
Canopy storage capacity
Trunk storage capacity
Drainage partioning coefficient
Ratio between the evaporation rates from the saturated trunk and canopy

Rainfall interception modelling: is the wet bulb approach adequate to estimate mean evaporation rate from wet/saturated canopies in all forest types?

Highlights

- Saturated crowns of individual sparse trees behave as wet bulbs
- Evaporation from fully ventilated canopies is well estimated by the wet bulb approach
- When applicable, this approach may be preferable to the Penman-Monteith model
- Fully ventilated canopy conditions do not depend solely on crown cover fraction
- Proper evaluation of wet canopy evaporation is critical to Gash's interception model