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2 requirements for sustainable water use

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Abstract

While the beneficial effects of urban vegetation have long been recognized, growing conditions in urban environments, especially for street trees, are typically harsh and limited by low water availability. Supplemental irrigation may be used to preserve aesthetic quality and ability to provide ecosystem services of urban vegetation but requires careful management of available economic and water resources to reduce urban water footprint. To this purpose, decision-makers need quantitative tools, requiring few, physically-based parameters and accounting for the uncertainties and future scenarios of the hydroclimatic forcing. Focusing on in-row and isolated trees, a minimalist description of street tree water balance is proposed here, including rainfed and irrigated conditions, and explicitly accounting for tree water requirements, growing conditions (in terms of soil properties and extension of bare soil, permeable and impervious pavements surrounding the tree), and rainfall unpredictability. The proposed model allows the quantification of tree cooling capacity, water stress occurrence, and irrigation requirements, as a function of soil, plant, and climate characteristics, thus providing indications regarding the tree ability to provide ecosystem services and management costs. In particular, an analysis of different planting designs suggests that a balanced design consisting in bare soil and permeable pavement with size equal to the lateral canopy extension is optimal for water conservation, tree cooling capacity, and health. The proposed model provides useful indications towards the definition of site-specific guidelines for species selection and planting design, for sustainable urban vegetation.

KEY WORDS: urban vegetation; street trees; soil moisture; stochastic rainfall; plant water stress; irrigation

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I. INTRODUCTION

While at the beginning of the 20th century only 14% of the world population lived in urban settings, this percentage is now 50% (Konijnendijk, 2000), and it is predicted that over 5 billion people will reside in metropolitan areas by the year 2030 (United Nations, 2005; Young, 2010). Increasing urban population causes the conversion of large parts of natural landscape to urban environments, with significant repercussions on local climate, regional hydrological cycle, as well as habitat and biodiversity presence (Kalnay and Cai, 2003; Rees and Wackernagel, 2008). Within the urban environment, vegetation plays important social, cultural, economic, and environmental roles, ranging from positive effects on human health and improved social dynamics, increased housing prices and business district activity (Jorgensen and Gobster, 2010; Kuo and Sullivan, 2001; Maas *et al.*, 2006; Payton *et al.*, 2008; Wolf, 2005), to beneficial environmental impacts such as reduced runoff, improved soil drainage, soil erosion control, watershed protection, and provision of wildlife habitats and ecological corridors (Fernandez-Juricic, 2000; Xiao and McPherson, 2002). Moreover, when managed properly, urban vegetation provides local ecosystem services such as urban heat island mitigation, cooling and reduction of energy demand in adjacent buildings (Imhoff *et al.*, 2010; Shashua-Bar *et al.*, 2009), and alleviation of air pollution and dust (Beckett *et al.*, 1998; McPherson *et al.*, 2011; Nowak *et al.*, 2006).

Despite the local variations in composition, pattern, and spatial extent of the urban landscape (Quattrochi and Ridd, 1998; Thorsson *et al.*, 2011), urban vegetation is generally subject to biophysical and ecological conditions that are radically different from the surrounding rural and natural environments, in particular regarding soil features and local climate (Coder, 1996; Dwyer *et al.*, 1992, 2002; Gill *et al.*, 2007; Home *et al.*, 2010; Konijnendijk, 2000; Lohr *et al.*, 2004; Swanwick *et al.*, 2003). Growth conditions are even more severe for isolated trees located in parking lots and in-row along streets, and soils are often characterized by high compaction levels and surface crusting, limiting water infiltration, drainage capacity, and oxygenation (Craul, 1999; Pauleit, 2003). Contamination by anthropogenic materials (e.g., calcium from nearby construction weathering and de-icing compounds) may further negatively impact soil quality (Pauleit, 2003). Finally, urban vegetation is subjected to the effects of dust and pollution (Takagi and Gyokusen, 2004) and may need to withstand stringent pruning requirements for aesthetic reasons, as well as vandalism

60 and root injuries due to nearby construction (Foster and Blaine, 1978; Hauer *et al.*, 1994).

61 Maintaining a viable urban vegetation requires significant resources (economic resources 62 for purchasing, planting, and maintenance of plants; supply of fertilizers and water for 63 irrigation). Thus decision makers are faced by the complex problem of evaluating the trade-64 offs between the benefits of urban vegetation and the related costs, towards sustainable urban 65 tree design and management strategies (Clark *et al.*, 1997; Dwyer *et al.*, 2003; Ferrini and 66 Fini, 2011). In particular, species selection and planting design are key steps to facilitate 67 subsequent management and to enhance tree life span. Historically, species selection has 68 been mainly driven by aesthetic criteria (e.g., tree architectural features), often resulting in 69 the choice of non-native species, likely ill-adapted to the local climatic conditions (Balling 70 *et al.*, 2008) and potentially invasive (Niinemets and Penuelas, 2008). As a result, tree life 71 span in urban areas tends to be significantly reduced with respect to nearby rural areas 72 (Berrang *et al.*, 1985; Foster and Blaine, 1978; Nowak *et al.*, 1990). A more sustainable 73 species selection needs to represent a compromise between aesthetic appeal and functional 74 aspects and tolerance to the harsh conditions typical of urban sites (Pauleit, 2003; Richards, 75 1983; Sæbø *et al.*, 2003).

76 Among the limitations imposed by the urban environment, water deficit is generally 77 recognized as the principal limiting factor controlling the growth of urban trees (Clark and 78 Kjelgren, 1990; Cregg, 1995), particularly when combined with high air temperature and 79 low air humidity and insufficient nutrient availability (Flückiger and Braun, 1999). The 80 combination of poor soil infiltration, scarcity of the permeable surfaces (often concentrated 81 in the immediate vicinities of the tree trunk; Fig. 1a), and enhanced atmospheric water 82 demand results in frequent and intense episodes of plant water stress, which are not limited to 83 arid and semi-arid climates (Whitlow *et al.*, 1992). Plant water stress may negatively impact 84 vegetation growth and aesthetic quality, but also limit the beneficial cooling associated to 85 plant transpiration because of extended stomatal closure (Bowler *et al.*, 2010; Chen *et al.*, 86 2011; Jenerette *et al.*, 2011; Kjelgren and Clark, 1993; Porporato *et al.*, 2001). Furthermore, 87 water shortage interferes with plant defense mechanisms, increasing the predisposition to 88 parasite and pathogenic fungi attacks and tree mortality in general (Cregg and Dix, 2001; 89 Flückiger and Braun, 1999), with catastrophic losses in case of low species diversity, that 90 is typical of some but not all urban environments (Raupp *et al.*, 2006; Sjöman *et al.*, 2012; 91 Walker *et al.*, 2009). Hence, under specific climatic conditions, tree water requirements

92 and planting design, supplemental irrigation may be a necessity to sustain transpiration and
93 hence the beneficial effects of urban vegetation. Currently, water needs for public and private
94 landscape represent 40-70% of total municipal requirements (Hilaire *et al.*, 2008). Such high
95 water requirements are partly explained by past inadequate species selection and by poor
96 planting design, but also by water applications often exceeding plant demands (Balling
97 *et al.*, 2008; Salvador *et al.*, 2011). In light of recently reported water shortages (Jenerette
98 and Larsen, 2006), enhanced governmental restrictions on agricultural and municipal water
99 use (Brennan *et al.*, 2007; MacDonald *et al.*, 2010), and the projected climate change and
100 increase in urban population, quantitative tools are needed to address the 'urban water
101 challenge' (Pataki *et al.*, 2011a). Specifically, decision-makers increasingly require tools for
102 optimal species selection and planting design (Sæbø *et al.*, 2003; Sjöman and Nielsen, 2010),
103 to effectively manage available resources and limit city water footprints, particularly in
104 semi-arid regions.

105 The specificities of the urban environment make it difficult to exploit existing ecohydro-
106 logical knowledge relative to natural and managed rural ecosystems. Furthermore, while
107 some data have been published on irrigation requirements of container-grown ornamen-
108 tal plants under nursery conditions (Drunasky and Struve, 2005; Hagishima *et al.*, 2007),
109 data relative to water requirements of mature urban trees are still scarce (Pataki *et al.*,
110 2011b; Roberts and Schnipke, 1994). More importantly, as typical of other ecohydrological
111 problems, the question of sustainable water management is complicated by the inherent
112 intermittency and unpredictability of rainfall occurrence (Rodriguez-Iturbe and Porporato,
113 2004) and by the projected shifts in rainfall patterns in the next decades, which render the
114 available historical climatological data insufficient for an effective long-term planning of wa-
115 ter use. The few existing models describing soil water availability to urban trees are based
116 on yearly-averaged rainfall input (e.g., Lindsey and Bassuk (1991)) or driven by relatively
117 short meteorological observations (e.g., DeGaetano and Hudson (2000)), thus poorly char-
118 acterizing extreme events, such as long dry spells. In what follows, focusing on the case of
119 street trees, we propose an alternative approach explicitly including rainfall unpredictability
120 by means of a probabilistic description of rainfall occurrence, thus avoiding computationally
121 heavy simulations that needs to be forced by multi-decadal rainfall time series to include
122 extreme events. The proposed approach can be also applied for climate change scenario
123 analyses, for which only qualitative indications on projected changes are available at best.

₁₂₄ Our minimalist model, based on the probabilistic description of soil moisture and irrigation ₁₂₅ (Porporato *et al.*, 2004; Rodriguez-Iturbe and Porporato, 2004; Vico and Porporato, 2010, ₁₂₆ 2011a), provides a quantitative tool to assess plant water status, effective cooling capacity, ₁₂₇ and irrigation requirements, as a function of species selection and tree size (in terms of plant ₁₂₈ water requirements), planting design (in terms of extension of permeable and impervious ₁₂₉ surfaces around the tree trunk), rainfall patterns, and implemented irrigation strategy. This ₁₃₀ model provides quantitative indications in support of strategic decision making for adequate ₁₃₁ species selection, planting design, and management practices to maintain urban vegetation ₁₃₂ ecosystem services while limiting water requirements, under current and future precipitation ₁₃₃ patterns.

₁₃₄ II. MODEL DESCRIPTION

₁₃₅ A. Planting geometry of isolated and in-row street trees

₁₃₆ Within the variety of growing conditions of urban vegetation, we focus here on isolated ₁₃₇ or in-row trees growing in parking lots or along streets. In general, around these trees, it ₁₃₈ is possible to distinguish (up to) three areas with different permeability properties (Fig. ₁₃₉ 1a), which in turn impact the soil water balance of the tree rooting volume: i) an area of ₁₄₀ bare soil, A_B, often located immediately around the tree or shrub trunk; the infiltration ₁₄₁ capacity of the bare soil is determined by soil permeability, $\eta_B \leq 1$ (depending on soil ₁₄₂ properties, such as crusting, hydrophobicity, level of soil compaction, and mulching), and by ₁₄₃ soil saturation; ii) a partially permeable area, A_P, which allows the infiltration of a fraction ₁₄₄ $\eta_P < 1$ of the incoming rainfall; this area may be covered by tree grates or permeable ₁₄₅ pavement (e.g., interlocking concrete permeable pavement); and iii) an area of impervious ₁₄₆ pavement, A_I, which completely prevents water infiltration in the soil beneath, but that may ₁₄₇ generate a runoff towards the more permeable areas if adequately sloped and designed (i.e., ₁₄₈ in absence of curbs preventing water flow); the fraction of rainfall on the impervious surface ₁₄₉ that may potentially infiltrate in the more permeable areas is defined by the coefficient ₁₅₀ $\eta_I < 1$. Pervious concrete (similar to standard concrete but lacking the fine aggregates) ₁₅₁ is here assimilated to impervious pavements, on the basis of recent experimental results ₁₅₂ suggesting insignificant differences between pervious and impervious paving (Morgenroth

and Buchan, 2009; Viswanathan *et al.*, 2011). Fig. 1a shows a few examples of planting
design: all the three above mentioned regions are apparent in III. In other locations, the bare
soil may be reduced to a minimum (I), or the permeable pavement area may be altogether
absent (VI), or a curb may prevent the free flowing of water from the impervious pavement
to the permeable areas (IV). The extreme case of absence of permeable and impervious
pavements, e.g., a tree located in a wide lawn (V) is equivalent to the case of an isolated
tree in a natural environment. The lateral extensions of both canopy and root zone constitute
further geometric constraints. To account for them, we define A_R as the area over which
the root system extends horizontally and A_C the projected area of the canopy. The latter
is relevant for the tree water balance because the vegetation canopy, in particular when leaf
area index is high, may partially intercept rainfall, thus reducing the amount of water that
can potentially infiltrate in the permeable areas or create a beneficial runoff from the nearby
impervious surfaces. It is also useful to define the total area that contributes to the soil
water balance pertaining a single tree, i.e., $A_T = A_B + A_P + A_I$.

As apparent in Fig. 1a), the specific geometry of the areas surrounding the tree is highly
variable, in compliance with aesthetic and practical reasons. Spacing between adjacent trees
often represents a compromise among providing adequate soil volumes and water availability
(DeGaetano and Hudson, 2000), achieving the required ecosystem services (aesthetic quality,
air cooling, and pollution reduction), and preserving the ability to exploit the area under-
neath for foot or vehicular traffic (e.g., McPherson (2001)). In the following quantitative
analyses, we will focus on the case of circular symmetry, which works best for isolated trees.
The radii r_i fully define the areas affecting the tree soil water balance, $A_i = \pi r_i^2$, where
the subscript i may refer to bare soil ($i = B$), permeable ($i = P$) or impervious ($i = I$)
pavements, canopy extension ($i = C$) or rooting zone ($i = R$). The geometry of the problem
for this specific case is represented in Fig. 1b. The obtained results can be easily extended
to other geometries, such as the squares employed in several locations (Fig. 1a).

B. Soil moisture balance over tree rooting volume

A previously proposed stochastic model of the soil water balance suitable for natural and
agricultural environments (see e.g., Laio *et al.* (2001); Rodriguez-Iturbe *et al.* (1999); Vico
and Porporato (2011a)) is here adapted to the case of isolated or in-row trees. The temporal

183 dynamics of the soil water content in the plant rooting zone can be effectively described by
184 the following water balance

$$nA_RZ_R\frac{ds(t)}{dt} = R(t) + I(s(t)) - ET(s(t)) - LQ(s(t)).\qquad(1)$$

185 The state variable $s(t)$ represents the relative soil moisture averaged over the soil volume
186 A_RZ_R, where most of the plant roots are located and over which soil features are assumed
187 uniform, with Z_R being the characteristic rooting depth, A_R the area over which the root
188 system extends (see Fig. 1b), and n the soil porosity. The main input to the soil water
189 balance, $R(t)$, is represented by rainfall, either directly falling over the permeable area or
190 falling over nearby areas and being brought over by runoff. Water may also be supplied by
191 irrigation applications, $I(s(t))$. The main losses occur through soil water evaporation and
192 plant transpiration, $ET(s(t))$, runoff and deep percolation, $LQ(s(t))$. It is assumed that
193 there is no interaction between the root volume and any existing water table. All the fluxes
194 in Eq. (1) are interpreted at the daily time scale.

195   The actual volumetric input by rainfall to the rooting zone depends on the interaction
196 among surface permeabilities (and runoff generating capacity), canopy, and root lateral
197 extension. Regarding the impact of canopy, experimental evidence suggests that canopy
198 interception may reduce both the frequency of effective (i.e., non-canopy intercepted) rainfall
199 events and their effective depths (Daly *et al.*, 2008; Guswa, 2005). To quantify the volume of
200 potentially infiltrating rainfall it is thus necessary to consider the geometry of the problem,
201 by accounting for the fraction of area subjected to canopy interception effect, the extension
202 and permeability of bare soil and permeable pavement, and the distance of the contributing
203 permeable and impervious areas from the edge of the rooting zone, r_{nR}. Depending on root
204 lateral extension, three cases need to be considered: i) the rooting zone extends under the
205 entire permeable surface till the permeable/impervious surface interface (i.e., $r_R = r_B + r_P$),
206 ii) the rooting zone does not extend under the entire bare soil and permeable area (i.e.,
207 $r_R < r_B + r_P$), and iii) the rooting zone extends also under the impervious surface (i.e.,
208 $r_R > r_B + r_P$ depicted in Fig. 1b). The occurrence of the latter case, i.e., the rooting zone
209 extending also beyond the permeable/impervious surface interface, depends on soil type
210 and compaction level, construction details, water availability and its location, and features
211 of the nearby areas. The site-specificity of these features partly explains the contrasting
212 conclusions from studies on root extension under impervious pavement, with stunted root

213 growth in certain locations and relatively well developed, but concentrated, roots in others

214 (e.g., Reichwein (2003); Čermák *et al.* (2000)). Due to its complexity, the third case is

215 not considered here, i.e., it is assumed that roots do not generally extend under impervious

216 areas. For the purposes of defining the occurrence of water stress and irrigation requirements,

217 assuming that roots do not extend under the impervious pavement results in conservative

218 estimates of water stress frequency and severity, because the assumed smaller rooting zone

219 has lower buffering capacity against water dynamics and does not allow the exploitation of

220 other water stores that might be available with more extensive rooting systems.

221 　　In the first case (i.e., $r_R = r_B + r_P$), all the infiltrated water from the permeable area A_P

222 and a fraction η_I of surface runoff generated by the nearby impervious surface A_I contribute

223 to the rooting zone soil water content. For a generic rainfall event of depth $h(t)$, the water

224 volume contributing to the soil water balance (1) can be quantified as

$$R(t) = \left(A_T^{(\eta)} - A_T^{(\eta k)} \right) h(t) + A_T^{(\eta k)} h'(t) \tag{2}$$

225 where $A_T^{(\eta)} = \sum_{i=B,P,I} \eta_i A_i$ and $A_T^{(\eta k)} = \sum_{i=B,P,I} \eta_i k_{i,C} A_i$; $h(t)$ is the rainfall event depth,

226 and $h'(t)$ is the effective rainfall depth below the canopy (i.e., after canopy interception;

227 see II.C below). The coefficients $k_{i,C}$ (with $i = B, P, I$) are the fractions of the bare soil,

228 permeable, and impervious areas respectively influenced by the presence of the canopy, while

229 η_i are the respective surface permeability, driving the fraction of rainfall volume infiltrating

230 in non-saturated soils. In this case, lateral water redistribution between the root volume and

231 the nearby soil is neglected, even though it may contribute to root volume water depletion,

232 unless artificial boundaries are present.

233 　　In the second case, where the lateral extension of roots is less than the bare soil and

234 permeable pavement combined areas (i.e., $r_R < r_B + r_P$, as in the case depicted in Fig.

235 1b), the infiltration from the excess permeable surface and the runoff generated by the

236 surrounding impervious pavement does not directly contribute to soil water content of the

237 rooting zone, but rather it enhances water content outside the rooting volume. In absence

238 of artificial boundaries, soil water beyond the rooting volume may be laterally redistributed

239 according to existing soil water potential gradients. While a precise description of the soil

240 water lateral redistribution lies beyond the scope of the proposed model, it is simply assumed

241 here that only a fraction of the water volume infiltrating over a ring of width dr at a generic

242 distance r from the edge of the rooting zone will finally contribute to the tree available

243 water. The contributed fraction is assumed to decrease exponentially with the distance

244 from the rooting zone edge. Thus, the contribution of the infinitesimal ring of permeable

245 surface is $dR_{P,nR}(t) = 2\pi\eta_P h(t) r_{nR} e^{-r} dr$, where the rainfall depth $h(t)$ is substituted by $h'(t)$

246 should the infinitesimal area $2\pi r_{nR} dr_{nR}$ be subject to canopy interception. With the further

247 assumption to simplify the notation that the areas beyond the rooting zones are not subject

248 to canopy interception (as discussed below, canopy seldom extends beyond the rooting zone),

249 the total contribution of the permeable area beyond the rooting extension is $R_{P,nR}(t) =$

250 $\int_{r_R}^{r_B+r_P} dR_{P,nR} = 2\pi\eta_P h(t)\left[1 + r_R - (1 + r_B + r_P)e^{-r_{nR}}\right]$, where $r_{nR} = r_B + r_P - r_R$ is the

251 lateral extension of the area with permeable pavement beyond the rooting zone (Fig. 1b).

252 Similarly, the water volume contributed by the nearby impervious surface to plant accessible

253 soil moisture is here considered exponentially decreasing with increasing distance between

254 the edge of the rooting area and the position of the permeable/impervious surface interface,

255 i.e. $R_I(t) = e^{-r_{nR}}\eta_I h(t) A_I$ (where $k_{I,C}$ has been set to zero under the assumption that

256 $r_C \leq r_R$; see below). Accordingly, the water volume contributed to the soil water balance

257 for $r_R < r_B + r_P$ from a generic event of depth $h(t)$ is

$$R(t) = h'(t) \sum_{i=B,P} \eta_i k_{i,C} A_i + h(t)\left\{2\pi\eta_P\left[1 + r_R - (1 + r_B + r_P)e^{-r_{nR}}\right] + \eta_I A_I e^{-r_{nR}}\right\}. \quad (3)$$

258 Regarding the losses, the individual plant is responsible for a daily volumetric water

259 uptake, which in general depends on species, amount of transpiring leaves (and hence tree

260 size), plant activity (driven by temperature, solar radiation, and plant water status, in turn

261 function of soil moisture), plant general conditions (e.g., impact of pollutants, diseases,

262 and pest infestations), and atmospheric water demand (as defined by air temperature and

263 humidity, and wind speed). As such, water uptake accounts for the specificities of the urban

264 growing environment, including potentially higher temperatures and vapor pressure deficits

265 (Kjelgren and Clark, 1993; Litvak *et al.*, 2012; McCarthy and Pataki, 2010; Wang *et al.*,

266 2011). Losses through soil water evaporation are driven by soil moisture in the superficial

267 layers of the bare soil area and, to a lesser extent, under the permeable pavement. Because of

268 the geometry typical of street trees, often implying relatively large trees growing on a rather

269 small areas of bare or mulched soil, soil water evaporation is generally much less relevant

270 than plant transpiration. Thus, in what follows, we focus on losses by plant transpiration.

271 While most of the results presented below are valid for a generic transpiration function

$_{272}$ $ET(s(t))$, for the quantitative results below a piecewise linear dependence of transpiration
$_{273}$ water volume on soil moisture is assumed (Rodriguez-Iturbe *et al.*, 1999), i.e.,

$$\rho_w ET(s(t)) = \begin{cases} T_{max}\frac{s(t)}{s^*} & s(t) < s^* \\ T_{max} & s(t) \geq s^* \end{cases}, \tag{4}$$

$_{274}$ where T_{max} represents the mass of transpired water per tree per day when the plant is under
$_{275}$ well watered conditions (depending on species and amount of transpiring leaves), ρ_w is the
$_{276}$ density of water, and s^* is the soil moisture level corresponding to incipient plant water
$_{277}$ stress (i.e., below which plant transpiration is reduced because of stomatal closure). In
$_{278}$ what follows, we will often refer to the volumetric water losses per unit rooting volume, i.e.,
$_{279}$ $\rho(s(t)) = (nZ_R A_R)^{-1} ET(s(t))$.

$_{280}$　The other loss term included in the soil water balance (1), $LQ(s(t))$, combines losses
$_{281}$ through surface runoff and deep percolation from the bottom of the rooting volume. For
$_{282}$ simplicity, following Milly (2001) and Porporato *et al.* (2004), it is assumed that deep perco-
$_{283}$ lation and runoff take place instantaneously (at the daily time scale) whenever soil moisture
$_{284}$ reaches a threshold s_1, typically slightly above soil field capacity. For soils within closed-
$_{285}$ bottom containers or other confined spaces, the threshold s_1 may approach soil saturation,
$_{286}$ to mimic the poor drainage typical of these growing conditions.

$_{287}$　Finally, depending on tree water requirements, rainfall input, and landscaping strategy,
$_{288}$ an irrigation system may be implemented. This additional water input is included in the
$_{289}$ modeling scheme as detailed in Vico and Porporato (2010, 2011a). In particular, as opposed
$_{290}$ to fixed-schedule water applications, we consider the case of demand-based irrigation, where
$_{291}$ irrigation applications are triggered by soil moisture reaching a pre-set 'intervention point'
$_{292}$ $\tilde{s}$ (Vico and Porporato, 2011a). If a certain water stress is considered tolerable, the inter-
$_{293}$ vention point can be set below the incipient stomatal closure s^*, thus performing a deficit
$_{294}$ irrigation (English and Raja, 1996). Currently deficit irrigation of urban vegetation is often
$_{295}$ applied as the result of municipal level water efficiency ordinances and limited technical or
$_{296}$ economic resources, rather than in response to environmental concerns (Parés-Franzi *et al.*,
$_{297}$ 2006). Several deficit irrigation applications are under active consideration (Delcambre and
$_{298}$ Rossignol, 1999; Shooshtarian *et al.*, 2011; Suleiman *et al.*, 2011) and increasingly limited
$_{299}$ water availability will likely force the adoption of new guidelines for species selection and
$_{300}$ management, favoring species for which a limited water stress does not significantly impact

301 the tree aesthetic quality. Furthermore, depending on the employed irrigation technique,
302 we distinguish between i) a more traditional irrigation, in which each irrigation application
303 will provide instantaneously (at the daily time scale) a given amount of water, that restores
304 soil moisture to a pre-set 'target' level, $\hat{s}$; each irrigation application provides a volume
305 $nZ_R A_R(\tilde{s} - \hat{s})$; and ii) the more sophisticated micro-irrigation, which is idealized here as a
306 continuous supply of water that balances losses through evapotranspiration (i.e., providing
307 a volume $ET(\tilde{s})$ per day), initiated when the soil moisture reaches the intervention point,
308 thus maintaining soil moisture at the intervention point till the next (effective) rainfall event
309 (Vico and Porporato, 2010). In an urban setting, the first strategy may correspond to rather
310 labor-intensive activities, such as periodic water applications through plant water bags (Fig.
311 1a, V) or direct manual watering with hoses or trucked water. Conversely, micro-irrigation
312 requires the installation of a permanent irrigation system (e.g., sub-irrigation and drip ir-
313 rigation systems), allowing more frequent or even continuous water applications. As such,
314 micro-irrigation is currently limited to specific locations where economic resources and in-
315 frastructures are available, and there is the need to maintain certain vegetation, e.g., for
316 touristic reasons.

C. Inclusion of rainfall stochasticity

318 Rainfall unpredictability can be explicitly included in the above soil water balance by
319 idealizing rainfall occurrence as a series of instantaneous events occurring according to a
320 marked Poisson process, with average frequency λ. Rainfall event depths are assumed to be
321 exponentially distributed, with average depth α (Rodriguez-Iturbe *et al.*, 1999; Rodriguez-
322 Iturbe and Porporato, 2004). Within this framework, the effective rainfall depth under the
323 canopy can be well described as a censored Poisson process, occurring according to frequency
324 $\lambda' = \lambda e^{-\Delta/\alpha}$, where Δ is a vegetation-dependent depth-threshold (Rodriguez-Iturbe *et al.*,
325 1999). Rainfall events smaller than Δ are completely intercepted by the canopy. We further
326 assume that the mean effective rainfall depth is reduced to $\alpha' = \kappa_C \alpha$ (Daly *et al.*, 2008).
327 The presence of the canopy (and the existence of an interception threshold Δ) generates two,
328 partially dependent, Poisson processes: i) the uncensored rainfall process providing water to
329 areas unaffected by the canopy, which occurs with mean frequency λ, and ii) the censored
330 Poisson process driving precipitation under the canopy, which occurs with mean frequency

331 λ'. Considering in a rigorous way both processes would undermine the analytical tractability

332 of the whole problem. As an approximation, effective rainfall is assumed to reach the ground

333 with average frequency λ_{eff}, representing the area-weighted average of λ and λ', i.e.,

$$\lambda_{\text{eff}} = \left(1 - \frac{A_T^{(k)}}{A_T}\right)\lambda + \frac{A_T^{(k)}}{A_T}\lambda' \tag{5}$$

334 where $A_T^{(k)} = \sum_{i=B,P,I} k_{i,C} A_i$. This approximation works particularly well when the

335 vegetation-dependent threshold Δ is small with respect to the average event depth α (so

336 that λ' does not significantly differ from λ), a relatively common case even in presence of

337 large canopies (Daly *et al.*, 2008; Guswa, 2005).

338   The effective rainfall contributing to the soil water balance occurs according to a modified,

339 censored Poisson process, with frequency λ_{eff}, and providing water volumes extracted by an

340 exponential distribution with average volume α_V, obtained by setting $h = \alpha$ and $h' = \kappa_C \alpha$

341 in Eqs. (2) and (3) for $r_R = r_B + r_P$ and $r_R < r_B + r_P$ respectively. The effective depth

342 contributing to the soil water content in the rooting zone is given by

$$\alpha_{\text{eff}} = \alpha_V / A_R. \tag{6}$$

343 **D. Soil moisture probability density function (pdf) and irrigation requirements**

344   With the above simplifications and assuming stochastic steady state, it is possible to

345 obtain analytically the soil moisture probability density function (pdf), $p(s)$, both in absence

346 of irrigation and with a generic demand-based irrigation scheme, by exploiting the crossing

347 properties of the soil moisture process. In fact, after the soil moisture process has reached

348 the stochastic steady state (i.e, $\partial p(s)/\partial t = 0$), the frequency of upcrossing of a generic soil

349 moisture threshold must equal the frequency of downcrossing of the same threshold. For a

350 generic normalized loss function $\rho(s) = (nZ_R A_R)^{-1} ET(s)$ and including irrigation, the soil

351 moisture pdf reads (Vico and Porporato, 2011a) is

$$p(s) = C\frac{e^{\int_{\tilde{s}}^{s}\left(\gamma - \frac{\lambda_{\text{eff}}}{\rho(u)}\right)du}}{\rho(s)}\{1 + \int_{\tilde{s}}^{s}\left[\gamma\theta(\hat{s} - u) - \delta(\hat{s} - u)\right]e^{\int_{\tilde{s}}^{u}\left(\gamma - \frac{\lambda_{\text{eff}}}{\rho(y)}\right)dy}du\}, \tag{7}$$

352 where $\gamma = nZ_R/\alpha_{\text{eff}}$, $\theta(\cdot)$ is the Heaviside function, and $\delta(\cdot)$ the Dirac delta function. The

353 normalization constant C can be obtained by imposing $\int_{\tilde{s}}^{s_1} p(s)ds = 1$. For $\tilde{s} \to 0$ and $\hat{s} \to 0$,

354 the above pdf simplifies to the case of absence of irrigation. For $\hat{s} \to \tilde{s}$, the case of micro-
355 irrigation is retrieved, even though a more straightforward derivation of the soil moisture
356 pdf for micro-irrigation is also available (as detailed in Vico and Porporato (2010)). Eq. (7)
357 can be easily particularized for the piecewise linear loss function in (4), which is used for
358 the quantitative analyses below.

359 The crossing properties of the soil moisture process can also be exploited to obtain the
360 average irrigation requirements in terms of irrigation frequency and required water volumes.
361 Following Vico and Porporato (2010, 2011a), the average frequency of the irrigation treat-
362 ment is the frequency of downcrossing of the threshold $\xi = \tilde{s}$, i.e., $\nu^{\downarrow}(\tilde{s}) = \rho(\tilde{s})p(\tilde{s})$, while
363 the volume of irrigation water applied over a period of duration T_{seas} is given by the amount
364 of water provided at each application times the number of applications over the period, i.e.,

$$V_t = nZ_RA_R(\hat{s} - \tilde{s})\nu^{\downarrow}(\tilde{s})T_{seas} = nZ_RA_R(\hat{s} - \tilde{s})\rho(\tilde{s})p(\tilde{s})T_{seas}. \tag{8}$$

E. Plant average transpiration and water stress

366 The above described stochastic framework allows also the quantification of plant average
367 transpiration and the occurrence and severity of plant water stress, as a function of species,
368 tree size, planting design, root zone features, and precipitation patterns, under unpredictable
369 rainfall. Plant transpiration and water stress are key quantities to describe plant ability to
370 provide ecosystem services: on the one hand, average transpiration over the season is a
371 measure of the effective capacity of the tree to provide its potential cooling effect; on the
372 other, water stress provides some indications regarding tree growth and aesthetic value as
373 well as its health and susceptibility to pest attacks, even though the response to water stress
374 is highly species-specific.

375 Average mass daily transpiration over the season can be obtained from the soil moisture
376 pdf (7) as

$$\langle T \rangle = \int_{\tilde{s}}^{s_1} \rho_w ET(s)p(s)ds, \tag{9}$$

377 where $\rho_w ET(s)$ is defined in (4). The ratio $\langle T \rangle / T_{max}$ quantifies how the specific growing
378 conditions (climate, planting geometry, irrigation) reduce the ability of the street tree to

379 provide cooling, with reference to the maximum potential cooling effect (proportional to

380 T_{max}).

381   Regarding water stress, to account for frequency, duration, and intensity of plant water

382 stress within a single indicator, we employ the 'dynamic water stress' or mean dynamic

383 stress over the growing season $\overline{\theta}$ (Porporato *et al.* (2001)):

$$\overline{\theta} = \begin{cases} (\frac{\overline{\zeta}'\overline{T}^{\downarrow}(s^*)}{kT_{seas}})(\nu^{\downarrow}(s^*)T_{seas})^{-\frac{1}{2}} & \text{if} \quad \overline{\zeta}'\overline{T}^{\downarrow}(s^*) < kT_{seas} \\ 1 & \text{otherwise} \end{cases} . \tag{10}$$

384 In the above definition, $\overline{\zeta}'$ is the average static water stress, $\overline{T}^{\downarrow}(s^*)$ is the average time spent

385 by the soil moisture process below the threshold s^*, $\nu^{\downarrow}(s^*)T_{seas}$ is the average number of

386 downcrossings of the threshold s^* over the period T_{seas}, and k is an index of plant resistance

387 to water stress. The interested reader is referred to Porporato *et al.* (2001) for a discussion

388 on the rationale behind these stress measures. The frequency of downcrossing of level s^*,

389 $\nu^{\downarrow}(s^*)$, is linked to the soil moisture pdf as $\nu^{\downarrow}(s^*) = \rho(s^*)p(s^*)$, while the average time spent

390 by the process below the same threshold, $\overline{T}^{\downarrow}(s^*)$, can be obtained as $\overline{T}^{\downarrow}(s^*) = \nu^{\downarrow}(s^*)^{-1}P(s^*)$,

391 where $P(\cdot)$ is the cumulative density function. In turn, the average static stress, $\overline{\zeta}'$, is defined

392 as mean level of plant water stress, provided that the plant is under stress, i.e.,

$$\overline{\zeta}' = P(s^*)^{-1}\overline{\zeta} = P(s^*)^{-1} \int_0^1 \zeta p_Z(\zeta)d\zeta, \tag{11}$$

393 where ζ depends on soil moisture as $\zeta(t) = \max\{s^{*-q}(s^* - s(t))^q, 0\}$, and $p_Z(\zeta)$ is the

394 probability density function of the static stress, obtained from $p(s)$ through the derived

395 distribution technique (see Porporato *et al.* (2001) for details). The parameter q is a measure

396 of the nonlinearity of the effects of soil moisture on plant status, with higher q for plants

397 more sensitive to a small change in water availability. While in principle this definition of

398 water stress can be employed both in absence and in presence of irrigation, we limit the

399 analyses of tree water stress to the case of absence of irrigation. In fact, the choice of the

400 irrigation strategy should be based on considerations relative to acceptable plant water stress

401 levels, thus making the quantification of water stress in irrigated settings less relevant.

F. Model parameterization

1. Tree size and water requirements

To fully characterize street tree water balance, information on tree level transpiration rates, canopy and root extensions are needed. Because little information is currently available for mature urban trees (Pataki *et al.*, 2011b), parameterization of the above model may require resorting to additional assumptions or to the combination of different sources of information, as discussed next.

Regarding tree water requirements, leaf level transpiration rates for specific species/location combinations can be obtained e.g. by means of gas exchange measurements, to quantify stomatal conductance. Upscaling such leaf area transpiration rate to the canopy level requires knowledge of the total tree transpiring leaf area (a function of tree size). For most of currently available data on transpiration rates in urban settings, the only information available on tree dimension is trunk diameter at breast height (DBH), with canopy extensions being reported only in some cases. To circumvent such lack of information, existing allometric relationship may be used to estimate canopy height and radius from DBH (see, e.g., McHale *et al.* (2009)); alternatively, realistic assumptions are to be made on canopy radius of the species under scrutiny. A selection of existing data on transpiration rate and canopy extension relative to the most common species in North American cities, growing in parks or along streets, is reported in Table I.

Regarding root dimensions, to our knowledge no dataset on plant transpiration includes information about root extension, depth, and role played by the specific geometry of the planting site. Thus the choice of related model parameters needs to rely on other indirect information and assumptions. In absence of external constraints, root and canopy radial extensions tend to be similar (Craul, 1985; Schenk and Jackson, 2002). Furthermore, as discussed in II.B, roots extending under impervious surfaces tend to contribute little to tree available soil water. Hence, analyses are limited to the case of roots not extending beyond the permeable/impervious interface, a conservative assumption for the quantification of water stress and irrigation requirements. As a result, in the following analyses, we assume that roots fully exploit the soil area below the permeable surfaces, but do not effectively extend beyond canopy area, nor below the impervious surface (i.e., $r_R = \min\{r_B + r_P, r_C\}$; Fig.

432 1b). It can be expected that the average rooting depth, Z_R, is generally smaller in an urban

433 setting than under natural conditions, because of either the negative effect of soil compaction

434 and low soil aeration or existing physical constraints (compacted or otherwise inhospitable

435 layers, closed-bottom containers). A direct consequence of these limitations to rooting depth

436 is that deeper planting soils may not fully compensate for narrow planting designs (Craul,

437 1985).

438　　　To explore the effect of species selection and tree size, a sensitivity analysis is conducted

439 on the tree transpiration rate under well watered conditions (see III below). As hinted at

440 above, for set climatic conditions (solar irradiance, air humidity and temperature), tran-

441 spiration rate per tree is a function of tree species (via maximum stomatal conductance)

442 and tree canopy size (via total leaf area). Literature data suggest that the variability of

443 stomatal conductance is rather small across species belonging to the same functional group

444 and adapted to similar climatic conditions (see, e.g., Körner et $al.$ (1979) for a synthesis).

445 Hence, in the sensitivity analysis on tree water requirements below, it is assumed that larger

446 trees have a higher transpiration rates, thus providing indications both regarding species

447 selection (via the typical size of mature trees) and the effect of tree growth over time. In

448 absence of more detailed information, in what follows, we assume that total daily transpira-

449 tion scales with tree canopy volume, which in turn (for an idealized spherical canopy), scales

450 as r_C^3. Hence, higher total transpiration corresponds to higher r_C; in turn, r_C potentially af-

451 fects root lateral extension (being $r_R = \min\{r_C, r_B + r_P\}$). Conversely, because of potential

452 urban-specific constraints on root ability to extend downward (Grabosky et $al.$, 2001), it is

453 assumed that tree dimension does not significantly influence average rooting depth (i.e., in

454 all the analyses, Z_R is kept constant also when varying T_{max}).

455　　*2. Planting design*

456　　　In the following simulations, it is assumed that the plant trunk is located within an area

457 of bare soil of radius $r_B = 1$ m. The radius of the area influencing the tree water balance

458 (through either direct infiltration or runoff) is $r_T = r_B + r_P + r_I$, a value that depends mainly

459 on planting design and existence of curbs (Fig. 1). For non-isolated trees and in absence

460 of pavement features impeding water free flow, r_T represents the semi-distance between

461 adjacent trees, which in turn is set by desired tree density or level of canopy cover and

462 shade. We explore the impact of permeable pavement ring size r_P (and consequently the

463 size of the impervious ring, $r_I = r_T - (r_B + r_P)$), both assuming set tree density (i.e., for

464 set r_T) and altering the fraction of permeable vs. impervious surfaces around the isolated

465 tree thus allowing the distance between adjacent tree to vary as well. In the first case, a

466 distance between adjacent trees of 15 m (corresponding to $r_T = 7.5$ m) is used as an example.

467 This value is in good agreement with typical municipal guidelines on street tree planting

468 and well balances the needs to achieve an adequate canopy cover and to exploit the areas

469 underneath for other uses. Furthermore, it is assumed that the bare soil area A_B does not

470 present extensive crusting, so that $\eta_B = 1$. We consider a permeable pavement that allows

471 the infiltration of a fraction of rainfall $\eta_P = 0.45$, while the impervious pavement contributes

472 to the tree soil water balance with runoff representing a fraction $\eta_I = 0.1$ of the precipitated

473 water.

474   *3. Rainfall forcing*

475   With the idealization of rainfall occurrence as a marked Poisson process, rainfall pattern

476 is fully characterized by the average event depth α and the average event frequency λ.

477 We focus to the summer period (May-September at intermediate latitudes in the Northern

478 hemisphere), when trees are fully active, temperatures and atmospheric water demands tend

479 to be high, and hence the risk of water stress is highest. Accordingly, rainfall parameters

480 α and λ are averages for the same period rather than for the entire year. For a specific

481 location, these parameters can be inferred from daily rainfall records. In section III, we

482 explore the effect of the predicted intensification of extreme rainfall events and increased

483 frequency of dry spells by climate change (see e.g. Easterling *et al.* (2000)), by decreasing λ

484 while increasing α so that the total seasonal rainfall $R_{tot} = T_{seas}\alpha\lambda$ is maintained constant.

485 Additional locations may be investigated by altering R_{tot}.

486   *4. Rainfall interception*

487   Because rainfall interception by urban canopies has not been experimentally character-

488 ized, we set rainfall interception threshold Δ at 3 mm, consistently with observations under

489 natural canopies (Daly *et al.*, 2008; Guswa, 2005; Helvey and Patric, 1965). Qualitative con-

490 siderations suggest that this is a reasonable assumption for relatively dense urban canopies,
491 while the question is more complex for individual trees. In fact, under optimal conditions,
492 isolated trees may achieve higher leaf area index than forest trees, thanks to the light avail-
493 ability from the sides, but harsh urban growing environments may limit leaf and branch
494 production thus resulting in lower-than-natural interception rates. In alternative to natural
495 canopy data, species-specific interception thresholds can be inferred from empirical relation-
496 ships linking leaf area index to canopy interception storage capacity (see e.g., Aston (1979);
497 Thompson *et al.* (1981)).

498 　　*5. Irrigation parameters*

499 　　If irrigation is implemented, we assume that a deficit irrigation is performed for water
500 conservation purposes. While the effects of water limitations are highly species-specific and
501 deficit irrigation should account for these specific responses, Kopinga (1985) suggests that
502 urban tree transpiration should be at least 75% of its well-watered value to maintain an
503 acceptable vegetation health and aesthetic quality. Following this indication, in presence
504 of irrigation, a deficit irrigation with intervention point $\tilde{s} = 0.75s^*$ is assumed (i.e., the
505 minimum acceptable soil moisture level is set at $0.75s^*$). For traditional irrigation it is
506 assumed that water applications are such that soil moisture level is restored to 80% of soil
507 water holding capacity, i.e., the soil moisture target level is set to $\hat{s} = 0.8s_1$. While shallower
508 irrigation applications may be more efficient for water conservation purposes, the assumed
509 almost soil saturating irrigation application limits the frequency of required applications
510 (Vico and Porporato, 2011b), with clear economic advantages when the water application
511 is labor-intensive. Conversely, if a more sophisticated micro-irrigation system is in place,
512 shallow and almost continuous water applications are possible. In this case, the irrigation
513 event is idealized as a continuous application of water, fully balancing evapotranspiration
514 losses at $\tilde{s}$ till the next (effective) rainfall event.

515 **III. IMPACT OF PLANTING GEOMETRY, SPECIES SELECTION, AND CLI-**
516 **MATE ON TREE WATER STATUS AND IRRIGATION REQUIREMENTS**

517 To provide useful indications for adequate and sustainable species selection and plant-
518 ing design under different climatic scenarios, in this section we explore the effect of tree
519 transpiration rate under well watered-conditions, extension of the permeable pavement ring,
520 planting density, and rainfall pattern on effective rainfall input (Fig. 2), soil moisture (Fig.
521 3), tree effective cooling capacity and dynamic water stress in absence of irrigation (Fig. 4),
522 as well as on irrigation requirements (in terms of water volumes and application frequencies;
523 Figs. 5 and 6). The Wolfram Mathematica codes used to produce the results presented in
524 this paper are available from the authors upon request.

525 **A. Effect of permeable pavement extension on soil moisture probability density**
526 **function**

527 In the proposed idealization of the problem (Fig. 1b), the dimension of the permeable
528 pavement plays a complex role on soil moisture dynamics, through its impact on the amount
529 of rainfall contributing to tree available soil water, as well as the lateral extension of the
530 root for large trees (with potentially wider rooting zones for higher r_P) and hence overall
531 soil water storage volume (Fig. 2). Consequently, for a set tree density (i.e., a given r_T;
532 black lines in Fig. 2), average infiltrable water volume $\overline{R}$ and average soil moisture increase
533 with the area of permeable pavement, till the point beyond which the enhanced infiltrated
534 water cannot be fully exploited because it infiltrates beyond the rooting zone (Fig. 2b, black
535 line). A similar pattern is observed when the distance between adjacent trees is allowed to
536 increase linearly with r_P (i.e., r_I is kept constant, while r_T increases; Fig. 2a, grey dashed
537 line), even though the decline in contributing water is less sharp when $r_P > r_C - r_B$ (Fig.
538 2b, grey line).

539 For the case of set tree density, some examples of numerically generated soil moisture
540 time series with no irrigation for three radii of permeable pavement and in presence of
541 two irrigation strategies (and intermediate permeable pavement radius) are reported in Fig.
542 3a,c, along with the corresponding soil moisture pdf under stochastic steady state conditions
543 (Eq. 7; Fig. 3b,d). As a consequence of the dependence of $\overline{R}$ on r_P (Fig. 2b), there is an

544 intermediate dimension of the permeable pavement ring that maximizes soil water content.

545 This is apparent in both the soil moisture dynamics and the corresponding pdfs, where the

546 highest average soil moisture levels are obtained for r_P such that $r_B + r_P = r_C$ (which

547 corresponds to $r_P = 2$ m in Fig. 3), while extremely low or high r_P result in very similar

548 pdfs of soil moisture (Fig. 3b, dotted and solid lines). Assuming such intermediate r_P,

549 Fig. 3 (bottom) illustrates the effect of irrigation applications (solid lines refer to micro-

550 irrigation, dashed ones to traditional irrigation). Obviously, for both irrigation methods, the

551 soil moisture process tends to spend more time at higher values than for rainfed conditions.

552 Nevertheless, the almost soil saturating target level $\hat{s}$, imposed to traditional irrigation for

553 practical reasons, causes wide fluctuations in soil moisture, mainly between the intervention

554 point $\tilde{s}$ and the target level $\hat{s}$, with excursions above the latter threshold caused by either

555 very deep rainfall events (see the jump in soil moisture at around $t = 20$ d in the example

556 reported in Fig. 3c) or precipitations immediately following an irrigation application (after

557 $t = 120$ d in Fig. 3c). Conversely, the more sophisticated micro-irrigation results in the

558 soil moisture process spending a finite amount of time at the intervention point $\tilde{s}$, while

559 waiting for the next effective rainfall event. This fact is mirrored by the mixed pdf of soil

560 moisture, consisting in a continuous part (solid line) and an atom of probability in $\tilde{s}$ (solid

561 bar), representing the non-zero probability that the soil moisture process is at $\tilde{s}$ (Vico and

562 Porporato, 2010).

B. Tree water stress with no irrigation

564   Tree water requirements, rainfall pattern, and fraction of permeable vs. impervious

565 pavement around the tree nonlinearly affect tree cooling capacity, $\langle T \rangle / T_{max}$, and dynamic

566 water stress, $\overline{\theta}$. For each T_{max}, there is an intermediated permeable area that maximize

567 $\langle T \rangle / T_{max}$ and minimizes the value of $\overline{\theta}$, corresponding to $r_P = r_C - r_B$ (dashed line in Fig.

568 4a,d), which progressively increases with T_{max} (with which the canopy lateral extension

569 grows with power 1/3; see II.F.4). Assuming a set tree density, for larger and more water-

570 demanding trees (i.e., higher T_{max}; Fig. 4a,d), dynamic water stress increases nonlinearly

571 with decreasing permeable areas, in particular at low r_P.

572   The effect of shifts in the rainfall pattern is explored in Fig. 4b,f, where total rainfall

573 over the growing season is held constant while increasing α and simultaneously decreasing

574 λ. Low r_P results in low cooling capacities and high water stress levels regardless of rainfall

575 pattern, because it limits effective root lateral extension and hence tree available water

576 storage capacity. For medium-to-high r_P, both very low and very high rainfall frequencies

577 are detrimental for cooling capacity and plant water status: infrequent but deep rainfall

578 events enhance losses through runoff and deep percolation, thus reducing the amount of

579 water available for plant transpiration; conversely, frequent but shallow rainfall events are

580 mostly intercepted by the canopy, thus limiting soil water recharge. Permeable pavement

581 extension $r_P = r_C - r_B$ and intermediate λ are ideal for tree ability to provide ecosystem

582 services. The effect of rainfall pattern becomes less and less marked for permeable pavement

583 extending beyond the canopy in particular regarding cooling capacity, because, in this case,

584 soil water recharge from outer areas quickly tapers off with increasing distance.

585   The assumption of set distance between adjacent trees is relaxed in Fig. 4c,f, where the

586 combined effects of permeable and impervious pavement dimensions are explored for set

587 species and climatic conditions. As expected, higher tree density (i.e., lower distances from

588 the origin in Fig. 4c,f) has negative effects on tree cooling capacity and water status, because

589 of the limited area that can be exploited for water collection and soil moisture recharge.

590 More interesting is the quantification of the differential effect of an increase in either r_P

591 or r_I. Similar reductions in cooling capacity and dynamic water stress can be achieved

592 with a smaller increase in permeable pavement extension than in impervious pavement area,

593 particularly at intermediate tree densities. Under these conditions, larger permeable areas

594 allow a wider extension of roots as well as a more efficient collection of precipitated water,

595 which could not be achieved with an equivalent amount of impervious surface, imposing

596 limits to the amount of rainfall effectively contributing to meet tree water requirements.

597 Hence, at intermediate tree densities (dashed line in Fig. 4c corresponds to $r_T = 7.5$ m),

598 maximizing permeable areas may improve plant water status, while simultaneously limiting

599 the negative effect caused by increased tree density. Conversely, extremely dense trees limit

600 the lateral extension of non-competing roots and hence the buffering effects of soil volume

601 regardless of the pavement permeability, while more isolated trees benefit the most from

602 intermediate permeable area extension (the optimal width of the paved area corresponds to

603 $r_P = r_C - r_B$).

C. Irrigation requirements and optimal irrigation strategy

If irrigation is implemented, irrigation requirements (water volumes and application frequency), as well as sustainability, cost, and feasibility of traditional vs. micro-irrigation strongly depend on species selection, tree size, rainfall pattern, and planting geometry (Figs. 5 and 6).

Fig. 5a shows how the required volumes for traditional irrigation increase almost linearly with transpiration rates T_{max}; similar patterns are obtained for micro-irrigation, although with lower total water requirements than for traditional irrigation, and with less steep increases with increasing T_{max} (not shown). The pattern is more complex when altering rainfall timing while maintaining rainfall totals (Fig. 5b). For any rainfall frequency, the minimum water requirements are to be expected in connection with planting designs with $r_P = r_C - r_B$ (corresponding to those designs limiting tree water stress; Fig. 4). At this optimal permeable pavement width, the difference in terms of water requirements between micro-irrigation and traditional irrigation is maximized, in particular for more frequent rainfall events, with traditional irrigation requiring up to twice as much water as micro-irrigation (not shown). In fact, with more frequent rainfall events, it becomes more likely that an irrigation application is immediately followed by a rainfall event, the water input of which is then partially lost to runoff and deep percolation because of the relatively high soil moisture at the event time. Furthermore, infrequent but deep rainfall events may result in higher water requirements than less intermittent rainfall patterns, despite the lower intercepted fraction of water typical of the former rainfall pattern (Fig. 5b). Irrigation is often required during the inter-storm periods to sustain plant transpiration and, when rainfall occurs, saturation-excess may result in the loss of a significant fraction of the precipitated water. Finally, trees planted at high density (i.e., low $r_P + r_I$) will have higher average irrigation requirements than sparser trees, because in the former case the almost continuous canopy enhances rainfall interception and the precipitated water is split between adjacent trees. To facilitate soil water recharge and limit irrigation water requirements, permeable areas should be maximized at high tree density, while an intermediate $r_P = r_C - r_B$ should be sought for lower densities (Fig. 5c).

Required irrigation frequency for traditional irrigation determines its practical applicability in the urban context or whether a more sophisticated system is necessary. Irrigation frequency significantly increases with T_{max}, regardless of planting geometry (Fig. 6 a) and,

635 for a set T_{max}, the minimum frequency occurs at $r_P = r_C - r_B$. For altered rainfall patterns

636 the main determinant of irrigation frequency is the extension of the permeable area, with

637 extremely high irrigation frequencies for very low r_P (i.e., extremely small effective rooting

638 volumes that cannot efficiently buffer plant water uptake). Conversely, at higher r_P, re-

639 quired irrigation frequency is less sensitive to changes in rainfall frequency and extension of

640 permeable pavement (Fig. 6b).

D. Strategies for species selection and planting design

642 As apparent from the above results, the choice of tree species, size, and planting design

643 requires considering several contrasting needs, the relevance of each one depending on the

644 specific location. On the one hand, it is necessary to consider the provisioning of ecosystem

645 services by the street tress, and how they are altered by growing conditions: average transpi-

646 ration per tree provides a measure of the ability to providing a cooling effect, while dynamic

647 water stress provides an indication regarding the tree aesthetic quality and health. On the

648 other hand, for those species, planting designs, and climatic conditions where irrigation is

649 necessary to preserve adequate ecosystem service provisions, irrigation requirements needs

650 appropriate consideration.

651 To illustrate the usage of the proposed decision tool, we focus on the effect of permeable

652 pavement dimensions on two trees, with 60 and 100 kg d^{-1} tree^{-1} water requirements (solid

653 and dot-dashed gray lines respectively in Figs. 4a,d, 5a, and 6a). Under rainfed conditions,

654 the less water demanding tree has an effective cooling capacity of 83% of its potential for

655 $r_P = 1.8$ m, and at least 70% for other permeable pavement dimensions. Similarly, the

656 dynamic water stress is lowest at such optimal r_P ($\overline{\theta} = 0.2$). Conversely, for the more

657 demanding (and larger) tree, maximum cooling is 54% of potential, at $r_P = 2.4$ m. Smaller

658 permeable pavement areas may reduce the cooling ability to 40% of potential, with dynamic

659 water stress levels reaching 0.55. While in most species a certain level of dynamic water

660 stress may not significantly limit aesthetic quality and longevity, it is not possible to provide

661 a general threshold above which such ecosystem services can no longer be provided. In fact,

662 the effects of medium-to-high dynamic stress on tree status strongly depend on the species-

663 specific response to water limitation. Some species may loose their leaves in response to

664 extended periods of water stress, other may sustain damages if exposed to frequent stress

665 episodes. Hence, in most cases, the definition of the conditions under which a supplemental

666 irrigation should be implemented to preserve ecosystem services beyond cooling capacity

667 will require the evaluation of species specific response to water stress indicators, ranging

668 from the dynamic water stress, $\overline{\theta}$, to the length of periods of water stress, $\overline{T}^{\downarrow}(s^*)$ and their

669 frequency, $\nu^{\downarrow}(s^*)$. While clearly extremely relevant for planning, information on the species-

670 specific response to water stress tends to be difficult to access for urban planners, as recently

671 discussed for the case of Scandinavia by Sjömen and Nielsen (2010).

672   When irrigation is necessary to preserve tree ecosystem services, the proposed model

673 can provide quantitative information on irrigation requirements, as a function of tree water

674 needs (Figs. 5 and 6). To assess irrigation feasibility, consideration needs to be given to

675 required volumes and irrigation frequency. Maximum acceptable volumes depend on total

676 water allocation and number of trees to be watered. For the cases under scrutiny, the most

677 demanding tree would require between 6 and 8 m^3 per season, depending on planting geome-

678 try (Fig. 5a), a figure that might not be acceptable under water shortage or when concerning

679 a high number of plants. Furthermore, the previous results provide a quantitative basis to

680 assess under which circumstances traditional irrigation is a feasible option or the more so-

681 phisticated micro-irrigation may be needed. As discussed in Vico and Porporato (2011b),

682 regardless of existing conditions, micro-irrigation has lower water requirements (not shown),

683 thanks to its higher efficiency. The water savings associated to micro-irrigation may trans-

684 late in an economic advantage when water has high costs. Nevertheless, micro-irrigation has

685 high installation and maintenance costs, in particular in urban settings where damages may

686 occur because of vandalism and pedestrian traffic. Traditional irrigation applied through

687 replenishment of tree bags or with direct irrigation with hose has low investment costs, but

688 high application costs, associated to labor costs (and higher water expenses, when the cost of

689 water is significant). Because of the relatively low required application frequency (Fig. 6a),

690 traditional irrigation is likely to remain the most economically viable option in most cases.

691 The only exceptions are trees with very high water demands or growing in locations with ex-

692 tremely low rainfall inputs, when the installation and maintenance costs of micro-irrigation

693 are lower than the costs associated to high frequency applications of traditional irrigation,

694 thus making the more sophisticated system advantageous also under the economic point of

695 view. Aside from the water conservation and economic questions, other aspects may play a

696 role in the choice of the most appropriate management strategies. In particular, in the ab-

₆₉₇ sence of occasional deep rainfall events, micro-irrigation may be responsible for salt build-up ₆₉₈ in the soil, especially when using saline water for irrigation or in areas with winter de-icing ₆₉₉ compound applications. Also, there are some indications that irrigation may result in the ₇₀₀ development of shallower root systems (Bijoor *et al.*, 2012), with possible implications for ₇₀₁ tree stability and susceptibility to droughts. Finally, for long term planning, our framework ₇₀₂ can easily account for tree growth, which will be reflected on total tree water requirements, ₇₀₃ and can explicitly include changes in the rainfall pattern due to climate change scenarios, ₇₀₄ such as those investigated in Figs. 5b,e 5b, and 6b.

₇₀₅ **IV. CONCLUSIONS**

₇₀₆   A minimalist description of the soil water balance for urban trees was proposed, explicitly ₇₀₇ including rainfall unpredictability within a probabilistic framework, while still only requiring ₇₀₈ few, physically-based parameters characterizing rainfall pattern and vegetation response to ₇₀₉ water availability. The proposed model allows us to quantify the effect of species selection, ₇₁₀ tree size, and planting design on total average seasonal transpiration (and thus effective ₇₁₁ cooling capacity), tree water status (and thus health and aesthetic quality), and irrigation ₇₁₂ requirements. Hence, this minimalist description represents a first necessary step towards ₇₁₃ the definition of site-specific guidelines for species selection and planting design, to limit ₇₁₄ city water footprint while preserving street tree ability to provide ecosystem services. The ₇₁₅ planting design that maximizes cooling capacity while minimizing water stress occurrence ₇₁₆ and irrigation requirements may be achieved by bare soil and permeable pavement with ₇₁₇ combined area equal to the canopy extension. Because of the complex balance between root ₇₁₈ lateral extension and efficient soil water recharge by precipitated water, denser trees benefit ₇₁₉ more from permeable than impervious surfaces, while isolated trees benefit the most from ₇₂₀ intermediate permeable area extensions. When irrigation becomes necessary to maintain ₇₂₁ the desired ecosystem services, small permeable areas and trees planted at high density ₇₂₂ require higher irrigation input to maintain low water stress than a more balanced design. ₇₂₃ Because of its higher efficiency, micro-irrigation has lower total water requirements, and ₇₂₄ may be an adequate irrigation strategy for low permeable area extensions when the high ₇₂₅ required frequency of traditional irrigation may be unpractical and water savings by micro- ₇₂₆ irrigation are the highest. Intermediate rainfall frequencies and event depths allow the

727 minimization of water stress occurrence and severity, and irrigation requirements. Shifts

728 from this rainfall regime, particularly towards deeper but less frequent rainfall events, have

729 negative repercussions for tree cooling capacity and water stress, and enhance irrigation

730 requirements, especially for trees surrounded by wide permeable areas. This is true also for

731 trees with optimal or larger permeable pavements, even though the situation remains more

732 positive than for narrow permeable zones. The results presented here can provide helpful

733 indications for the definition of guidelines towards a sustainable design of urban vegetation

734 under current and future climate scenarios. The predictive power of the proposed model

735 would be greatly enhanced by a wider availability of data on plant water requirements under

736 urban-specific growing conditions.

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Figure 1 a) Examples of street trees planting design, including the usage of a tree bag for irrigation purposes, and b) schematic representation of the geometry of the problem for the circular symmetric case. (Photo credits: S. Manzoni, A. Porporato, G. Vico)

Figure 2 a) Geometry of the problem and b) average volumetric rainfall input $\overline{R}$ for varying permeable radial extensions r_P with fixed and decreasing tree density (black and gray lines respectively). Panel a) depicts lateral root extension r_R (solid line), radial extension beyond the rooting zone r_{nR} (dotted line), radial extension of the permeable and impervious pavements, r_P and r_I (dot-dashed and dashed lines respectively).

Figure 3 Examples of numerically generated soil moisture time series (a) in absence of irrigation and (c) in presence of micro- and traditional-irrigation, and corresponding probability density functions of soil moisture (b,d). In (a,b) r_P increases from 0 (absence of permeable pavement; solid line) to 2 m (dashed line), to 4 m (dotted line), while $r_I = r_T - (r_P + r_B)$ decreases accordingly. In (c,d) solid line refer to micro-irrigation, dashed line to traditional irrigation (in both cases $r_P = 2$ m). Other parameters are $Z_R = 0.5$ m, $n = 0.43$, $T_{max} = 70$ kg d^{-1} tree^{-1}, $s^* = 0.28$, $s_1 = 0.62$, $\alpha = 12$ mm, $\lambda = 0.2$ d^{-1}, $\Delta = 3$ mm, $\kappa_C = 0.6$, $r_B = 1$ m, $r_T = 7.5$ m, $\eta_P = 0.45$, $\eta_I = 0.1$. In c,d), the irrigation parameters are $\tilde{s} = 0.75s^*$ and $\hat{s} = 0.8s_1$; the atom of probability (solid bar in d) is not to scale.

Figure 4 a-c) Dependence of tree effective cooling capacity with respect to potential, $\langle T \rangle / T_{max}$, and (d-f) dynamic water stress $\overline{\theta}$ (bottom) on planting geometry, species selection, and rainfall pattern: a, d) effect of permeable pavement dimension r_P and tree transpiration requirements T_{max} (r_C varies along with T_{max} from 2.5 to 3.8 m as $r_C = 0.73 T_{max}^{\frac{1}{3}}$, where the constant is chosen so that $T_{max} = 70$ kg d^{-1} tree^{-1} for a $r_C = 3$ m canopy); b, e) effect of r_P and rainfall frequency and depth, with constant total rainfall over the growing season $R_{tot} = 341$ mm (i.e., $\alpha = R_{tot}(T_{seas}\lambda)^{-1}$ decreases from 48 to 5 mm as λ increases); and c, f) effect of tree density and extension of permeable and impervious pavement (r_P and r_I respectively). The growing season length is assumed to be $T_{seas} = 142$ d. For the definition of dynamic stress, $q = 1$, $k = 1$. All the other non-varying parameters are as in Fig. 3. In (a,d), the thick dashed line represent the permeable pavement extension such that $r_P + r_B = r_C$, while the gray horizontal lines represent the low and high water demanding trees discussed in III.D (solid and dotdashed lines repectively). In (c,f), the thick dashed line indicate the parameter combinations for which $r_T = 7.5$ m (i.e., the case explored in the other panels).

Figure 5 Seasonal water requirements V_t for traditional irrigation as a function of a) permeable pavement dimension r_P and tree transpiration requirements T_{max}, b) r_P and rainfall frequency and depth (with constant $R_{tot} = 341$ mm), and c) extension of permeable and impervious pavement, r_P and r_I respectively. In a), the thick dashed line represenst the permeable pavement extension such that $r_P + r_B = r_C$, while the gray horizontal lines represent the low and high water demanding trees discussed in III.D (solid and dotdashed lines repectively). In c), the dashed line corresponds to $r_T = 7.5$ m (i.e., to the case explored in the other panels). All the other non-varying parameters are as in Fig. 4.

Figure 6 Required application frequency $\nu^{\downarrow}(\tilde{s})$ for traditional irrigation as a function of a) permeable pavement lateral extension r_P and tree transpiration requirements T_{max} and b) r_P and rainfall frequency λ (with constant $R_{tot} = 341$ mm and variable α). In a), the thick dashed line represent the permeable pavement extension such that $r_P + r_B = r_C$, while the gray horizontal lines represent the low and high water demanding trees discussed in III.D (solid and dotdashed lines repectively). All the other non-varying parameters are as in Fig. 4.

Table I Main tree parameters for several species belonging to the most common genera in North American cities (as shown by data presented by Raupp et al. (2006) and McPherson and Rowntree (1989)); additional data mainly on transpiration for less common species can be found in Bush et al. (2008); Chen et al. (2011); Hilaire et al. (2008); Litvak et al. (2011); McCarthy and Pataki (2010))

Species	City (location)†	T_{max} (kg d⁻¹ tree⁻¹)	A_C (m²)	DBH (cm)	Ref
Acer campestre L.[a]	Brno, Czech Rep. (S)	64.6	29.8	22.4	Čermák et al. (2000)
Acer campestre L.[b]	Brno, Czech Rep. (S)	140.7	58.9	40.3	Čermák et al. (2000)
Fraxinus pennsylvanica	Lincoln, NE (LP)	49.4[c]	17.5 ± 1.36	15.3 ± 0.49	Cregg (1995)
Fraxinus pennsylvanica	Lincoln, NE (SP)	40.8[c]	18.4 ± 1.24	13.5 ± 0.48	Cregg (1995)
Fraxinus pennsylvanica	Lincoln, NE, Campus (P)	70.1[c]	22.4 ± 4.14	17.4 ± 1.63	Cregg (1995)
Fraxinus pennsylvanica	Saint Paul (P)	69.1 ± 25.8	75.9 ± 11.14	38.6 ± 11.4	Peters et al. (2010)
Fraxinus pennsylvanica	CTC Minneapolis, MN (P)	92.5 ± 34.5	101.6 ± 59.8	41.1 ± 2.0	Peters et al. (2010)
Gleditsia tricanthos[d]	Los Angeles Arboretum, CA (P)	89.9 ± 23.6	-	45.2± 5.5	Pataki et al. (2011b)
Quercus rubra	CTC Minneapolis, MN (P)	-	85.1 ± 30.1	42.9 ± 7.7	Peters et al. (2010)
Ulmus parvifolia[d]	Los Angeles Police Ac., CA (P)	67.7 ± 15.8	-	28.9± 2.5	Pataki et al. (2011b)
Ulmus pumila	Lauderdale Saint Paul, MN (P)	107.1 ± 38.1	90.8 ± 70.6	50.8± 12.6	Peters et al. (2010)
Ulmus thomasii	Saint Paul, MN (P)	80.4 ± 28.6	68.1 ± 36.3	44.4± 7.0	Peters et al. (2010)

†Location is P for parks and other extensively green areas, S for trees growing along streets or isolated in parking lots, LP or SP for large or small planter respectively. [a]Shaded tree with nearby sidewalk, with r_R=3.6 m; [b]Exposed tree with garden, with r_R=5.3 m; [c]Originally expressed in mmol m⁻² s⁻¹ and transformed in kg d⁻¹ tree⁻¹ assuming a 12-hr day and a leaf area index of 4 (in agreement with Cregg (1995)); [d]Irrigated
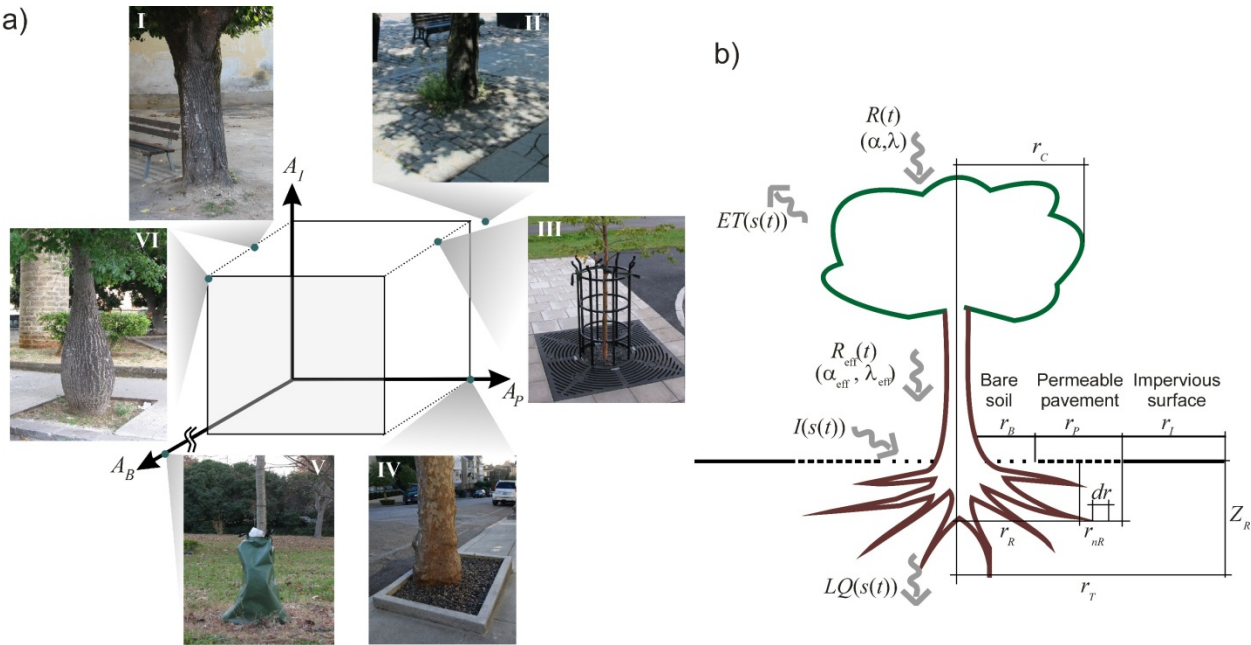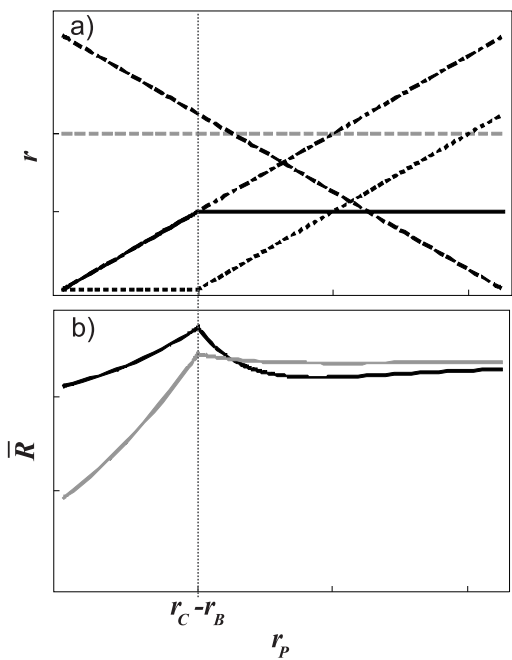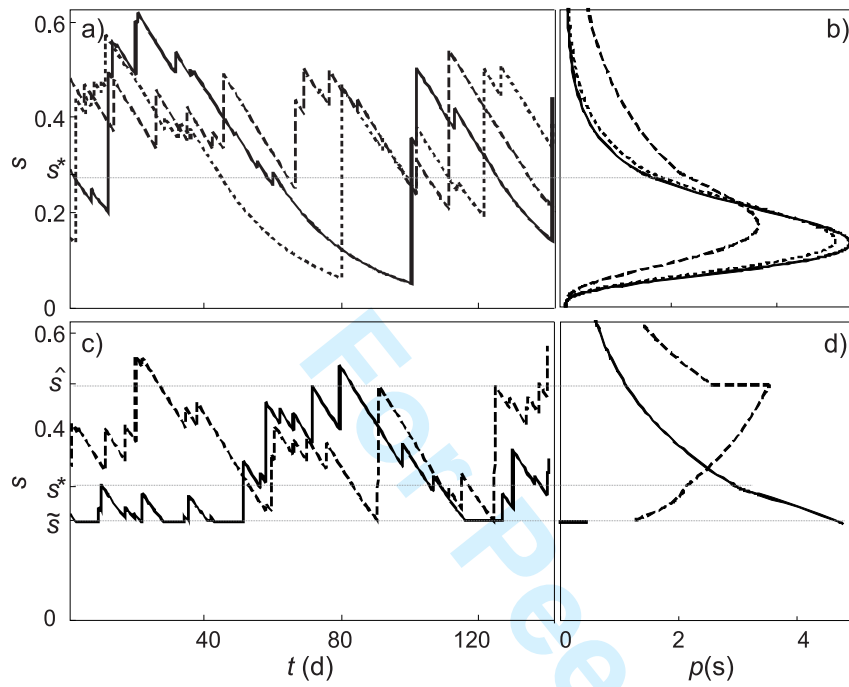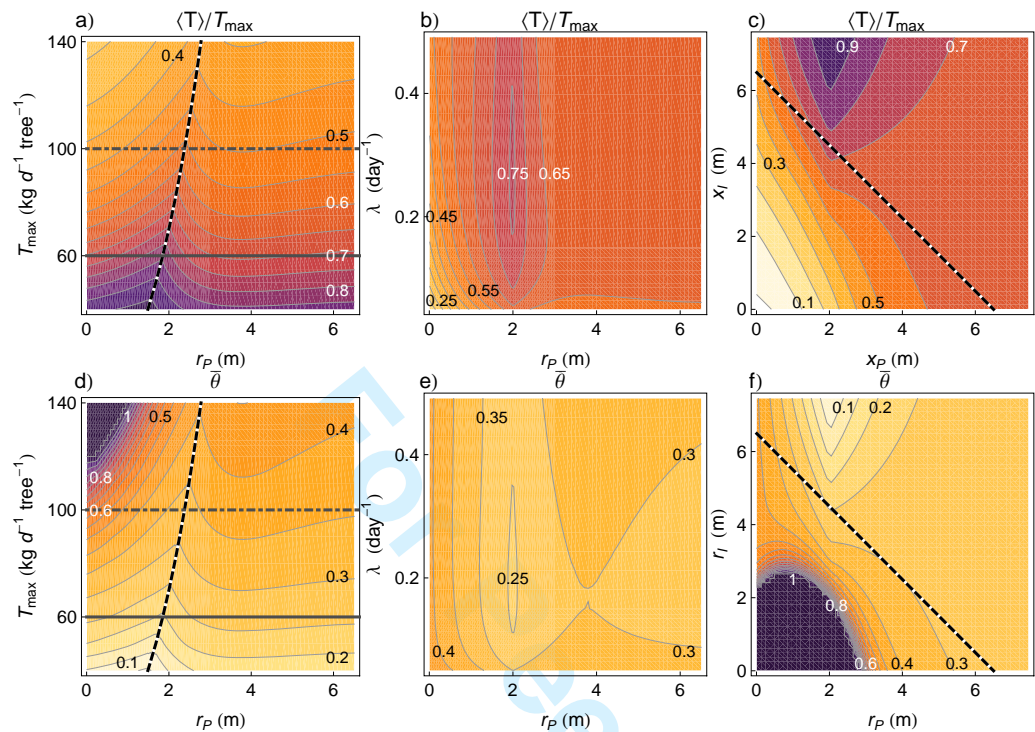
Figure 1

a)

b)

Figure 2

Figure3

Figure 4

Figure 5

Figure 6