Regional patterns and drivers of water flows along environmental, functional and stand structure gradients in Spanish forests.

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Abstract

The study of the water cycle in the forest at large scales, such as countries, is challenging due to the difficulty of correctly estimating forest water flows. Hydrological models can be coupled to extensive

10 forest data sources, such as national forest inventories, to estimate the water flow of forests over large extents, but so far the studies conducted have not analysed in detail the role of stand structure variables or the functional traits of the forest on predicted blue/green water flows. In this study, we modelled the water balance of Spanish forests using stand structure and species data from forest inventories to understand the effects of climate, stand structure, and functional groups on blue water flows. We

15 conducted model simulations across a gradient of different climatic biomes and predominant functional trait species. We calculated both the blue water (surface runoff and drainage to groundwater) and green water (evapotranspiration). Our analysis focused on relative blue water, the ratio between blue water and total precipitation. Climatic, stand structure, and topographic variables were used to interpret the determinants of variation of relative blue water. The results showed that higher relative blue water is

20 mainly concentrated in the wetter regions of Spain and during the autumn-winter season. Leaf Area Index (LAI) of the forest stand is the most important predictor of relative blue water, exhibiting a

negative effect until it reaches a plateau at higher levels. Deciduous forests showed a greater relative

blue water content than evergreen functional groups, primarily due to leaf fall during the autumn-winter

season. This study highlights the significant importance in a Mediterranean region of seasonal

25   distribution in water flow and how seasonal LAI can act as a crucial filter for ex[=] water.

1. Introduction

Forests are one of the most important ecosystems on the planet and constitute a supplier of carbon

and water for the humanity (MEA, 2005). Although many studies have been done on the carbon pools

30   and cycle in forests (Gower, 2003; Pregitzer and Euskirchen, 2004), the water cycle is more complex to

study, even though water is the main determinant of vegetation worldwide (Begon and Townsend,

2021). The water cycle in forests depends on the precipitation that falls in the forest, which can be

partitioned in two main flows, the green water and the blue water (Caldwell et al., 2016; Schlesinger

and Jasechko, 2014). On the one [=] l, the green water is the evapotranspiration flow from the forest to

35   the atmosphere, formed by the water transpired by plants, together with the evaporation of intercepted

precipitation by vegetation and the evaporation from the soil sur[=] Climate, specific traits, stand

forest structure, and their interactions determine the partitioning of precipitation between green water

and blue water. Evapotranspiration in trees is determined by local climate conditions, such as air

temperature, radiation, vapour pressure deficit or soil water availability (Granier et al., 2000).

40   Moreover, the transpiration is different among species depending on their specific traits, as leaf area,

xylem traits determining the efficiency of water transport or leaf phenology (evergreen and deciduous)

(Ford et al., 2011). Stand forest structure can also increase the evapotranspiration when the canopy tree

or shrub density (LAI) is high through the transpiration (Granier et al., 2000) and/or the interception of

vegetation. On the other hand, blue water can be split into two flows: the surface runoff and the surplus

45   of groundwater by the system and available downstream. Green water reduces the amount of blue water

produced at local scale but recycles the water through the evapotranspiration at global scale (Ellison et

al., 2012). Green water amount is usually greater than blue water's in forests and grasslands in

comparison with croplands or wetlands due to the greater transpiration of the former (Oki and Kanae,

2006). Green water represents around 40-70 % of water flow in temperate and boreal forests (Jasechko

50   et al., 2013), and even 90-100 % in dryer environments, including Mediterranean forests (Ungar et al.,

2013). The combination of different rainfall dynamics, transpiration, stand structure, and specific life

traits can modify the trade-off between green and blue water. For instance, water yield can be affected

by the temporal distribution of rainfall events (seasonality and torrentiality). Relative water interception

by trees decreases when rainfall increases, being greater in arid environments compared to humid

55   forests (Levia and Frost, 2003). In Mediterranean forests the interception is greater than in temperate

forests due to the smaller rainfall amount and intensity and the higher evaporation caused by the higher

temperature (Limousin et al., 2008). However, evaporation of intercepted water is lower during late-

summer intense convective storms since the rainfall intensity is very high and of short time

(torrentiality) (Llorens and Domingo, 2007). Physiological and phenological differences among species

60   also modulate water flows. Evergreen Mediterranean trees can reduce their transpiration in summer

(isohydric behavior) but deciduous trees increase it due to higher water demand (anisohydric behavior)

(Baquedano and Castillo, 2006; Klein, 2014; Link et al., 2014; McDowell et al., 2008). Therefore,

Mediterranean forests show transpiration seasonality, with a reduction in stomatal conductance during

the summer drought, while the transpiration in temperate forests follows leaf phenology more closely

65 (Llorens et al., 2011). Finally, evergreen trees can intercept water along the year while deciduous trees

intercept less water when they lose their leaves.

Water balance in forests has been studied mainly at local and landscape scales, like in watersheds

(Caldwell et al., 2016; Guzha et al., 2018; Schwärzel et al., 2020) or forest stands (Benyon et al., 2017;

Simonin et al., 2007). Analyses at regional scales have also been carried out (Hoek van Dijke et al.,

70 2022; Mastrotheodoros et al., 2020; Sun et al., 2005), analysing the water flow variation by topoclimate

or landscape vegetation cover with hydrological models. Nevertheless, due to their scale of analysis,

those studies have not examined the role of stand structure or forest species traits. Therefore, there is a

lack of studies at regional scales analysing the spatial distribution of blue and green water and how their

trade-off is affected by stand structure and species composition. The study of water fluxes in forest

75 ecosystems is an important challenge to forest management. Ecohydrological simulations have been

shown as a valuable tool to understand water fluxes at bigger scales than only with field data (Hoek van

Dijke et al., 2022; Mastrotheodoros et al., 2020). In our study, we analysed the spatial pattern and trade-

off of blue and green water in Spain using ecohydrological simulations with the MEDFATE water

balance model (De Cáceres et al., 2023, 2015) using detailed field stand structure and species

80 composition derived from forest inventory data. We simulated water flows and their green and blue

water components at daily resolution, and we studied the spatial distribution of relative blue water and

its monthly distribution. Spain is an adequate region to study the trade-off between blue and green

water, because it shows contrasting climate gradients, in terms of temperature, rainfall amount and

seasonal distribution. Importantly, it includes a contrasted climate between the Mediterranean area —

85 with hot temperature, low precipitation and seasonal drought— and the temperate area —with warm

temperature, higher rainfall amount and without seasonal drought (Rivas-Martínez et al., 2011). In

addition, peninsular Spain harbours both temperate and Mediterranean forests that span a broad gradient

of forest types and stand structures that can modify the trade-off between blue and green water. The

questions addressed by the study are: 1) Which are the spatio-temporal patterns of the trade-off between

90 blue and green water along the Spanish Peninsula and among climate subregions? 2) How this trade-off

between blue and green water varies among contrasting forest functional groups? 3) Which are the main

climatic and forest structural drivers of this trade-off between blue and green water?

2. Material and Methods

2.1 Study area

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The studied area spans the forested areas of Spain, including the Iberian Peninsula and the

Balearic Islands, but excluding the Canary Islands. This encompasses two climatic domains: the

temperate climate with Atlantic Sea influence, in the north and west parts of the Iberian Peninsula, and

the Mediterranean climate, in the rest of the territory. The temperate climate is wetter and colder (mean

100 temperature of 12.7 ℃ and annual precipitation of 1,500 mm), while the Mediterranean climate is hotter

and drier (mean temperature of 15.3 ℃ and annual precipitation of 650 mm). We have classified the

Iberian territory into six biomes (see map in Figure A1) according to the Iberian climate classification

of (Allué Andrade et al., 1990): (i) Arid (9.0 % of the Spanish surface), with warm winters and

summers and very low precipitation (< 400 mm); (ii) Temperate Mediterranean (34.8 %), hot in winter

105 and summer with low precipitation (< 600 mm); (iii) Continental Mediterranean (30.9 %), cold in

winter and hot in summer with low precipitation (< 600 mm); (iv) Submediterranean (11.0 %); cold in

winter and hot in summer with wetter precipitation (about 800 mm); (v) Atlantic (10.5 %), characterized

by a mild winter and summer and high precipitation (> 1000 mm); and (vi) Alpine (3.8 %), very cold in

winter and cool in summer and high precipitation (> 1000 mm).

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2.2. Forest inventory data

We used the permanent fields plots from the Spanish national forest inventories to characterize the

predominant species and stand structure variables across the study area. The Spanish national forest

inventories (SFI) are distributed with a systematic survey along the forested areas with a density of

115   ~1 plot/sq km. Specifically, we used the third inventory (SFI3) carried out in 1997-2008, which is the

most recent and complete survey available to date. Spanish permanent field plots have four concentric

circular sub-plots with radii of 5, 10, 15 and 25 m. Trees were identified and measured within variable

circular size plots (5 m radius for trees with dbh $\geq$ 7.5 cm, and trees with $2.5 \leq$ dbh ≤ 7.5 cm are

counted; 10 m radius for trees with dbh $\geq$ 12.5 cm; 15 m radius for trees with dbh $\geq$ 22.5 cm; and 25 m

120   radius for trees with dbh $\geq$ 42.5 cm). Moreover, the shrub species or genus within the 10-m-radius

subplot were measured with their corresponding percent cover values.

We focused on the field plots with > 70 % of plot basal area of the most predominant tree native

species (Table A1) and an overall basal area of > 3 sq m/ha (to ensure that very sparse woodlands,

which can hardly be considered a forest, were excluded), resulting in a total number of plots of 32,514.

125   Plots were classified according to the dominant species in terms of basal area, into five functional

groups: temperate (e.g., *Fagus sylvatica*) and Mediterranean deciduous (e.g., *Quercus pyrenaica*),

temperate (e.g., *Pinus sylvestris*) and Mediterranean coniferous (e.g., *Pinus pinea*) and sclerophylls (e.g., *Quercus ilex*) (see Table A1 for the classification of the tree species in these five groups).

130 2.3. Environmental variables

We downloaded the daily data of total precipitation and maximum, mean and minimum temperature for the 5 years before and after the date of survey for every plot (that is, 10 years per plot) from E-OBS data with WorldClim information at 1 km horizontal resolution (Moreno and Hasenauer, 2016); ftp://palantir.boku.ac.at/Public/ClimateData). Topographic variables of slope, aspect and altitude

135 were derived from a digital elevation model (DEM) at 25 sq m of the PNOA Spanish project through the IGN website (downloaded on 14/02/2022). We used these topographic variables to obtain daily values of the relative humidity, solar radiation and potential evapotranspiration (PET) per plot through the *meteoland* R package (De Cáceres et al., 2018). We characterized plot-level climatic conditions using three climatic indexes; moisture (mean annual precipitation/mean annual PET), continentality

140 (mean temperature of the hottest month - mean temperature of the coldest month) and seasonality ((standard deviation of monthly precipitation/mean of monthly precipitation) * 100).

A summary of the main stand structure and climate characteristic of the different functional groups and biomes is shown in Table A2.

2.4. MEDFATE model

145 MEDFATE model (version 2.9.3) has been designed to simulate plant water balances and soil in structurally- and compositionally-heterogeneous forest stands (De Cáceres et al. 2015; De Cáceres et

al., 2023). MEDFATE uses daily weather as input and most processes are simulated at daily time steps. Aboveground stand structure is represented in terms of total crown ratio (CR), height (H) and leaf area index (LAI) of a set of woody plant cohorts. The soil is represented by vertical layers having different

150 hydraulic properties and each cohort may have a different root distribution, specified using the depth corresponding to cumulative 50 % and 95 % of fine roots (Z50 and Z95, respectively). MEDFATE in Mediterranean forest has been validated to estimate plant water balance (De Cáceres et al., 2021, 2015). The validation showed a good accuracy for tree transpiration (from sap flow measurements) and topsoil moisture.

155 Each day, the model updates the leaf area for (semi-) deciduous vegetation based on a straightforward phenological model that dictates leaf budburst and leaf drop. This model relies on the SGDD parameter, representing the degree days needed for budburst (assuming evergreen plants maintain a consistent leaf area throughout the simulation). Subsequently, the model revises the light attenuation within the canopy, adhering to the Beer-Lambert model, as well as the canopy's water

160 storage capacity, which signifies the minimum water quantity required to saturate the canopy. Following the canopy status update, the model addresses the input of water from precipitation. Prior to augmenting the soil layers' water content, the model initially deducts the water loss from rainfall due to interception and surface runoff. Rainfall interception loss is estimated using the simplified version of the Gash model (Gash et al., 1995), while runoff is calculated according to USDA SCS curve number

165 method (Boughton, 1989). Processes related to lateral water transfer are omitted from consideration. Soil water storage capacity and water potential are derived from soil texture through pedotransfer functions (Saxton et al., 1986). When replenishing a specific soil layer, a portion of the water is

assumed to directly infiltrate the layer below, as determined by microporosity (Granier et al., 1999). The water percolating from the deepest layer is presumed to be lost through deep drainage.

170   To assess plant transpiration, the model initially calculates a distinct estimation of the maximum transpiration for the entire plant community —that is, without considering the soil water deficiency. This calculation is done for each taxon and takes into account the atmospheric evaporative demand. It involves two taxon-specific parameters: Tmax and b Tmax. The actual transpiration of a cohort relies on the maximum transpiration of the stand, determined for the corresponding taxon, and the proportion

175   of shortwave radiation absorbed by the plant cohort, as detailed by Korol et al., 1995. Moreover, the cohort's transpiration is influenced by the vertical distribution of fine roots, the soil moisture profile, and two parameters specific to the taxon: Ψextract and cextract. These parameters represent the soil water potential at which 50 % of the maximum transpiration occurs, and the slope of a Weibull function that regulates the rate of transpiration decline, respectively. The plant's water status is expressed as a

180   plant water potential, denoted as Ψplant, which is defined as an "average" of the soil water potential in the rhizosphere. The model monitors the effects of drought by assessing the proportion of hydraulic conductance lost due to stem cavitation, referred to as PLC. Increases in PLC occur whenever Ψplant decreases, following a xylem vulnerability curve characterized by the parameters VC_stemc and VC_stemd. PLC sets limits on actual transpiration rates and does not decrease even when Ψplant

185   increases. It is worth noting that the effects of cavitation can only be reversed, i.e., PLC can be reduced, through the formation of new sapwood, as outlined by Choat et al., 20

2.5. MEDFATE application

MEDFATE was run on each selected SFI3 plot using daily weather data (temperature and precipitation, PET, radiation and relative humidity) corresponding to a 10-yr period centered on the year of the SFI3 sampling (1997-2008). Data from forest inventory plots included tree height (*H*) and tree diameter at breast height, which was used to obtain estimates of foliar biomass (hence leaf area after multiplying by *SLA*) and crown ratio (*CR*) via species-specific allometries. In the model, *SLA* (Specific Leaf Area (sq *mm/mg*)), *the ratio of leaf area to leaf dry mass*, is constant for every specie (De Caceres et al., 2023). Taxon-specific parameter details are shown in supplemental material of De Caceres et al., 2023. soil data of each forest inventory plot was extracted from the SoilGrids database (Hengl et al., 2017). For all plots four soil layers down to a total depth of 4 m were initially considered, but the deepest layers were merged into a rocky layer (95 % of rocks) following the depth of the R horizon. A monotonous increase in rock fragment content across soil layers from the surface to the rocky layer was defined based on surface stoniness classes determined in SFI3 plot surveys.

2.6. Statistical analysis

Our analyses focused on relative blue water, the ratio between simulated annual mean blue water and the total precipitation as response variable. The variation of relative blue water across biomes and functional groups was analysed using beta regression models (Ferrari and Cribari-Neto, 2004). We used beta regressions because the response variable was a proportion. A post-hoc Tukey's test was applied for pairwise comparisons between groups (i.e., biomes and functional groups).

The effect and importance of climate and stand structure variables in the trade-off of blue/green
water of every functional groups were analysed with XGBoost regression. XGBoost is a machine

210   learning system that builds a sequential series of shallow regression trees with a gradient boosting
technique (Chen and Guestrin, 2016). XGBoost regression was used because it allows to analyse lineal
and non-lineal responses and correlated variables. A regression tree is trained by splitting the input
dataset into increasingly homogeneous subsets at each decision nodes and choosing the split that
maximizes the distance between different terminal nodes. 14 different climatic variables calculated as

215   the mean annual values of the 10 years of climate data for every plot (mean, maximum and minimum
temperature, solar radiation, aridity and continentality indexes) and the mean of seasonal variables
(precipitation of spring, winter, summer, and autumn; seasonality index) were used as predictors. A
topographic variable (slope) and two stand structure variables (basal area and LAI of the plot) were also
included. One model for each of the five functional groups was computed. The models were tuned for

220   finding the best hyperparameters and they were evaluated using a k-fold cross-validation procedure
(Ten-fold with five repetitions), following a stratified random sample into k subsamples of the dataset.

A forward feature selection method for selecting the predictor variables with a spatial cross-
validation (Meyer et al., 2018) was used. The models were built for each predictor pair combination and
the best was selected. The remaining predictors were tested by adding them to the best combination

225   pair. This procedure continued until neither of the remaining predictors resulted in an improvement of
the model. Variable importance in the retained variables was evaluated by computing the fractional
contribution of each feature to the model based on the total gain of these variables splits (*Gain*), the

relative number of times a feature is used in trees (*Frequency*) and the relative value of the feature observation (*Cover*). We estimated the R^2 to test the accuracy of the final models.

230   All statistical analyses were conducted with R v. 4.1.1., with the packages *xgboost* (Chen et al., 2015) and *caret* (Kuhn, 2008).

3. Results

3.1. Spatial patterns of blue water in the Spanish forest

235   Forests with the highest absolute amount of blue water were mostly concentrated in the coast of the Atlantic Sea and in the Pyrenees (Figure 1A). The south of the Spanish Peninsula in the Temperate Mediterranean biome and some areas inside the Continental Mediterranean biome had relatively high values (> 300 . The rest of the country had low blue water values (< 300 mm), manly in the eastern and Mediterranean regions. Relative blue water showed a very similar spatial pattern, with the highest

240   values located in the coast of the Atlantic Sea and the Pyrenees (Figure 1B). In the southwest of Spain and in the Mediterranean mountain regions the relative blue water was also high (> 5   ). Forests in the eastern Mediterranean region had the lowest values. The Arid and Continental Mediterranean biomes showed a very large percentage of plots (> 70 %) with low relative blue water (< 15 %), whereas the Atlantic and Alpine biomes showed higher plots (> 50 %) with high blue water (> 30 %) (Table A3).

245   Temperate Mediterranean and Submediterranean biomes showed more intermediate values, although the Temperate had the % of plots with highest blue water (> 60 %) among all biomes. The results of the

beta regression model and post-hoc Tukey´s test indicated that there were differences among biomes in the percentage of blue water (Table 1, Figure 2): relative blue water was higher in the Atlantic and Alpine biomes (mean over 25 %) followed by the Temperate Mediterranean and Submediterranean biomes, with the Arid and Continental Mediterranean biomes showing the lowest values (mean of 10-15 %).

Blue water (mm)
☐ <= 100
☐ 100 - 300
☐ 300 - 500
☐ 500 - 700
■ > 700

Blue water (%)
☐ <= 15
☐ 15 - 30
☐ 30 - 45
☐ 45 - 60
■ > 60
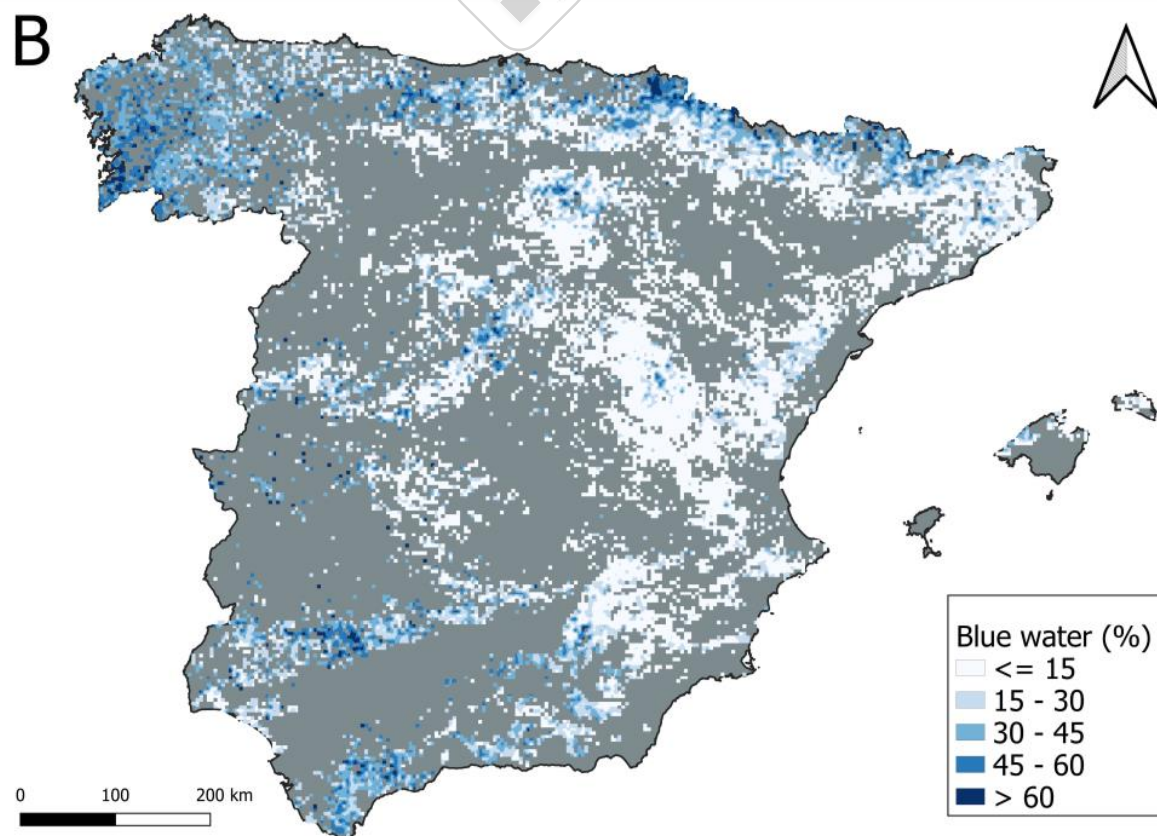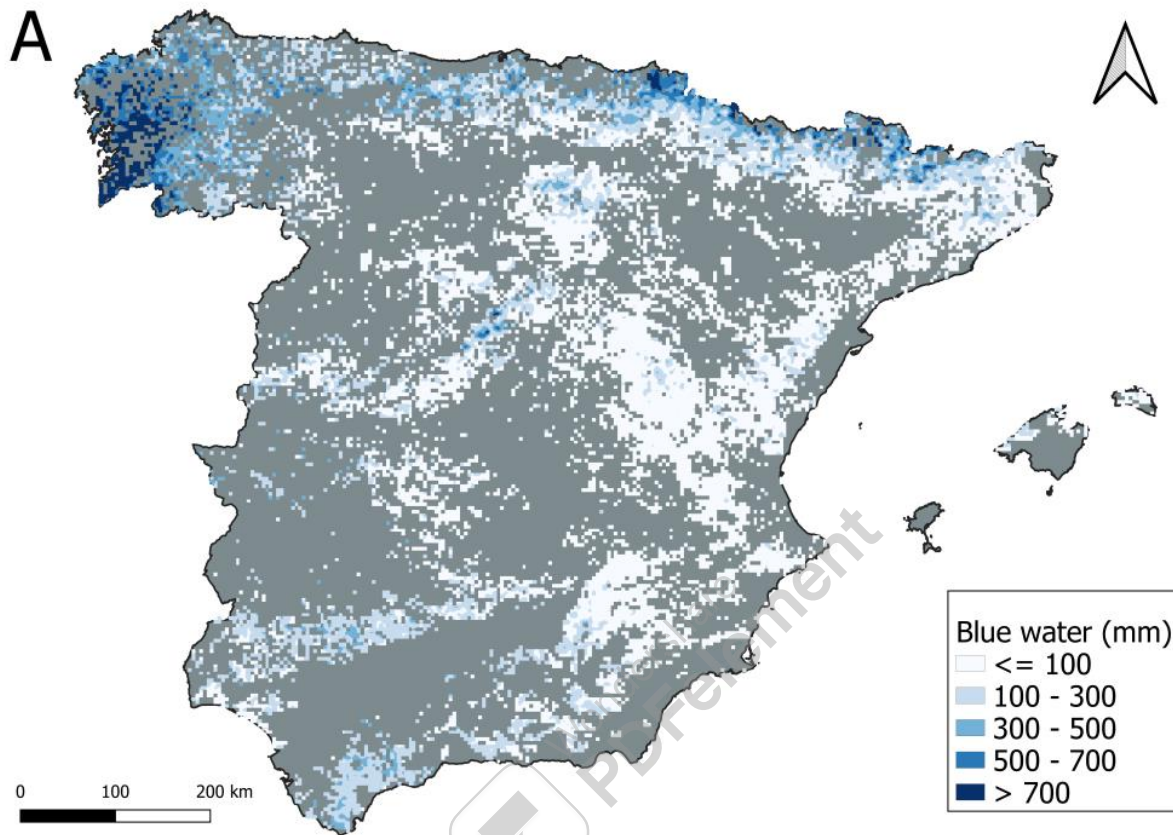
Figure 1. Total (A) and relative (B) blue water in the Spanish Peninsula and Balearic Islands. In grey,
no forest covers.

Table 1. Results of the beta regression models on relative blue water (%): for the different biomes,
indicating the estimate, standard deviation (SE), statistic and p-value of each of them.

Variable	Estimate	SE	Statistic	p-value
Intercept (Arid)	-1.90	0.02	-71.1	< 0.001
Temperate Mediterranean	0.49	0.02	17.6	< 0.001
Continental Mediterranean	-0.28	0.02	-10.1	< 0.001
Submediterranean	0.22	0.02	7.8	< 0.001
Atlantic	1.21	0.02	41.8	< 0.001
Alpine	1.06	0.03	33.0	< 0.00

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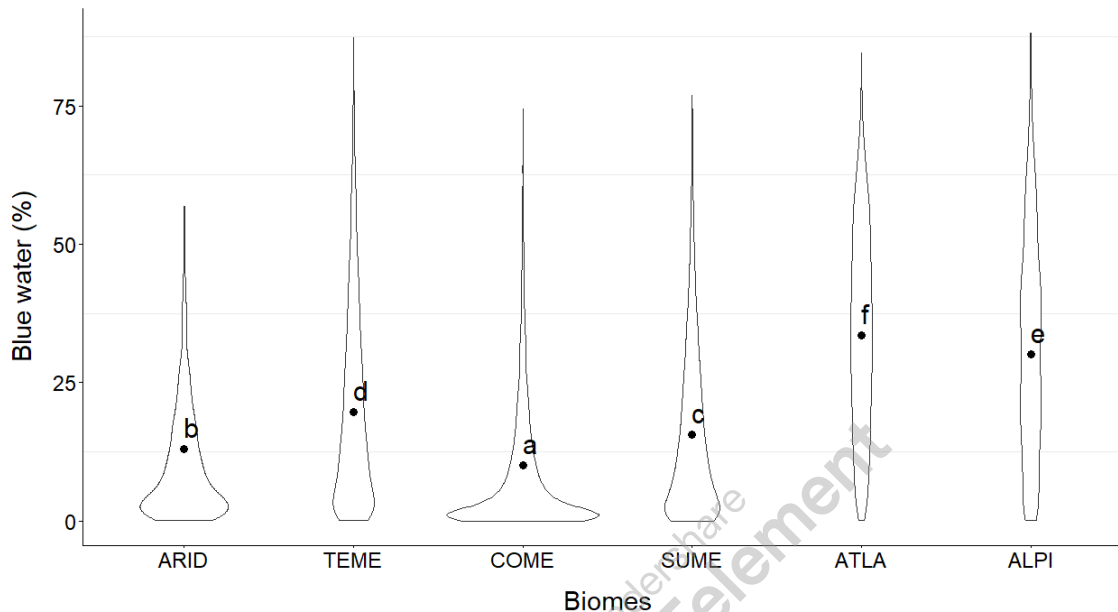
Figure 2. Percentage of blue water in the different biomes. Different letters denote significant differences among biomes ($p < 0.01$) after Tukey's test. Abbreviations of the biomes: ARID, Arid; TEME, Temperate Mediterranean; COME, Continental Mediterranean; SUME, Submediterranean; ATLA, Atlantic; ALPI, Alpine.

3.2. Patterns of blue water among forest functional groups

Beta regressions models and post-hoc Tukey´s test indicated that there were also differences among functional groups in the percentage of blue water (Table 2, Figure 3). Relative blue water was

high in temperate deciduous (35 %) followed by temperate coniferous, Mediterranean deciduous and sclerophylls (20-25 %). Mediterranean coniferous had the lowest value (close to 10 %).

Table 2. Results of the beta regression models on relative blue water (%) for the different forest functional groups, indicating the estimate, standard deviation (SE), statistic and p-value of each of them.

Variable	Estimate	SE	Statistic	p-Value
Intercept (Temperate deciduous)	-0.47	0.01	-33.2	< 0.001
Mediterranean deciduous	-0.76	0.02	-33.7	< 0.001
Temperate coniferous	-0.93	0.02	-42.4	< 0.001
Mediterranean coniferous	-1.42	0.01	-85.7	< 0.001
Sclerophylls	-1.02	0.01	-53.8	< 0.001

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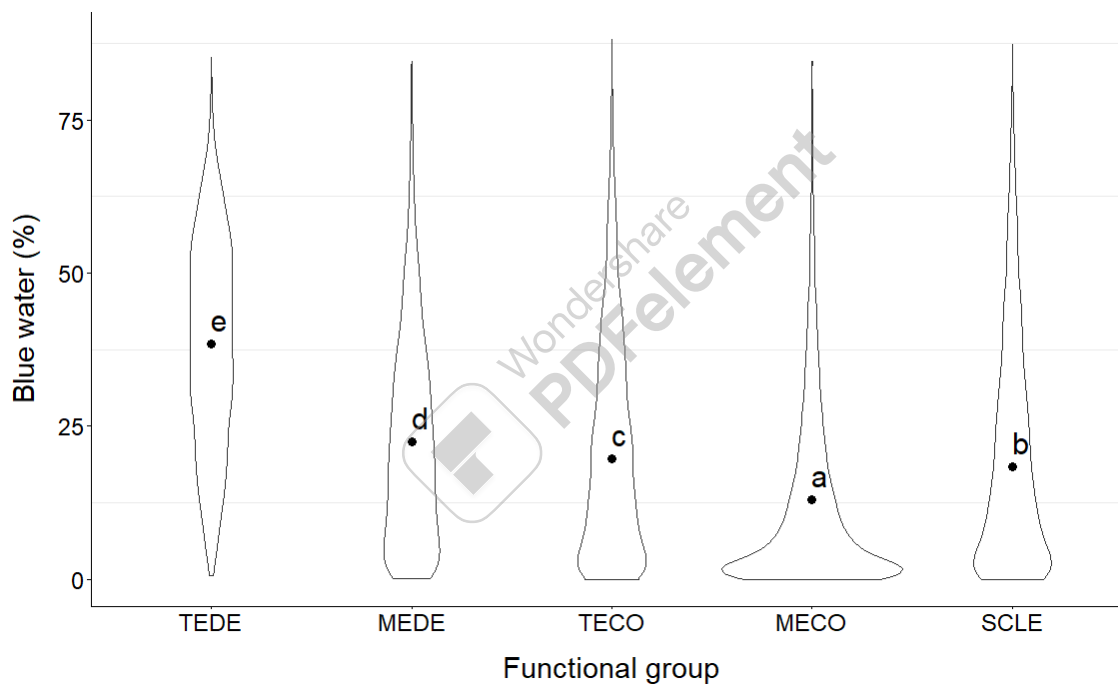
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Figure 3. Percentage of blue water of the different functional groups of species. Different letters denote significant differences among forest types ($p < 0.01$) after Tukey's test. Abbreviations of the functional groups: TEDE, Temperate deciduous; MEDE, Mediterranean deciduous; TECO, Temperate coniferous; MECO, Mediterranean coniferous; SCLE, sclerophylls.

The analysis of seasonality using monthly-aggregated data showed that the amount of blue water in forests of the different functional groups strongly varied throughout the year. In the Temperate

deciduous forests, total blue water was higher than total evapotranspiration in autumn and winter (Figure 4A), whereas in other functional groups, the values of the two flows were similar along the year, except in spring-summer, when the green water was higher. In the Mediterranean coniferous forests, evapotranspiration was higher than blue water all year long. Relative flows showed that blue

305   water was minimum in the summer season in all groups and higher than evapotranspiration only in autumn-winter in temperate deciduous forests (Figure 4B).

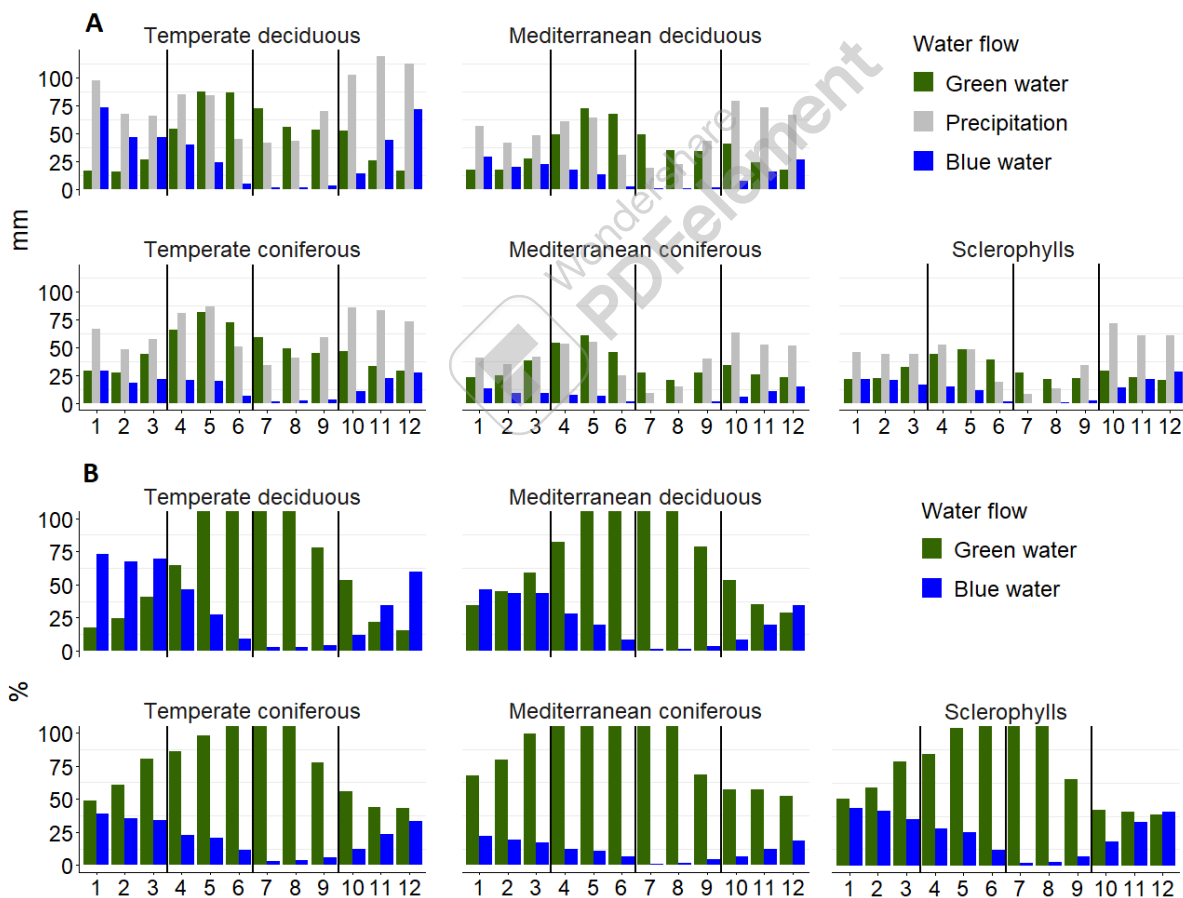
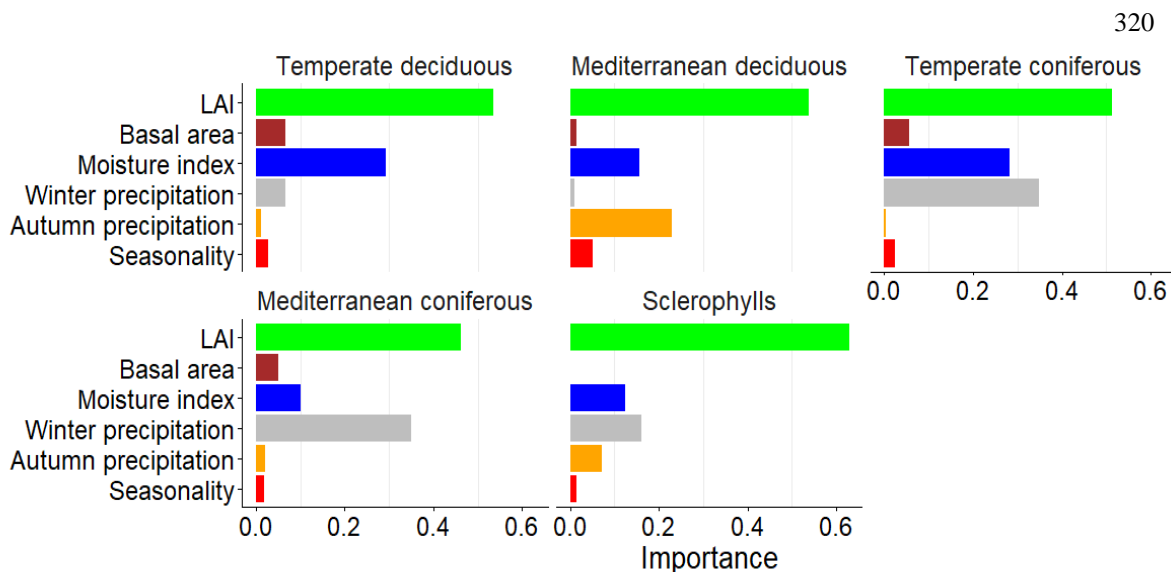



Figure 4. Total (A) and relative (B) green water and blue water, and total precipitation by different functional groups throughout the year. Note that evapotranspiration can be higher than precipitation during summer months, due to plant transpiration and bare soil evaporation of water available in the soil. Relative evapotranspiration has been truncated to 100 % of precipitation with the aim to improve the visualization of water export. A line marks the seasons in the months.

3.3. Main drivers of the trade-off between blue and green water

XGBoost models showed high accuracy, with $R^2 > 75$ % in most functional groups (Table A4). These analyses revealed that LAI was the most important predictor of relative blue water in all functional groups (Figure 5). The second and third most important variables were moisture index and winter precipitation, except for Mediterranean deciduous, which was autumn precipitation. The other variables retained in the models had low significance.

325 Figure 5. Average importance from Gain, Cover and Frequency values for every predictor variable
retained in the XGBoost models for the five functional groups.

Partial dependence plots showed that LAI had a strong and negative effect on relative blue water
(Figure 6). Nevertheless, this effect was different depending on the functional group. The temperate
deciduous forest showed the highest percentage of blue water for the whole LAI gradient, being always
330 with a value over 20 %. The other forest types showed similar patterns among them, with a larger drop
until LAI < 3 and values around 10 % afterwards. The only exception was the group of Mediterranean
conifers, which showed lower % of blue water than the other groups throughout the LAI gradient.
Moisture index showed a positive effect in all groups. The three angiosperm groups had similar slope
and showed higher values than the two gymnosperm groups (Figure 6B). Winter precipitation had a
335 positive effect in all functional groups except in the Mediterranean deciduous (Figure 6C). Temperate
deciduous forests showed higher values through the whole winter precipitation gradient.

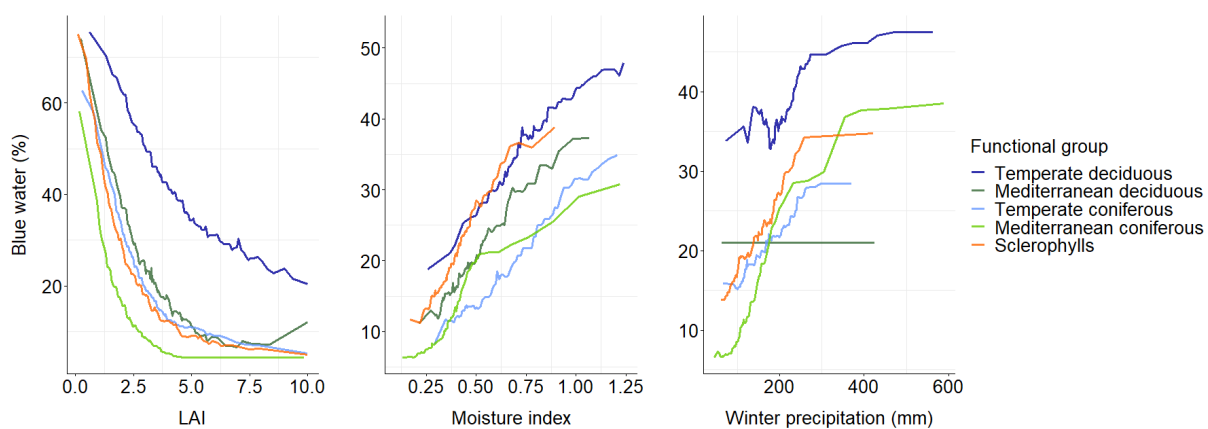



Figure 6. Partial dependence plots for the three main predictor variables (A, LAI; B, Moisture index; C, Winter precipitation) and their effect on blue water percentage for the different functional groups.

4. Discussion

4.1. Spatio-temporal patterns

Blue water spatial patterns showed that most Spanish forests have a proportion of the precipitation below 15 % as blue water (Figure 2). This pattern was expected, since most of the Spanish forests are in Mediterranean climate, and in these dry environments the evaporative demand is high and the majority of water is consumed by evapotranspiration or intercepted by the canopy (Ungar et al., 2013). In contrast, in the Atlantic and alpine biomes, the proportion of rainfall as blue water can be higher than 25 %, because these biomes are wetter and colder than the Mediterranean and, thus, the evapotranspiration is lower and precipitation is higher (Kosugi and Katsuyama, 2007; Mastrotheodoros et al., 2020). Moreover, in some mountain areas in the continental Mediterranean biomes (e.g., Sierra Nevada, Sierra de la Demanda), the amount and proportion of blue water is also high (Figure 1A, 1B). These regions are wetter than the rest of Mediterranean biomes and an increase of precipitation determines an increase in blue water (Helman et al., 2017). Interestingly, in other areas of southern Spain, in the temperate Mediterranean biome, the proportion of blue water can also be higher than 20 % (e.g., Sierra Morena; Table A3), not because they have a higher rainfall but because this biome has very open forests, with LAI values lower than the rest of biomes (Table A1).

The analysis of seasonal dynamics by forest type showed that, in forests of all functional groups, there is more blue water during autumn and winter months. In contrast, the evapotranspiration was higher in spring-summer. In Mediterranean climates there is a decoupling between rainfall and temperature (Baldocchi and Xu, 2007), with higher rainfall in spring and autumn and higher

365 temperatures in summer. For this reason, plants have more photosynthetic activity and growth in spring (when rainfall is high) and more transpiration in summer (when temperature is highest) (Baquedano and Castillo, 2006; Link et al., 2014), when trees use the groundwater stored in the soil (Jost et al., 2005). Water loss by run off or deep drainage is higher in autumn-winter because water is not fully exploited by the forest in this lower-photosynthetic period and, thus, green water is lower than would be possible

370 by falling rain (Helman et al., 2017; Williams et al., 2012). According to our results (Figure 4) blue water, which is the balance of these two fluxes, is concentrated in this period of lower or dormant vegetation activity (i.e., late autumn and winter).

4.2. Differences of blue water between forest functional groups

375 The analysis of the percentage of blue water of the different functional groups of species showed that temperate deciduous forests had the highest value, followed by Mediterranean deciduous forests (Figure 3). The rest of forest types had lower values (Figure 3), mainly the Mediterranean coniferous, which have shown a high green water of almost 90 % (Ungar et al., 2013). The seasonal dynamics of these flows in the different forest types show that deciduous forests have more blue water in autumn and

380 winter months than evergreen forests (Figure 4). This indicates that the main factor that explains the differences in relative blue water between forest types is the shedding of leaves (or its lack of shedding)

during the cold part of the year. Although deciduous trees are mainly anisohydric and their evapotranspiration is higher than that of evergreens (Klein et al., 2014), they shed their leaves in autumn and their interception and evapotranspiration are lower than those of evergreens in autumn/winter (Figure 4). Moreover, due to their shape coniferous needles intercept more the rainfall than the deciduous ones for the same area of leaves (Carlyle-Moses, 2004). Although green water is higher in deciduous than in evergreen forests in summer (Figure 4), total annual blue water seems to be more determined by leaf phenology, which conditions the destination of the autumn-winter precipitation and determines the differences between deciduous and evergreen forests. Also, climate partial plots showed that at the same level of moisture index and winter precipitation, deciduous forests have greater relative blue water than coniferous and sclerophylls (Figure 6B-C).

But once the differences between deciduous and evergreen forests are highlighted, the next aspect that stands out when comparing the different types of forests is that, for each category of leaf phenology, the proportion of blue water depends mainly on climate. Thus, temperate deciduous forests have more relative blue water than Mediterranean deciduous ones (Figure 3). Temperate deciduous forests, which are the ones exporting most blue water in relation to their precipitation, are mainly concentrated in the Atlantic and alpine biomes, where precipitation is higher and transpiration is lower, while Mediterranean deciduous forests are concentrated in Mediterranean biomes, where precipitation is lower and transpiration is higher (Table A2). The same pattern happens in evergreen forests: temperate coniferous forests have percentage of blue water higher than Mediterranean coniferous forests because precipitation in the biomes where they are more abundant is also higher than in the Mediterranean. The lowest value of blue water in Mediterranean coniferous forests is particularly relevant, because this is

the most abundant forest type in Spain, and it is predominant in the Mediterranean biomes (Table A1). Finally, sclerophyll forests have more blue water than Mediterranean coniferous forests, although both

405 are situated in Mediterranean biomes and are evergreen. Sclerophyll forests have higher transpiration than Mediterranean coniferous ones (del Campo et al., 2019; Sánchez-Costa et al., 2015) but the total LAI of their stands is lower (Table A2), which determines the different pattern obtained (as explained in the next section).

410 **4. 3. Differences in stand structure determining blue water**

The analysis of the drivers affecting relative blue water showed that LAI is the most important predictor of blue water (Figure 5). In our simulations, relative blue water was often very high (> 60 %) when LAI was < 1. Transpiration and interception are higher when the LAI of the stand is higher and, therefore, the water is transpired and intercepted by leaves. But the temperate deciduous forests showed

415 higher blue water for the same LAI values. Deciduous trees present higher evapotranspiration than evergreens at the same level of LAI (Baldocchi et al., 2010) but, as described previously, LAI effect is modulated by leaf phenology, since blue water in these forests is concentrated in winter. When LAI is very low, evergreen forests can show a higher relative blue water. For instance, the temperate Mediterranean biome showed more % of plots with a higher relative blue water than Atlantic or alpine

420 biomes (Table 0) because the mean LAI of their forests is lower than the rest of biomes (see Table A1). This points out the importance of stand structure and composition, since in a drier environment, LAI values higher than 2-3 sq m/sq m can strongly reduce the relative blue water. This effect is higher if the forest is evergreen, which is the predominant type in the Mediterranean. Relative blue water of

Mediterranean deciduous forests is higher than that of evergreens, because a decrease of LAI in
evergreen forests decreases tree transpiration but increases evaporation from the soil surface, which is
high in the Mediterranean climate even in winter (Raz-Yaseef et al., 2010). Management of blue water
in forests has been focused in modifying the basal area of the stand (del Campo et al., 2014).
Nevertheless, in this study basal area was a bad predictor of the blue water in comparison with LAI.
LAI of the stand increases with basal area until a threshold and then it remains stable (Figure A2).
Although the increase of basal area through time reduces blue water (Caldwell et al., 2016), a plateau is
expected in the long term, since LAI will not increase more after a maximum is reached. For this
reason, blue water did not reduce excessively when LAI was higher than 3 (Figure 6A). The reduction
of basal area in the forest through thinning is a recurrent way of increasing blue water (Ameztegui et al.,
2017; del Campo et al., 2018; Simon and Ameztegui, 2023), but this non-linear relationship between
basal area and LAI implies that only a heavy management for reducing basal area would be effective for
reducing the LAI of the stand and, thus, increasing blue water.

5. Conclusion

Ecohydrological models like MEDFATE allow to model different species and stand structures,
improving our insights about the role of forests in water flows. Thus, we can split the fluxes of water at
stand level and understand the role of species, climate and stand structure variables in the different
water flows: transpiration, interception, runoff, etc. Nevertheless, using model simulations to estimate
water flows is not the same as actually observing them, and can led to artifactual results. In this sense, it
is necessary to continue improving the ecohydrological model design parametrization to improve their

445 accuracy, including the completion of traits of many species for the parameterization, a better soil

database, or the inclusion of lateral water flows (in the case of MEDFATE model). Model evaluation is

another key aspect to increase realism and usefulness of predictions. The model MEDFATE has been

validated in Mediterranean forests at local scale with field ground data, but it has not been validated at

country scale, and it might have lower accuracy in the Atlantic or alpine biome or with some tree

450 species. Nevertheless, despite accepting these limitations, the lack of field data at bigger scales

encourages the use of models to study water flows at country or continental scale. In the current context

of global change, the knowledge of water fluxes in forests is essential to be able to define strategies to

improve the water budget, and especially in dry environments like the Mediterranean, where water is

scarce and the previsions are in the line of increasing drought periods. Thus, in the context of global

455 change we are suffering (Hoerling et al., 2012; Lionello et al., 2014), the low amount and proportion of

blue water in great part of Spain is an important problem in the water supply for the agriculture or

human consumption in the region (Ellison et al., 2012). The consequences that this lack of blue water

might have on the entire silvoagropastoral system in the whole region, aggravated by the harsher

conditions expected in the future, should make us reflect on what kind of forest management could be

460 more effective in the next decades.

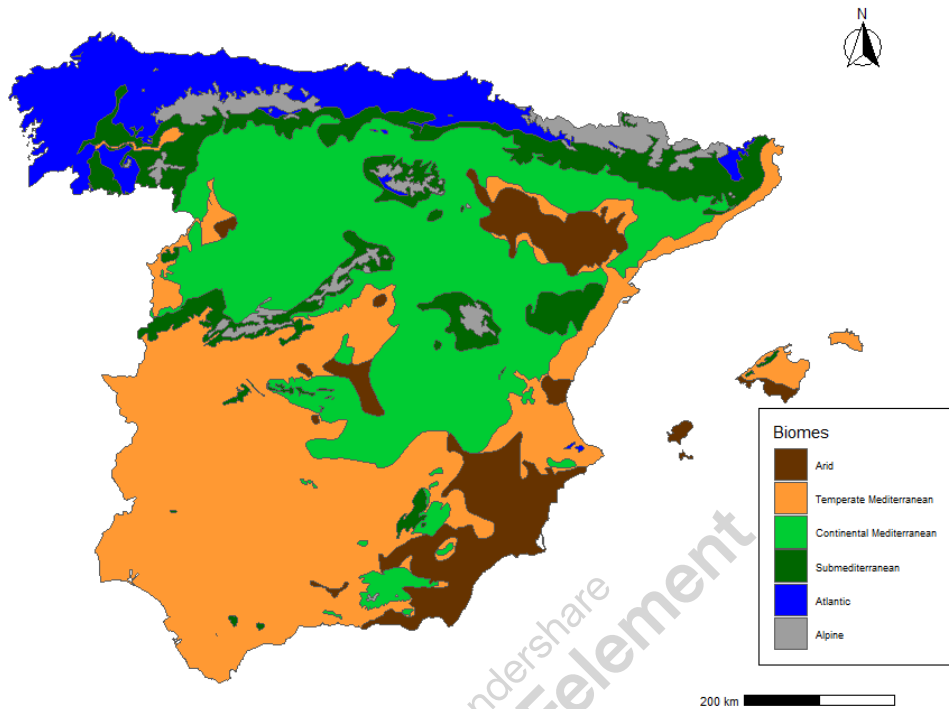
Appendices

475 **Figure A1.** Climatic biomes in the Spanish Peninsula and Balearic Islands.

Table A1. Classification into functional groups of the predominant tree species in the study area and the number of plots of each of them.

Functional group	Predominant species	Number of plots
Temperate deciduous	*Betula pendula*	11
Temperate deciduous	*Castanea sativa*	611
Temperate deciduous	*Fagus sylvatica*	1864
Temperate deciduous	*Populus tremula*	19
Temperate deciduous	*Quercus petraea*	336

Temperate deciduous	*Quercus robur*	807	480
Mediterranean deciduous	*Quercus canariensis*	134	
Mediterranean deciduous	*Quercus faginea*	1077	
Mediterranean deciduous	*Quercus pyrenaica*	1413	
Temperate coniferous	*Abies alba*	98	
Temperate coniferous	*Abies pinsapo*	8	
Temperate coniferous	*Pinus sylvestris*	4312	485
Temperate coniferous	*Pinus uncinata*	275	
Mediterranean coniferous	*Juniperus thurifera*	603	
Mediterranean coniferous	*Pinus halepensis*	5746	
Mediterranean coniferous	*Pinus nigra*	3439	
Mediterranean coniferous	*Pinus pinaster*	4682	
Mediterranean coniferous	*Pinus pinea*	1489	490
Sclerophyll	*Arbutus unedo*	101	
Sclerophyll	*Quercus ilex*	4542	
Sclerophyll	*Quercus suber*	947	

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Table A2. Characteristics Mean and standard deviation of stand structure variables and climate variables grouped in the different forest functional forest types groups by biome. Basal area (m^2 ha^{-1}); LAI T = Tree LAI; LAI S = Shrub LAI; MeanT = Mean annual temperature (ºC); TPre = Mean Total annual precipitation (mm). Mean and standard deviation are showed for all the values.

Functional group	Biome	Nº plots	Basal area	LAI of Trees	LAI of Shrubs	MeanT	TPre	Seasonality	Moisture	Continentality
Temperate	Alpine	1506	26.9±14.7	2.3±1.3	0.9±0.9	8.3±1.5	872±237	35.3±12.4	0.9±0.4	16.0±1.5

coniferous	Atlantic	828	26.3±14.3	2.7±1.3	1.3±1.0	10.5±1.2	910±147	31.0±8.2	0.8±0.2	15.1±0.9
	Continental Mediterranean	451	20.8±12.1	1.9±0.9	1.3±1.0	10.7±1.0	534±77	45.6±9.4	0.4±0.1	17.4±1.6
	Submediterranean	1908	21.8±12.5	2.2±1.1	1.3±1.0	10.2±1.3	685±152	36.5±10.7	0.6±0.2	16.3±1.3
	Alpine	370	25.1±12.2	4.4±1.6	0.7±0.9	8.7±0.9	866±158	32.8±7.6	0.9±0.3	14.8±1.0
	Atlantic	2597	24.2±12.1	3.5±1.6	1.4±1.1	11.5±1.4	995±218	34.5±8.9	0.9±0.2	13.4±1.5
	Continental Mediterranean	56	22.9±10.0	4.0±1.7	0.8±0.9	10.5±0.7	640±92	33.9±6.0	0.6±0.2	15.7±1.0
	Temperate Mediterranean	105	19.8±10.3	1.9±1.2	1.0±0.9	15.1±1.1	616±143	63.9±8.9	0.5±0.2	16.4±1.1
	Submediterranean	541	24.3±14.6	3.6±1.8	1.3±1.1	11.2±1.5	762±189	39.2±11.8	0.7±0.2	15.3±1.2
Mediterranean coniferous	Alpine	103	20.0±13.1	1.8±1	1.5±1.0	10.3±1.3	643±152	40.4±11.3	0.5±0.2	16.9±1.5
	Arid	1244	8.6±5.2	0.9±0.5	1.5±0.8	15.3±1.3	311±47	52.5±4.2	0.2±0	17.8±1.2
	Atlantic	910	22.8±12.1	1.8±0.9	2.0±1.0	13.3±1.2	1365±322	47.7±8.0	1.2±0.3	11.5±2.0
	Continental Mediterranean	5969	15.1±10.1	1.4±0.7	1.7±1.0	12.6±1.4	435±66	47.6±7.3	0.3±0.1	17.9±1.1
	Temperate Mediterranean	4770	13.5±8.7	1.2±0.6	1.5±0.8	15.2±1.5	418±90	57.5±8.4	0.3±0.1	18.0±1.8
	Submediterranean	2971	18.5±12.0	1.7±0.8	1.6±0.9	12±1.6	546±147	44.5±10.5	0.4±0.1	17.3±1.5
Mediterranean deciduous	Alpine	126	16.7±9.7	2.5±1.4	1.4±1.0	9.8±0.9	679±131	42.8±10.0	0.6±0.2	16.5±1.3
	Atlantic	421	17.7±10.3	2.6±1.5	1.8±1.0	11.4±1.1	864±160	37.6±9.6	0.7±0.2	14.1±1.2
	Continental Mediterranean	682	10.0±7.0	2.0±1.3	1.6±0.9	11.7±1.1	501±87	44.1±9.0	0.4±0.1	17.3±1.2
	Temperate Mediterranean	337	12.6±8.3	1.5±1.1	1.3±0.9	15.6±1.5	532±98	65.7±7.5	0.4±0.1	16.5±2.4
	Submediterranean	1176	15.1±9.6	2.4±1.3	1.6±1.0	11.4±1.2	610±140	43.2±11.7	0.5±0.1	16.6±1.3
Sclerophyll	Alpine	45	14.1±8.3	3.0±1.3	1.2±0.7	10.4±0.8	811±124	25.4±6.8	0.7±0.2	14.9±0.9
	Arid	46	6.9±4.0	1.5±0.9	1.1±0.7	13.5±1.1	368±44	56.4±4.4	0.3±0.1	18.3±0.7
	Atlantic	206	18.5±10.5	3.6±1.7	1.9±1.0	12.7±1.1	843±181	32.3±8.1	0.7±0.2	14.0±1.5

Continental Mediter-ranean	1754	9.2±5.8	2.1±1.3	1.5±1.0	12.4±1.2	456±67	46.7±8.6	0.4±0.1	17.8±1.2
Temperate Mediterra-nean	4229	8.6±5.9	0.9±0.7	1.0±1.0	16.3±1.2	493±86	64.2±7.2	0.3±0.1	17.7±2.0
Submediterranean	1295	13.6±8.1	2.7±1.4	1.6±0.9	12.6±1.5	591±126	39.0±11.3	0.5±0.1	16.4±1.3

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Table A3. Proportion of plots in the different categories of relative blue water in the different biomes. n, number of plots.

Biome	Distribution of values of Relative blue water (%)					
	n	0-15	15-30	30-45	45-60	>60
Arid	1,290	74.6	19.7	4.9	0.8	0.0
Temperate Mediterranean	9,444	39.7	22.0	14.9	11.5	11.9
Continental Mediterranean	8,912	78.0	13.4	5.3	2.0	1.3
Submediterranean	7,891	58.1	24.3	12.0	4.4	1.2
Atlantic	4,962	18.0	24.7	27.1	21.8	8.4
Alpine	2,150	23.1	25.6	25.8	16.8	8.7

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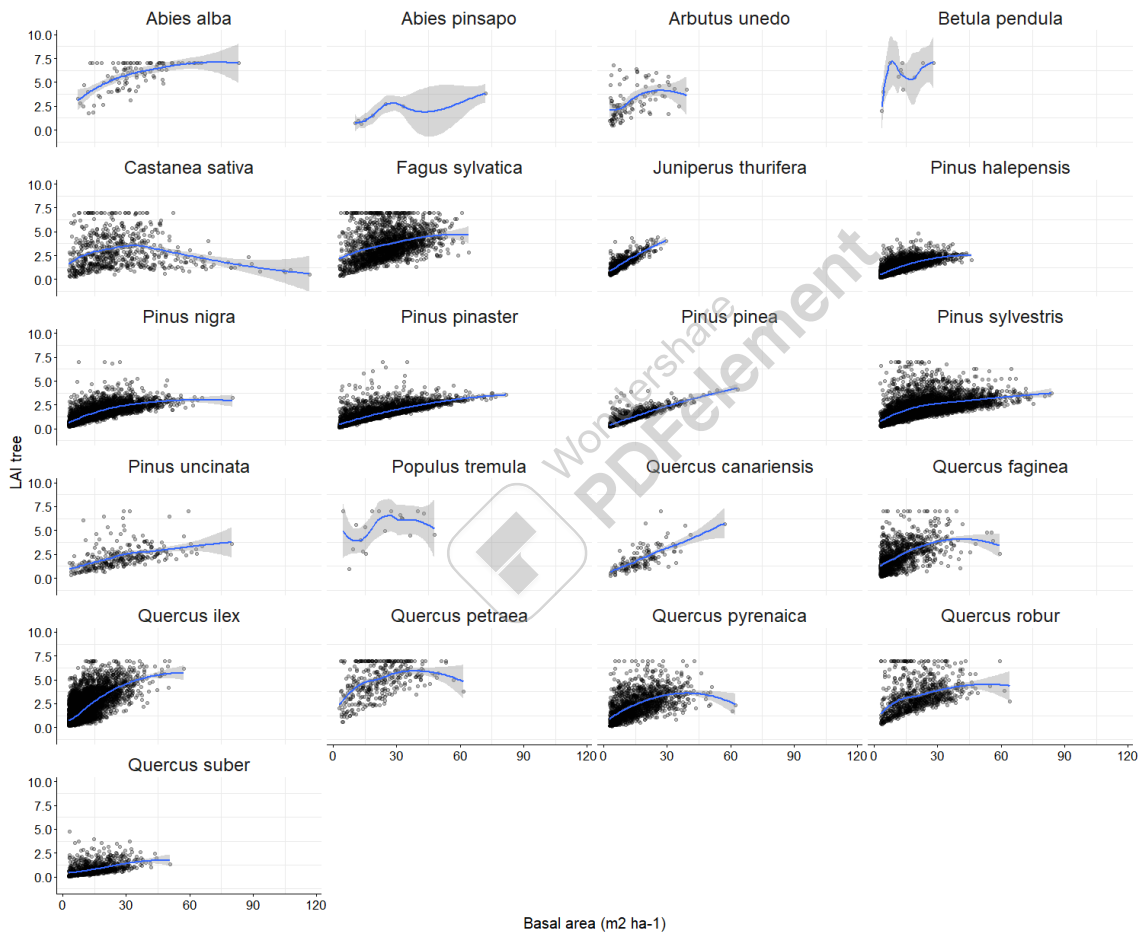
Figure A2. Relationship between the simulated LAI of the trees and basal area from the SFI3 by species.

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Table A4. Importance of the variables retained in the XGBoost models and their R^2 by functional
535 group.

Temperate coniferous (R^2=90,04)

Variable	Gain	Cover	Frequency
LAI	0,592	0,467	0,482
Moisture index	0,286	0,291	0,269
Winter precipitation	0,094	0,136	0,135
Basal area	0,019	0,067	0,079
Seasonality index	0,006	0,033	0,031
Autumn precipitation	0,002	0,007	0,004

Mediterranean coniferous (R^2=79,85)

Variable	Gain	Cover	Frequency
LAI	0,398	0,476	0,509
Winter precipitation	0,48	0,357	0,211
Moisture index	0,071	0,075	0,158
Seasonality index	0,019	0,011	0,025
Basal area	0,018	0,07	0,062
Autumn precipita-tion	0,014	0,012	0,035

Sclerophylls (R^2=89,97)

Variable	Gain	Cover	Frequency
LAI	0,772	0,563	0,55
Winter precipitation	0,089	0,221	0,174
Autumn precipitation	0,065	0,079	0,071
Moisture index	0,058	0,119	0,195
Seasonality index	0,017	0,018	0,011

Temperate deciduous (R^2=75,49)

Variable	Gain	Cover	Frequency
LAI	0,64	0,507	0,458
Moisture index	0,267	0,304	0,307
Winter precipitation	0,049	0,075	0,077
Basal area	0,031	0,078	0,09
Seasonality index	0,01	0,025	0,046
Autumn precipitation	0,003	0,011	0,022

Mediterranean deciduous (R^2=77,61)

Variable	Gain	Cover	Frequency
LAI	0,601	0,519	0,491
Autumn precipita-	0,262	0,235	0,191

tion			
Moisture index	0,102	0,17	0,194
Seasonality index	0,026	0,046	0,082
Winter precipitation	0,005	0,007	0,021
Basal area	0,004	0,022	0,02

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Code availability. The model code of MEDFATE is available at https://github.com/emf-creaf/medfate.

The MEDFATE model code is explained in De Cáceres et al. (2023).

545 **Data availability.** Spanish forest inventory data are available at

https://www.miteco.gob.es/es/biodiversidad/temas/inventarios-nacionales/inventario-forestal-nacional/.

Author contributions:

JSD, MC, JV and JR contributed to the study conception and design. JSD conducted the modelling with

550 the support of MC. All authors discussed the results and edited the manuscript.

Competing interests:

The authors declare that they have no conflict of interest.

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