DEVELOPMENT OF A FRAMEWORK FOR MODELLING STAND EVAPOTRANSPIRATION AT A LOCAL SCALE IN A COASTAL MEDITERRANEAN FOREST UNDER CLIMATE CHANGE

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Abstract: This work presents a novel approach for local-scale quantification of stand plant transpiration. The methodology integrates leaf-scale gas exchange, meteorological, and soil water content data with satellite data to upscale results to the stand-scale. Field data enables the calibration of a photosynthesis biochemical model, comprising three modules simulating species-specific net assimilation rates, stomatal conductance, and evapotranspiration rates (ET). ET values, calculated per species, calibrate a forest stand evapotranspiration (ETA) model based on NDVI. ET and ETA, along with other forest system fluxes, compute the forest water balance as soil water content (SWC). Both models effectively simulate SWC ($R^2_{species} = 0.98$, $R^2_{satellite} = 0.96$). Transpiration values and other water balance components are estimated using climate change scenarios (SSP 2.6 and SSP 8.5). Simulated stand evapotranspiration for 2022 is 1387.73 mm, while for SSP 2.6 and SSP 8.5 are 1216.49 mm and 1293.47 mm, respectively.

Keywords: Mediterranean ecosystem, ecological modelling, evapotranspiration, forest water balance, climate change.

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Introduction

This work introduces the critical role of evapotranspiration (ET) in ecosystem water cycling, particularly in arid and semi-arid Mediterranean environments. ET includes evaporation from soil and plant transpiration, and it is influenced by climate, water availability, and vegetation [21]. It significantly impacts the land-surface water and energy budget [18], and influences aquifer recharge in the Mediterranean region [6, 13, 20]. Estimating ET is challenging due to the heterogeneity in physical and physiological properties underlying plant water uptake and ecosystem water use [23, 27]. Various methods, including field observations and modelling approaches [7, 30], have been developed to quantify stand-scale transpiration [36]. However, the reliability of these models is constrained by appropriate parameterization and identification of dominant factors affecting forest transpiration [35]. Hydrological constraints have driven genetic and morphological adaptations within Mediterranean flora [32]. Predictions indicate that Mediterranean regions will experience severe or extended periods of drought, potentially causing shifts in species composition and forest coverage [33]. These alterations could promote drought-tolerant functional strategies [15], influencing environmental services rendered by forests, particularly those associated with the hydrological cycle. Evaluating ET across natural vegetation within the Mediterranean region is crucial for monitoring water stress and formulating sustainable restoration management policies [3, 4]. This study provides a replicable methodology for any ecological context, particularly those of reduced extensions, facilitating the development of strategies for monitoring and managing small forest areas. Local scale studies are essential for expanding our understanding of the relationships between vegetation composition, climate, ET, and water balance [21].

Materials and methods

Study area

The study was conducted in the "Bosco di Palo Laziale", located in the territory of Ladispoli (Rome, Lazio Region). This is a forested area of approximately 50 hectares, situated 230 meters from the sea, with an altitude ranging between 3 and 10 meters above sea level. It is a very dense Mediterranean forest composed of a declining oak grove and a high maquis. Between 2000 and 2003, about four thousand individuals (about 20 hectares), mainly of the Quercus genus, died due to stress from intense summer aridity and the spread of the fungus *Biscougnaxia mediterranea* [29]. According to the bioclimatic characteristics of the area, the site is characterized by a Mediterranean climate with precipitation concentrated in winter and autumn and aridity during the summer. The soil is of the clay-loam type composed of 45 % silt, 34 % clay and 21 % sand.

Climatic data

In situ climatic data were provided by the meteorological station "LADISPOLI - Palo Laziale", part of the monitoring network managed by the Integrated

Agrometeorological Service of the Lazio Region (SIARL) (https://www.siarl-lazio.it/). Climatic parameters recorded by the meteorological station are average daily temperature (T_{avg}, °C), maximum and minimum daily temperature (T_{max}, T_{min}, °C), average daytime and nighttime temperature (T_{day}, T_{night}, °C), daily rainfall (Prec, mmd^{-1}), daily potential evapotranspiration (Et_0, mmd^{-1}), daily relative humidity (RH, %), daily total and photosynthetically active radiation (RAD, PAR, MJm^{-2}) and atmospheric pressure (P_{atm}, hPa).

Gas exchange measurements

Gas exchange measurements and micrometeorological data were recorded using a portable infrared gas exchange analyser, Ciras-2 (Portable Photosynthesis System, © 2010 PP Systems) (https://ppsystems.com/). Main ecophysiological parameters measured by Ciras-2 were leaf temperature (Tl, °C), stomatal conductance (gs, $mmolH_2Om^{-2}s^{-1}$), transpiration rate (Et, $mmolH_2Om^{-2}s^{-1}$), and net photosynthesis rate (An, $\mu molCO_2m^{-2}s^{-1}$).

The measurements were carried out between March and October 2022 from 9 a.m. to 4 p.m. on the following species: *Phillyrea latifolia*, *Pistacia lentiscus*, *Quercus cerris* and *Fraxinus angustifolia sub. oxycarpa*, which together make up more than 70 % of the forest composition.

The sampling method includes "spot" measurements (single instantaneous measurements of the physiological parameters under environmental conditions) and the construction of photosynthesis response curves to CO_2 (from 400 ppm to 1000 ppm) at saturating PAR (1000 $\mu mol\ m^{-2}\ s^{-1}$) and constant temperature (25 °C), pressure (1020 mbar) and relative humidity (60 %).

Satellite data

The NDVI (Normalized Difference Vegetation Index) values were obtained from satellite imagery collections provided by the SENTINEL-2 mission. NDVI values with a resolution of 10 m/pixel were calculated, in Google Earth Engine environment (GEE, https://earthengine.google.com/), as the normalized difference of the near-infrared (NIR, 835.1÷833 nm) and red bands (Red, 664.5÷665 nm) (eq.1):

$$\mathrm{NDVI} = \frac{(\mathrm{NIR-Red})}{(\mathrm{NIR+Red})} \qquad 1$$

All available images for the period from January 2022 to December 2022 were used to extract the NDVI values. The images were processed to obtain a raster containing the median NDVI values per pixel for each month.

Framework: Bottom-Up and Top-Down Approach

The workflow involves integrating leaf-scale gas exchange measurements, meteorological and soil water content ground data (bottom-up approach) with satellite-derived data to up-scale results to stand-scale (top-down approach).

The field measurements allowed the calibration of a biochemical model of photosynthesis based on Farquhar and Von Cammer's ones [34], consisting of three interconnected modules designed to simulate net assimilation rates, stomatal conductance and transpiration rates. The species-specific stomatal control strategies were integrated in the model through the application of a constraint grounded in the theory of marginal carbon cost of water use [25]. According to this approach, optimal stomatal behaviour is achieved by maximizing carbon gain while minimizing water loss within a specific timeframe.

The species-specific ET values obtained from the biochemical model were used to calibrate the NDVI-based forest stand evapotranspiration (ETA) model [24].

The values of ET (evapotranspiration obtained from the biochemical model) and ETA (satellite-derived evapotranspiration) were alternately entered into equation 5, which allowed the quantification of soil water content. The accuracy of the output was assessed by comparing the simulated values with daily measured SWC data obtained from three soil probes placed at 30 cm of depth within the study area.

Subsequently, transpiration values (ET and ETA) and others water balance components were estimated by using precipitation and temperatures from the climate change scenarios (SSP 2.6 and SSP 8.5) as climate inputs.

Bottom-Up approach: Evapotranspiration leaf scale modelling

The species-specific stomatal conductance gs is obtained by eq.2:

$$\mathrm{gs(t)} = \mathrm{g_0} + 1.6\left(1 + \frac{(\mathrm{g_1} * \mathrm{fw})}{\sqrt{\mathrm{VPD}}}\right)\frac{\mathrm{An(t)}}{\mathrm{Cs}} \qquad 2$$

where VPD is the vapour pressure deficit, Cs is the atmospheric CO_2 concentration (410 ppm), An(t) is the net photosynthesis rates calculated using de Wit's [10], g0 ($molH_2Om^{-2}s^{-1}$) represents the residual stomatal conductance when the net assimilation rate reaches zero, while g1 ($Kpa^{0.5}$) is the sensitivity of the conductance to the assimilation rate [9, 25]. The values of g0 and g1 for each species are reported in the Table 1. The parameter fw applied to equation 2 represents the soil water stress factor as a function of the soil water content SWC ($m^3_{H_2O}m^{-3}_{soil}$), the wilting point Wp (0.194 $m^3_{H_2O}m^{-3}_{soil}$) and the field capacity Fc (0.322 $m^3_{H_2O}m^{-3}_{soil}$) [22].

Table 1 – Values of g_0 and g_1 for target species [22].

	Q. cerris	*F. angustifolia*	*P. latifolia*	*P. lentiscus*
g_0	0.030	0.019	0.046	0.018
g_1	2.06	1.91	2.12	2.06

The annual canopy transpiration ET (mmH_2Oy^{-1}) is calculated by integration over time of the instantaneous Et(t) (eq.3):

$$\mathrm{ET} = \sum_{1}^{365} \frac{(\lambda * \mathrm{gs(t)} * (\mathrm{VPD/Patm}))}{\lambda} * 3600 * \mathrm{photoperiod} \qquad 3$$

where λ is the latent heat of water vaporization (kJ mol^{-1}).

Top-Down approach: Evapotranspiration Forest scale modelling

For the computation of evapotranspiration (ETA, mmH_2Od^{-1}) from satellite data, the NDVI-CWS model [2, 24] has been modified by substituting the water stress factor (CWS) with fw (eq.2) [22].

ETA is given by eq.4:

$$\mathrm{ETA} = \mathrm{Et}_0 * \left[\mathrm{FVC} * \mathrm{Kc}_{\mathrm{Veg}} + (1 - \mathrm{FVC}) * \mathrm{Kc}_{\mathrm{Soil}}\right] * \mathrm{fw} \qquad 4$$

where Et_0 represents the potential evapotranspiration directly measured from the climate station, FVC denotes the fraction of vegetation cover, indicating the amount of leaf biomass transpiring in the pixel, obtained from the NDVI, 1-FVC corresponds to the portion of bare soil in the pixel subject to evaporation, Kc_{veg} and Kc_{soil} represent the vegetation and soil transpiration coefficients, respectively. Kc_{soil} is a constant value fixed at 0.2, while Kc_{veg} is calculated daily as the average of species-specific Kc_{veg} values obtained from the ratio of simulated evapotranspiration (Et, eq.3) to recorded potential evapotranspiration (Et_0) [1, 22].

Forest Water Balance

The equation of the water partition within the forest system, expressed as soil water content SWCi ($mmday^{-1}$), is determined by (eq.5):

$$\mathrm{SWC_i} = \mathrm{Prec} - (\mathrm{Int} + \mathrm{Inf} + \mathrm{Runoff} + \mathrm{ETA}) + \Delta \mathrm{SWC_{i-1}} \qquad 5$$

The soil water content component (SWC_i) depends on several factors: precipitation (Prec, $mmday^{-1}$), the amount of water intercepted and evaporated by the canopy surface (Int, $mmday^{-1}$), water that infiltrates the soil (Inf, $mmday^{-1}$), runoff (Runoff, mmd^{-1}) (given the absence of steep slopes leading to stagnant surface water), evapotranspiration (ETA, $mmday^{-1}$), and the change in soil water content from the previous day (SWC_{i-1}, $mmday^{-1}$). Int is function of the Leaf Area Index (LAI) and Kc_{veg}. Inf is determined by throughfall (Tf), saturation volume, and initial loss coefficient according to SCS-Curve number method [7]. Runoff is calculated by subtracting Int and Inf from rainfall. The final water balance is calculated using both bottom-up and top-down approaches for the calendar year and its quarters.

Climate Change Scenarios

To estimate the ET and ETA values and derived water forest balance under future climate change scenarios, data from the Coupled Model Intercomparison Project (CMIP6) were utilised. The study considered two Shared Socioeconomic Pathways (SSPs): SSP 8.5 and SSP 2.6 [19] for 2041-2070. To ensure a robust analysis, the averaged data from all available models was used. The standard deviation of the future climate change data was incorporated as a random factor in the predictive model for evapotranspiration-forest water balance.

The model was run several times for each of the two considered SSP scenarios. The results derived from these iterations were averaged, providing a comprehensive understanding of the potential impacts of future climate scenarios on forest water balance.

Results

Current ET and SWC simulations

The current evapotranspiration and the derived soil water content were calculated using the mass balance equation (eq.5). This allowed for the determination of the inflows and outflows that regulate the forest water balance at two different scales: species and forest canopy (Table 2, 3).

In 2022, the annual precipitation was 468.7 mm. The species-scale evapotranspiration (ETsp) and satellite-derived evapotranspiration (ETsat) were 1212.583 mm and 995.805 mm, respectively. The interception was 312.648 mm, leading to a throughfall of 155.952 mm. The runoff was 6.109 mm, resulting in an infiltration of 149.876 mm.

Table 2 – Inflow and Outflow values derived from bottom-up approach for annual and trimester period. Trim1(from Jan to Mar), Trim2 (from Apr to Jun), Trim3 (from Jul to Sept), Trim4 (from Oct to Dec).

	Prec	ETsp	Int	Tf	Run-off	Inf
2022	468.700	1212.583	312.648	155.952	6.109	149.876
Trim1	50.700	119.276	33.774	16.926	0.444	16.482
Trim2	31.000	405.615	21.062	9.938	0.057	9.881
Trim3	91.700	441.547	61.020	30.680	0.669	30.011
Trim4	295.300	246.144	196.792	98.408	4.939	93.503

Table 3 – Inflow and Outflow values derived from top-down approach for annual and trimester period. Trim1(from Jan to Mar), Trim2 (from Apr to Jun), Trim3 (from Jul to Sept), Trim4 (from Oct to Dec).

	Prec	ETsat	Int	Tf	Run-off	Inf
2022	468.700	995.805	312.648	155.952	6.109	149.876
Trim1	50.700	109.464	33.774	16.926	0.444	16.482
Trim2	31.000	365.303	21.062	9.938	0.057	9.881
Trim3	91.700	307.584	61.020	30.680	0.669	30.011
Trim4	295.300	213.453	196.792	98.408	4.939	93.503

Once the inflows and outflows from the forest system had been defined, it was possible to calculate the forest water balance, expressed as soil water content SWC (eq.5, Table 4) using the calculated evapotranspiration values.

The species-scale and stand-scale models simulated SWC values of 41225.01 mmy^{-1} and 41441.79 mmy^{-1}, respectively, closely aligning with the measured value of 42423.93 mmy^{-1} for 2022.

Table 4 – Evapotranspiration, measured SWC and simulated SWC_sp and SWC_sat values for annual and trimester period. Trim1(from Jan to Mar), Trim2 (from Apr to Jun), Trim3 (from Jul to Sept), Trim4 (from Oct to Dec).

	ET_sp	ET_sat	SWC	SWC_sp	SWC_sat
2022	1212.583	995.805	42423.929	41225.014	41441.792
Trim1	119.276	109.464	12627.000	12518.691	12528.502
Trim2	405.615	365.303	10199.100	9854.009	9894.321
Trim3	441.547	307.584	8177.700	7749.594	7883.558
Trim4	246.144	213.453	11288.100	11102.719	11135.411

Future ET and SWC estimation

By applying the SSP 2.6 and SSP 8.5 scenarios, it was possible to re-calculate the evapotranspiration and the associated inflows and outflows required for the quantification of the future forest water balance on a monthly scale (Table 5, 6).

In both scenarios, the total annual precipitation (757.6 mmy^{-1} for SSP-2.6 and 726.76 mmy^{-1} for SSP-8.5) is observed to be less than the total stand evapotranspiration (1216.496 mmy^{-1} for SSP-2.6 and 1293.347 mmy^{-1} for SPP-8.5).

Table 5 – Future Inflows and outflows values for SSP-2.6 scenario.

Months	Prec 2.6	ETsp 2.6	Int 2.6	Tf 2.6	Run-off 2.6	Inf 2.6	SWCsp 2.6
Jan	64.420	39.871	41.545	21.692	2.051	19.676	3938.619
Feb	61.380	45.433	39.191	20.369	1.821	18.608	4334.746
Mar	62.760	58.945	41.969	21.813	2.074	19.696	4085.448
Apr	66.800	85.711	43.435	22.551	2.214	20.261	4092.411
May	41.960	140.664	28.146	14.523	0.951	13.738	3827.107
Jun	26.780	166.742	17.761	9.178	0.389	8.824	3221.914
Jul	16.980	135.435	11.154	5.829	0.159	5.659	2646.540
Aug	19.900	138.307	13.073	6.817	0.217	6.567	2487.067
Sept	69.840	165.504	44.486	23.260	2.344	20.901	2407.236
Oct	112.820	138.125	74.585	38.941	6.206	33.273	2817.650
Nov	109.860	54.410	70.402	36.829	5.555	31.126	3194.757
Dec	104.100	47.350	68.999	36.049	5.348	30.503	3721.632
TOT	757.600	1216.496	494.744	257.851	29.330	228.833	40775.126

Table 6 – Future Inflows and outflows values for SSP-8.5 scenario.

Months	Prec 8.5	ETsp 8.5	Int 8.5	Tf 8.5	Run-off 8.5	Inf 8.5	SWCsp 8.5
Jan	63.360	41.929	41.986	21.820	2.075	19.738	3938.619
Feb	59.640	52.055	38.773	20.155	1.783	18.413	4334.746
Mar	54.060	67.484	35.828	18.627	1.539	17.171	4085.448
Apr	66.520	93.612	42.250	22.076	2.127	20.137	4092.411
May	41.700	146.342	27.381	14.143	0.902	13.202	3827.107
Jun	25.400	174.705	16.329	8.468	0.332	8.065	3221.914
Jul	16.520	139.311	10.969	5.751	0.155	5.606	2646.540
Aug	19.640	145.118	12.870	6.710	0.210	6.509	2487.067
Sept	61.460	178.009	41.707	21.838	2.080	19.697	2407.236
Oct	109.320	147.204	71.692	37.613	5.774	32.044	2817.650
Nov	109.980	58.150	71.577	37.582	5.760	31.751	3194.757
Dec	99.160	49.426	65.978	34.649	4.961	29.645	3721.632
TOT	726.760	1293.347	477.339	249.431	27.698	221.978	40706.783

Discussion

When ET and ETA are included in equation 5 and the other elements are kept constant, as they are independent of the physiological activity of the vegetation, the simulated values of soil water content (SWC_sat and SWC_sp) are close to those measured SWC (Table 4) (R^2species = 0.98, R^2 satellite = 0.96). This match allows us to indirectly state that the estimates of ET and ETA are realistic.

Both models demonstrated high ability in simulating soil water content (R^2species = 0.98, R^2 satellite = 0.96), further confirming the accurate estimation of evapotranspiration rates obtained through the application of biochemical and satellite models.

The water balance results (Table 4) indicate that evapotranspiration appears to consume most of the ecosystem water, while the contribution from infiltration and surface runoff is quantitatively negligible. These trends are consistent with those of semi-arid Mediterranean *Q.ilex* systems, where evapotranspiration is the main parameter driving the overall water balance, followed by interception by canopy and the contribution of groundwater cumulation that mainly occurs after extensive rainfall events [11, 14].

Local climate conditions, particularly during summer, are characterized by high temperatures and low or absent rainfall.

However, the level of soil water content never falls below the wilting point Wp (0. 194 $m^3_{H_2O}m^{-3}_{soil}$, equal to 58.2 mm), which is defined as the amount of water retained by the soil particles that is unavailable to the root's absorption.

Based on these considerations, is possible that there is another factor within the water balance that can compensate for the significant loss of water due to evapotranspiration.

Non-Rainfall Water Input, which includes dew and fog, are atmospheric water sources that play a significant role in the hydrological cycle and water supply of terrestrial ecosystems.

These phenomena can also occur in temperate climates where average annual amount of precipitation typically balances or exceeds evapotranspiration. Dew and fog are essential sources of water for plants in different areas, including (1) arid and semi-arid regions [16]; (2) Mediterranean coastal regions [5, 31]; (3) temperate ecosystems [17]; and (4) tropical climates [8, 12]. Dew and fog are produced in the lower part of the night-time stratified atmospheric boundary layer [26].

These condensation processes occur due to the radiative cooling of the Earth's surface after sunset, which results in long-wave radiation losses during clear nights [28]. This radiative cooling leads to a decrease in surface temperature below the dew point of the adjacent air, allowing dew to form on plant surfaces and fog to form on aerosol particles activated in the atmosphere near the surface.

Coastal regions and areas near oceans are typically more conducive to dew and fog formation. As the study area is a coastal region, it has a high relative humidity of around 80 %. It also experiences significant temperature fluctuations between day and night, particularly during the dry summer season. The forest structure, characterized by the dense coexistence of scrub shrub species and tree species, can create particular sub-canopy and internal microclimatic conditions. These conditions can promote the condensation phenomena, thereby contributing to the forest’s water balance as an additional source of water input.

Conclusion

A reliable estimate of the evapotranspiration values of forest stands provides insight into the interaction between various biotic and abiotic factors such as precipitation, evapotranspiration, vegetation structure and soil properties.

Vegetation exerts a role in the distribution of precipitation through its structural composition by controlling the amount of water that manages to infiltrate the soil and by drawing on the soil's water content for transpiration processes based on its physiological capacity to manage the water resource. The possibility of analysing these phenomena can provide details about how specific vegetation composition may influence the local water balance under current climatic conditions and based on expected future climate changes. The implemented multi-scale forest stand evapotranspiration and water balance models provide a valuable tool for estimating various hydrological parameters under current and future climatic conditions.

The proposed framework is particularly useful in providing guidance for the management of small, protected areas, such as the one under consideration, in which the possibility of access accurate information about the processes locally in place is an essential aspect for the success of intervention actions.

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