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Deliverable Nº 5

MATRIXES OF FOREST-WATER-SOIL-CLIMATE-FIRE RELATIONSHIPS UNDER DIFFERENT MANAGEMENT INTENSITIES FOR EACH BASIC FOREST STRUCTURE

UPV

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This document calculates the response matrix of forest-water-soil-climate-fire relationships under different management intensities for each basic forest structure.

MATRIXES OF FOREST-WATER-SOIL-CLIMATE-FIRE RELATIONSHIPS UNDER DIFFERENT MANAGEMENT INTENSITIES FOR EACH BASIC FOREST STRUCTURE

ACTION A.1: Updating and modelling of Serra’s forest and biomass management approach

INDEX

Deliverable 5; name: *Matrixes of forest-water-soil-climate-fire relationships under different management intensities for each basic forest structure*

Beneficiary responsible: UPV

Action A1: *Updating and modelling of Serra's forest and biomass management approach*

From month 3 – month 6

Name of the Deliverable	Number of associated action	Deadline
Matrixes of forest-water-soil-climate-fire relationships under different management intensities for each basic forest structure	A1	01/2019

1. Introduction

The plant-soil-atmosphere interaction constitutes forest ecosystems, and its understanding becomes crucial under every climate and environment. Water is of course included into this plant-soil-atmosphere continuum as forests have a strong interaction with water capable of control most of its functions. This interaction variates across hydro-climatic gradients (Asbjornsen et al 2011) where different strategies are used. Water-limited environments, such as arid or semiarid, show a more obvious water-plant relationship where plant growth is often controlled by stochastic pulses of water that directly affect plants' ability to adapt and survive (Schwinning and Sala 2004). Conversely, in humid environments, where wetlands or saturated soils are prevalent, this interaction is less noticeable but also intense, and the predominant controls on ecosystem functions are often water table fluctuations and hydroperiod (Rodriguez-Iturbe et al. 2007). In between these extremes, lie seasonal environments where water availability and scarcity fluctuate sharply and plants may exhibit unique adaptations that differ from more continuously water-limited or water-abundant environments (Jacobsen et al. 2008, Asbjornsen et al 2011). Hence, when managing a forest it is vital understanding and considering forest-water-soil-climate relationships. In the same way, when using modeling approaches, the characterization of this continuum becomes unavoidable, as it will reproduce the entire ecosystem dynamics which will rule the catchment water cycle. Many studies have addressed specifically the effects of forest management on this continuum (Bosh and Hewlett, 1982; Hibbert et al., 1982; Troendle et al., 2001), and have come to the conclusion that managing a forest for clean water, soil protection, carbon pools or other biogeochemical cycles, resilience towards global change, etc. means managing attending to plant-soil-water-atmosphere interactions, as the goods and services provisioning derived from the management will rely on how the manager shapes these interactions.

This Deliverable characterize plant-soil-water-atmosphere interactions of different forest structures and includes its potential effects on fire risk.

2. Background

The matrixes of forest-water-soil-climate-fire relationships under different management intensities for each basic forest structure were conceived in the project as the basic information to represent the forest upper catchment environments that will feed the DSS tool. These matrixes must be developed by using the basic forest structures, which in Serra's village case can be obtained combining Deliverables 3 and 4 (Table 1). From this combination, 13 different forest structures are identified, although only at 11 of them forest management could be considered. Hence, Riparian forest and *Olea europea* agricultural crops' (structures 20 and 21) would not be included into the analysis. In the case of riparian forest, it falls out of the forest management objectives as it is just restricted to the main river bank and in a poor state. Regarding to the *Olea europea*, as it is an agricultural crop, no forest management can be applied.

Table 1: Basic forest structures at Serra's village.

STRUCTURE	**DEFFINITION**
7	Shrub
8	Scattered Aleppo pine
9	Quercus suber
13	Evergreen hardwods forest
14	Mature Aleppo pine
16	Mature Pinus pinaster
18	Stem-exclusion Aleppo pine stands
19	Stem-exclusion conifer+ hardwods
20	Riparian forest
21	Olea europea
23	Very young Aleppo pine stands
25	Initation conifer+hardwods
26	Initation Pinus pinaster

This Deliverable uses experimental data from UPV regarding to soil moisture and stand transpiration. Without this data, the accomplishment of the Deliverable would not be possible.

3. Objectives

The aim of this Deliverable is to develop the response matrixes of forest-water-soil-climate-fire relationships under different management intensities for each basic forest structures obtained in the previous Deliverable.

4. Methodology

1.- First approach: the matrixes

1.1.- Methods

The forest-water-soil-climate-fire relationships were developed by using experimental field data and the process based model BIOME-BGC-MuSo v5.0 (Hidy *et al* 2016). First the model is calibrated and validated with the field data, and finally, the matrixes are built by launching multiple simulations.

The first matrixes correspond to the forest structure: Stem-exclusion Aleppo pine stands and Evergreen forests.

1.1.1.- Field data

Daily soil moisture (SM) and stand transpiration are used in this deliverable to calibrate and validate the process based model. Both data sets have been registered in four experimental forest plots, 2 of Aleppo pine post-fire regeneration located at Serra´s village (AP), and 2 of Evergreen hardwood forest (*Quercus ilex*) located at the public forest La Hunde (QU). At both experimental sites, in a representative area, one plot, control, was left with no forest management, and a contiguous managed plot, treatment, was established. The applied forest management (QU in May 2012 and AP in October 2012) consisted of a Juvenile thinning (AP) and thinning with shrub clearing (QU) that removed the trees with smaller diameters and doubled-trees. Coarse woody debris were removed outside the plots whereas fine woody debris were piled and grinded into mulch onto the plots. Total basal area removed in the treatments was 74% and 41% in AP and QU, respectively, and density reduction was 94% and 73%, respectively. Control and treatment plots were of 1500 m^2 area respectively, both NW oriented and divided into 3 replicates or experimental blocks from up-slope to down-slope in order to assure representative result. Among other variables, gross rainfall (Gr), SM and sap-flow were continuously registered in both plots from August 1, 2012 to September, 30, 2016. Gr was continuously measured by means of a tipping-bucket rain gauge with 0.2mm resolution (Davis 7852). SM was continuously measured for the whole period every 10 min, or every 5 s when raining, by means of capacitance probes (EC-5, Decagon Devices

Inc., Pullman, WA). Sensors were installed by digging three pits per block (9 per plot) along contour lines. In the central pit of each block, three sensors were horizontally poked at depths of 5, 15 and 30 cm into the unaltered up-slope pit face, whereas in the other two pits, only one sensor was inserted at 15 cm deep. Total sample size per plot (treated/control) was 15 sensors in 9 spots. Sap-flow was measured by means of sap-flow sensors based on heat ratio method (Burgess et al., 2001) in 9 trees per plot (3 per replicate) according to the frequency distribution of diameters. To up-scale the sap-flow to stand transpiration (T, mm), first the average sap-flow tree (SF tree, l/tree) was obtained by means of the weighting average according to the frequency distribution of diameters. Subsequently, this value was up-scaled by using the tree crown projected area (CPA, m^2/tree) as scalar, and correcting it with the plot forest cover (FC) as follows:

$$T = SF_{tree} \cdot \frac{1}{CPA} \cdot FC$$

1.1.2.- Process based modelling

The model used in this deliverable is BIOME-BGC-MuSo v5.0 (Hidy *et al* 2016). It is a biogeochemical model that simulates the storage and flux of water, carbon, and nitrogen between the ecosystem and the atmosphere, and within the components of the terrestrial ecosystem. The model uses a daily time-step and calculates the mentioned fluxes within 1 m^2, therefore, it is not a distributed model, however, its results are quite accurate when describing forest-water-soil-climate relationships.

The input data are referred to climate (precipitation, temperature, vapour pressure deficit and solar radiation) and the characteristics of the forest (soil, latitude and albedo). The output variables are more than 3000, among which we have selected: sol moisture, transpiration, evapotranspiration, out flow, gross photosynthetic production (GPP), biomass and leaf area index (LAI). GPP represents the total amount of CO_2 that is fixed by the plants through photosynthesis and it has proved to be a good indicator of ecosystem's health.

1.1.3.1.- Calibration and validation:

The calibration and validation steps were carried out by comparing simulated and observed SM and transpiration data of both, control and thinned plots. This comparison becomes a necessary step when using computational modelling in order to analyse to what extent the modelling results represent the reality. In this sense, first the model was calibrated using SM and transpiration of the water year 2013-2014. Subsequently, a validation was carried out by comparing the same variables but during the water years 2014-2015 and 2015-2016.

1.2.- Fire

The fire behaviour is introduced here by calculating the fire index Keetch and Byram-Based drought index (KDBI) developed by Keetch and Byram (1968), that uses daily soil moisture as input data.

2.- Alternative approach: distributed eco-hydrological modelling:

Another option is raised here, as a way to optimize and improve the accuracy of the DSS tool. Thus, instead of developing these matrixes using generic soil, vegetation and topographic variables, the methodology proposed here develops the matrixes that particularly represent each case study. An example of this methodology is presented here using Carraixet’s catchment and the eco-hydrological distributed model TETIS-VEG.

2.1.- TETIS-VEG model description

TETIS-VEG is the result of coupling a dynamic vegetation model to the distributed hydrological model called TETIS (Francés et al., 2007). Both, hydrological and vegetation sub-models, have simplicity of model structure in common (i.e. the used equations are as simple as possible in order to reduce the number of parameters). The sub-models are interconnected through transpiration and soil water content. In particular, the transpiration calculated in the hydrological sub-model depends on the LAI simulated by the dynamic vegetation sub-model. At the same time, the simulated LAI is affected by water stress, which is calculated using the hydrological sub-model. The TETIS-VEG model has been already successfully applied in water-controlled environments (Ruiz-Pérez et al., 2016, 2017).

5. Description of the activities

1.- Analysis of experimental data:

Soil moisture and stand transpiration from 3 experimental studies carried out by UPV were analysed and used to accomplish this Deliverable. A previous data processing was necessary to use the data. Going from the field signal registered with a data logger to a usable data constitutes a long process that requires long working days behind the computer. Subsequently, the data is statistically analysed by using RStudio software. As a result, time series of stand transpiration and soil moisture from 3 different basic forest structures and under different management intensities were obtained.

2.- Calibrating and validating the process-based model BIOME-BGS_MuSo:

This process consists on adjusting the parameters that represent the eco-hydrological behaviour of each forest structure to accurately reproduce the measured data derived from the previous point. This activity implies running more than 1000 simulations until a good fit is reached.

3.- Generating the response matrixes of forest-water-soil-climate-fire relationships under different management intensities with the process based model:

Once the model is calibrated and validated, at least 15 simulations per forest structure have to be carried out with the aim to accurately reproduce generic soil, topographic and climatic conditions.

4.- Calibrating and validating the distributed eco-hydrological model:

This activity is similar to number 2, but in this case, using the whole catchment, which include all forest structures at the same time.

5.- Generating the response matrixes of forest-water-soil-climate-fire relationships under different management intensities with the distributed eco-hydrological model.

Once the model is calibrated and validated, a long simulation of 25 years per management intensity is carried out to analyse and generate the response matrixes of forest-water-soil-climate-fire relationships under different management intensities.

6. Results and conclusion

The results of the calibration and validation procedure indicate the good performance of the model in representing these particular forest structures with and without forest management (see Table 2).

Table 2: Calibration, validation and evaluation adjustment values. NSE represents the Nash-Sutcliffe coefficient. RMSE is the Root Mean Square Error. SWC is Soil Water Content. Tr is stand transpiration.

Forest structure	**Calibration**				**Validation**			
	NSE		**RMSE**		**NSE**		**RMSE**	
	SWC	**Tr**	**SWC**	**Tr**	**SWC**	**Tr**	**SWC**	**Tr**
Stem-exclusion Aleppo pine stands	0.54	0.51	0.03	0.08	0.58	0.48	0.02	0.11
Stem-exclusion Aleppo pine stands THINNED	0.60	0.52	0.02	0.04	0.60	0.49	0.02	0.09
Evergreen forest	0.53	0.57	0.02	0.07	0.60	0.47	0.03	0.14
Evergreen forest THINNED	0.78	0.53	0.02	0.01	0.68	0.46	0.03	0.20

According to these results, the forest-water-soil-climate-fire matrixes under different management intensities are calculated by simulating 10 consecutive water years, with different management intensities. The management intensities used in this deliverable are:

- No management (CONTROL)
- Thinning 30 % of woody biomass (T- 30)
- Thinning 60 % of woody biomass (T- 60)
- Thinning 80 % of woody biomass (T- 80)

Tables 3 and 4 show the matrix that relates the forest structure with water (production and consumption), fire, biomass and CO_2 emissions during 10 water years. This matrix shows that even the lowest intensity thinning produces significant changes into forest-water-soil-climate-fire relationships.

Table 3: Forest-water-soil-fire relationships under different management intensities of basic forest structure 18 (Stem-exclusion Aleppo pine stands) represented as monthly average ± standard deviation, except for outflow, where the total amount of the simulated period is presented. * indicates significant differences (p-value < 0.05) with the no management situation (CONTROL).

	CONTROL	T-30 %	T- 60%	T- 80 %
Soil Moisture(cm/cm)	0.09 ± 0.03	0.09 ± 0.03	0.10 ± 0.04 *	0.13 ± 0.05 *
Biomass (KgC/m^2)	1.4 ± 0.11	1.1 ± 0.06 *	0.8 ± 0.20 *	0.4 ± 0.23 *
GPP (KgC/m^2)	0.11 ± 0.05	0.09 ± 0.04 *	0.08 ± 0.04 *	0.06 ± 0.04 *
KDBI	447.9 ± 149.8	446.5 ± 151.9	388.4 ± 184.0 *	233.9 ± 201.0 *
LAI (m^2/m^2)	2.4 ± 0.1	1.9 ± 0.1 *	1.3 ± 0.3 *	0.6 ± 0.3 *
Outflow (mm)	47.9	52.8 *	67.2 *	88.1 *
Transpiraiton (mm)	11.2 ± 12.4	11.7 ± 13.1 *	12.6 ± 12.5 *	13.7 ± 12.3 *
ET (mm)	24.6 ± 22.2	24.5 ± 22.4 *	24.4 ± 19.5 *	24.2 ± 15.8 *

Table 4: Forest-water-soil-fire relationships under different management intensities of basic forest structure 13 (Evergreen hardwods forest) represented as monthly average ± standard deviation, except for outflow, where the total amount of the simulated period is presented. * indicates significant differences (p-value < 0.05) with the no management situation (CONTROL).

	CONTROL	T-25 %	T- 45%	T- 60 %
Soil Moisture(cm/cm)	0.15 ± 0.03	0.15 ± 0.04 *	0.15 ± 0.04 *	0.16 ± 0.04 *
Biomass (KgC/m^2)	2.0 ± 0.1	2.6 ± 0.3 *	2.4 ± 0.5 *	2.1 ± 0.7 *
GPP (KgC/m^2)	0.10 ± 0.05	0.12 ± 0.07 *	0.11 ± 0.07 *	0.10 ± 0.07 *
KDBI	144.3 ± 41.2	155.3 ± 128.8	142.7 ± 123.7	129.5 ± 128.4 *
LAI (m^2/m^2)	2.0 ± 0.1	2.5 ± 0.3 *	2.3 ± 0.5 *	2.1 ± 0.7 *
Outflow (mm)	47.9	52.8 *	67.2 *	88.1 *
Transpiraiton (mm)	7.4 ± 5.1	14.7 ± 10.0 *	13.8 ± 9.7 *	12.8 ± 9.4 *
ET (mm)	21.6 ± 10.6	25.1 ± 13.5 *	24.2 ± 13.3 *	23.0 ± 13.0 *

Figures 1 to 7 show the evolution of each variable included into the matrix of the basic forest structure 18 (Stem-exclusion Aleppo pine stands) under different management intensities.

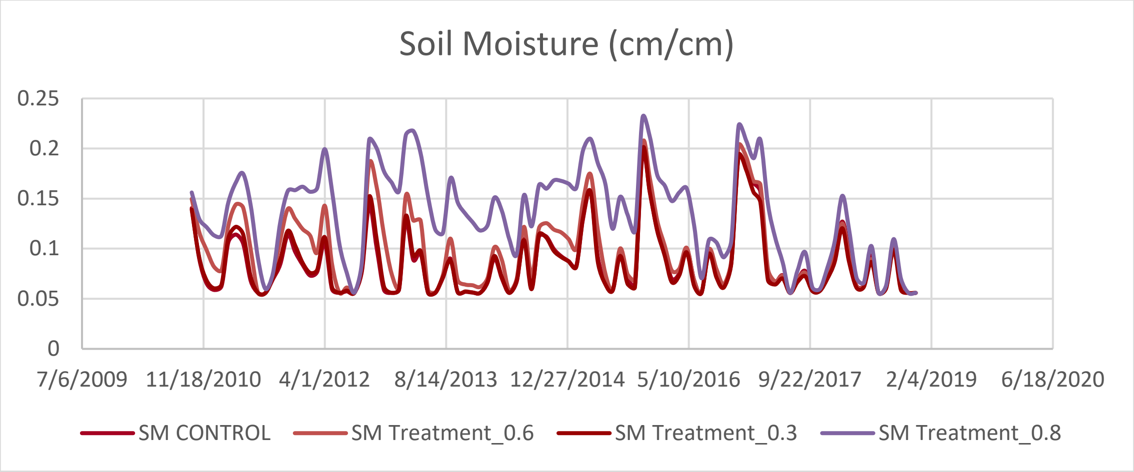

Figure 1: Daily soil moisture of the basic forest structure 18 (Stem-exclusion Aleppo pine stands) under different management intensities.

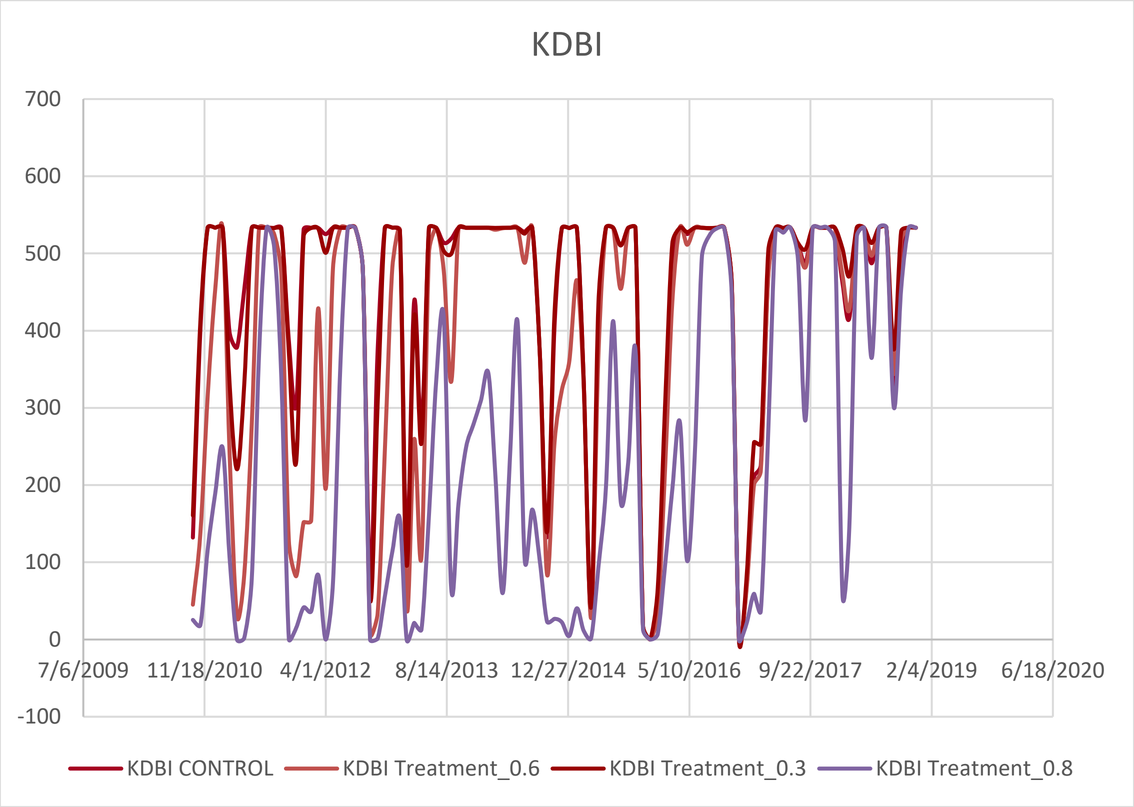

Figure 2: Daily KDBI index of the basic forest structure 18 (Stem-exclusion Aleppo pine stands) under different management intensities.

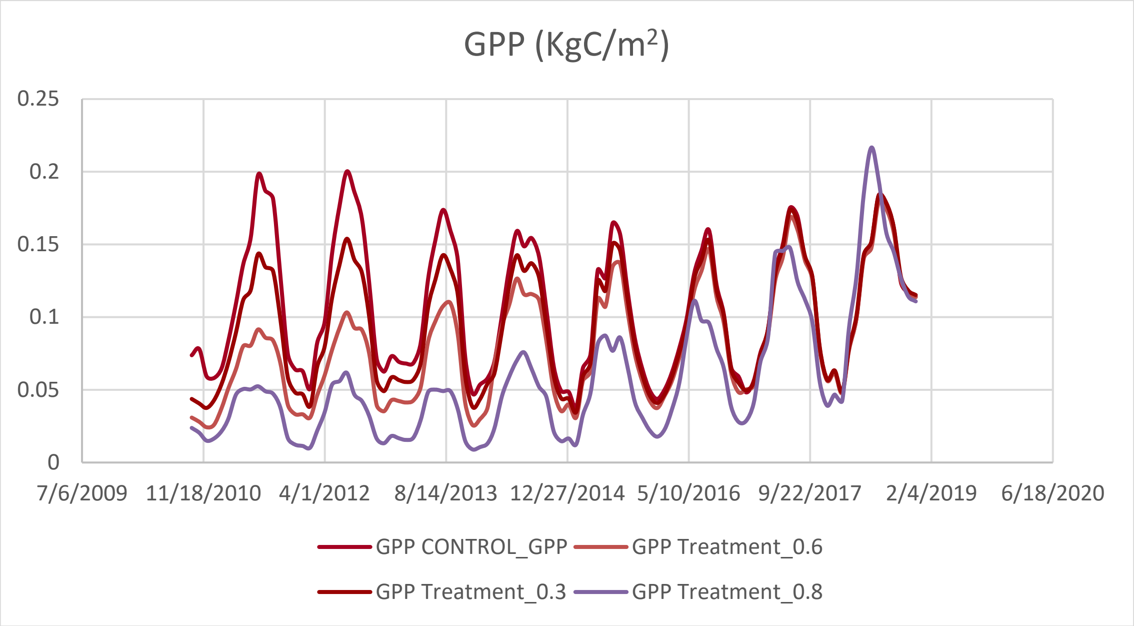

Figure 3: Daily GPP of the basic forest structure 18 (Stem-exclusion Aleppo pine stands) under different management intensities.

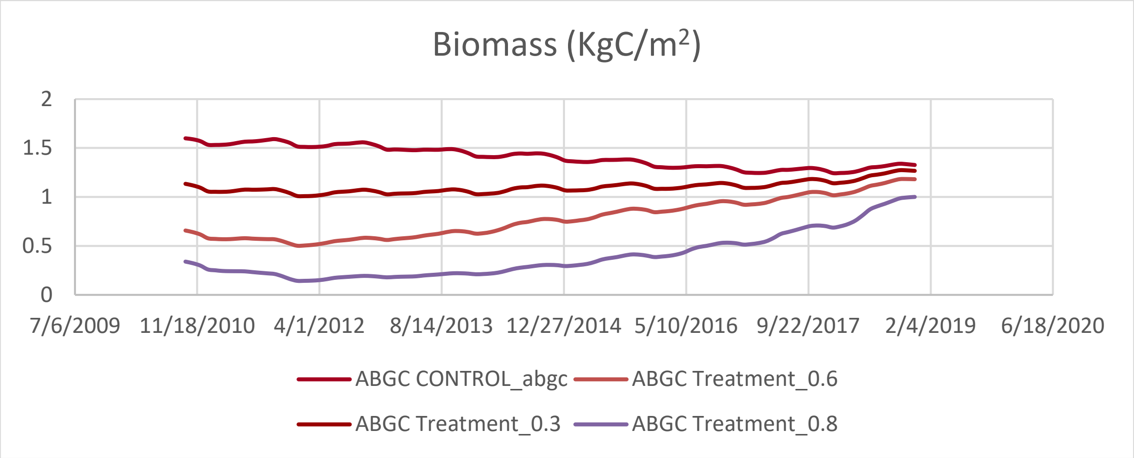

Figure 4: Daily biomass of the basic forest structure 18 (Stem-exclusion Aleppo pine stands) under different management intensities.

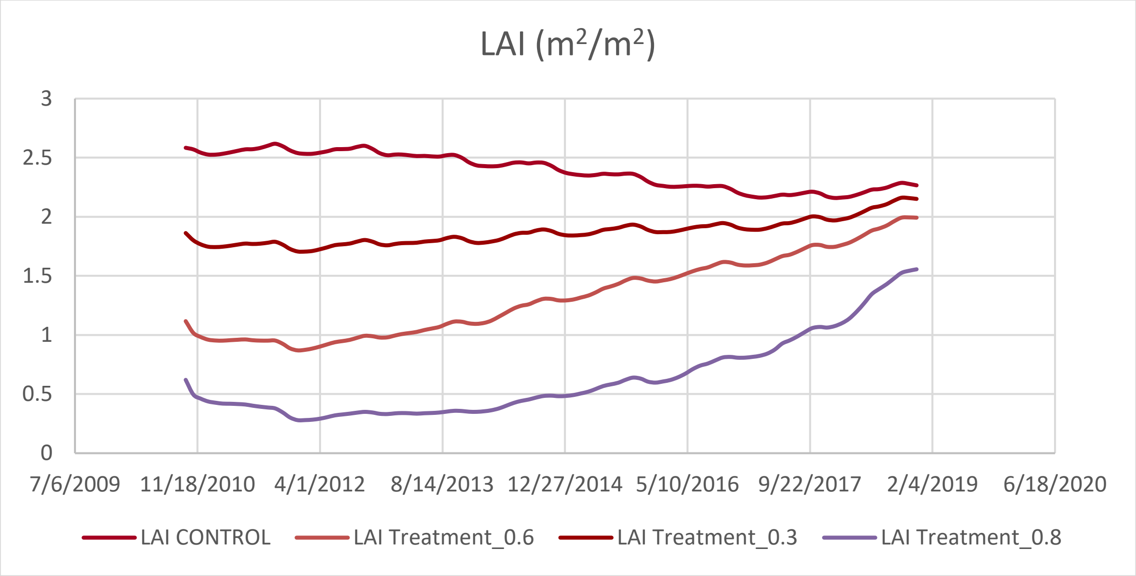

Figure 5: Daily LAI of the basic forest structure 18 (Stem-exclusion Aleppo pine stands) under different management intensities.

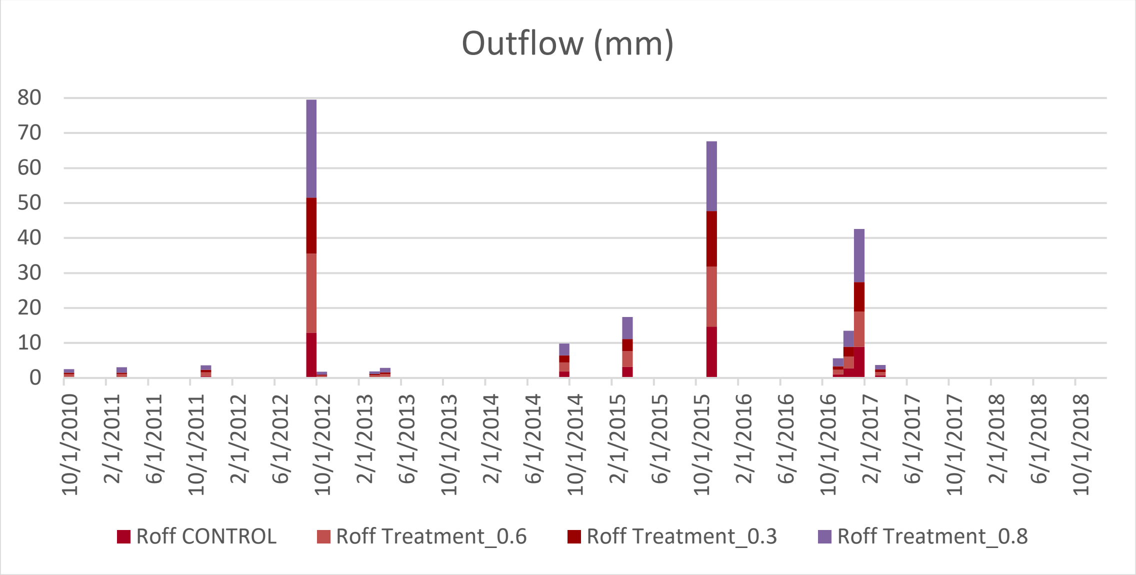

Figure 6: Daily outflow of the basic forest structure 18 (Stem-exclusion Aleppo pine stands) under different management intensities.

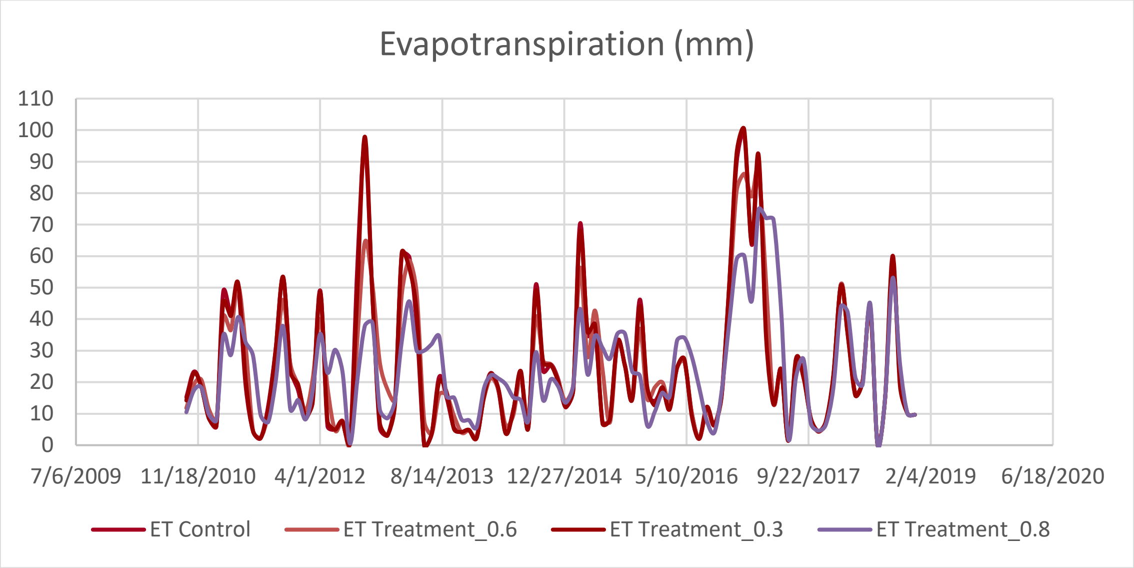

Figure 7: Daily evapotranspiration of the basic forest structure 18 (Stem-exclusion Aleppo pine stands) under different management intensities.

3.- Alternative approach: modelling

The main utility of the matrixes was its capability to represent the behaviour of basic forest structures regardless its soil, topography and climate. However, the application of this approach has been proved to be quite limited. On the one hand, the variability of the forest structure behaviour appears to be too high to be represented just in one single matrix. On the other hand, in order to develop the DSS tool, the matrixes need to be combined to a distributed hydrological model. Hydrological models are mathematical models representing the reality in a simplified form, and their parameters will be representative of the modelling scale and different to the ones measured in field (Mertens et al., 2005). Therefore, a new calibration will be needed, and the parameters that represent the forest structure might therefore change with the study site. As a result, in this deliverable the project team has decided not to use the basic matrixes but built these forest-water-soil-climate-fire relationships in each study case by means of calibrating and validating the hydrological model, a necessary step to use the DSS tool. In other words, the matrixes will be built, but using a distributed eco-hydrological model, which means they could be different among bio-ecological regions.

In order to confirm this decision, a first approach has been developed in Carraixet's catchment, which includes Serra's village (Figure 8). The parsimonious and dynamic eco-hydrological TETISVEG model proposed by Ruiz-Pérez et al. (2017) is used here to analyse the forest-water-soil-fire relationships under different management intensities of the basic forest structure 18 (Stem-exclusion Aleppo pine stands), and the implications at catchment scale of this forest management. First, the model is calibrated, validated and evaluated by using water discharge, field measurements (soil moisture and transpiration from AP) and satellite information (soil temperature from Landsat 8 OLI/TIRS Data). Then, the model is applied to simulate 10 different water years (2007–2017) with and without forest management. The results are analysed in terms of water production (outflow), biomass and fire risk and propagation.

The fire propagation is estimated by using FARSITE, where the total burned area of both scenarios, managed and unmanaged, is calculated by simulating 10 different forest fires within the 10 water years and during the highest fire risk period (summer). Each fire is simulated 3 times, using 3 different ignition points (upper, middle and lower area) and with a duration between 0.5 and 2 days.

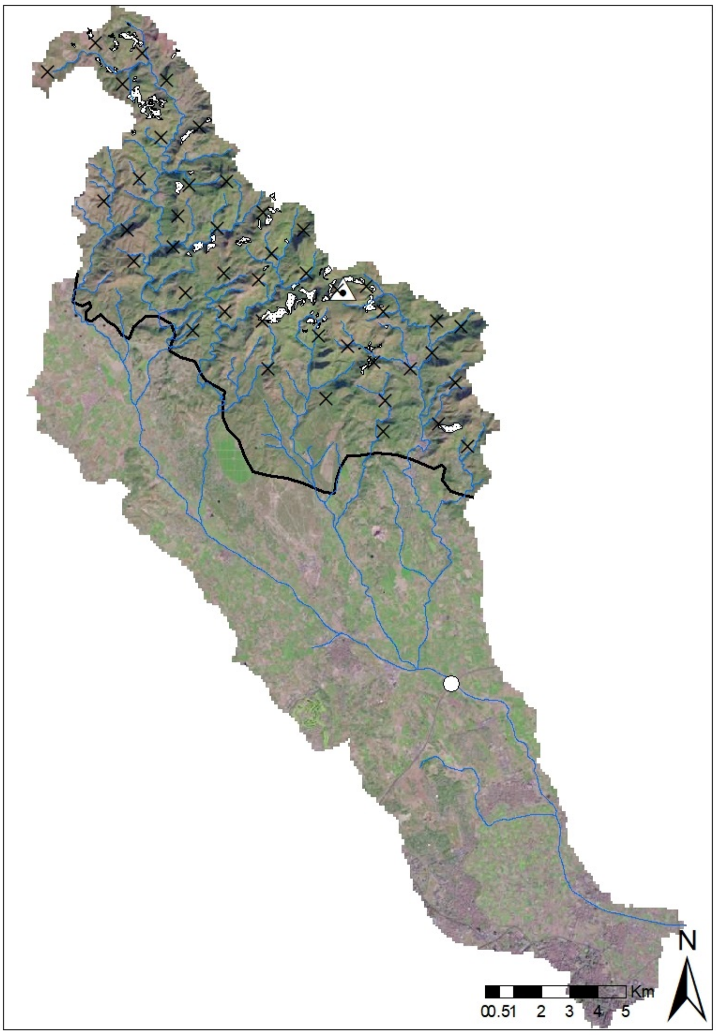

Figure 8: Carraixet’s catchment. Black line indicates the lower limit of the mountainous area. × indicates the location of the soil temperature points used in the model validation. Blue line is the river network. △ represents the field experimental plots. ⋄ indicates the populations that exclusively use groundwater. ∘ indicates the gauging station used during the calibration and validation of the model. Dotted polygons represent the Aleppo pine post-fire regeneration stands.

3.2.- RESULTS

3.2.1.- Calibration, Validation and Evaluation

The calibration and validation with the river discharge resulted in NSE indexes equal to 0.7 and 0.4, respectively. These results can be considered as satisfactory considering the difficulty of simulating intermittent rivers (Snelder et al., 2013; Ivkovic et al., 2014; Costigan et al., 2017). Likewise, the specific evaluation of transpiration and soil moisture dynamics within the experimental plots produced good results in both of them, control and treatment, indicating the good performance of the TETIS-VEG model in calculating the hydrological cycling of semiarid environments (Table 5). On the other hand, the spatial evaluation by comparing Land-surface temperature (derived from Landsat 8 OLI/TIRS Data) with simulated soil water content resulted in a significant negative relationship between both variables (Table 5). These results confirm the capability of the model in reproducing the natural correlation between temperature and soil water content under dry conditions (Redding et al., 2003), and therefore, its reliable performance in semiarid catchments.

Table 5: Calibration, validation and evaluation adjustment values. NSE represents the Nash-Sutcliffe coefficient. *p* represents the Pearson correlation coefficient. RMSE is the Root Mean Square Error.

Variable	**Location**	**NSE**	***p***	**RMSE**
Discharge (m^3/s)	Calibration	0.7	0.5	0.47
	Validation	0.4	0.5	0.47
Transpiration (mm)	Control	0.4	0.72	0.28
	Thinned	0.4	0.74	0.15
Soil moisture (cm/cm)	Control	-	0.44	-
	Thinned	-	0.43	-
Soil moisture *vs* Land-surface temperature	43 random points	-	0.60±0.11	-

3.2.2.- Modelling results

The local results at the managed stands showed a significant increasing of the stand ET, which was also significantly higher than that of the rest of the upper catchment area (see Table 6). In the case of deep percolation, a significant increase during 6 out of the 10 simulated water years was also obtained. Likewise, the effects of forest management at catchment scale on water contribution did significantly modify the general water budget, mainly by increasing the average ET. This ET increasing was not reflected on percolation nor runoff decrease, but a significant increase of percolation was also obtained. Nevertheless, deep percolation of the managed scenario only exceeded from that of the unmanaged in 6 out of the 10 simulated water years, remaining the same during the rest of the water years.

Table 6: Evapotranspiration (ET) and percolation values (mm/year) with and without forest management for the total upper catchment area and for the basic forest structure 18 (Stem-exclusion Aleppo pine stands).

Location	**Scenario**	**ET**	**Percolation**
Upper catchment	No management	304.1± 100.1	27.02± 25.20
	Thinned	304.8± 100.1	27.04± 25.21
Local stands	No management	305.6± 106.0	28.97± 22.29
	Thinned	316.7± 103.4	30.13± 27.08

The biomass production has been estimated in 15.3 T/ha, which in total reaches 4161.6 Mg of biomass. Regarding fire, forest management not only decreased fire risk, but also the fire propagation. Both parameters have been calculated in this deliverable by using the modified KBDI index following Garcia-Prats et al. (2015) and the FARSITE software, respectively. The results showed a significant decreasing of the fire risk that reaches 27± 17%, which implies changing from the very high fire risk category to above average fire risk. Likewise, the fire propagation did significantly decrease with the forest management, being the burned area 25.6± 14.1% lower than that of the unmanaged scenario (Table 6).

From this first approach, it can be stated that the effects of forest management on the target variables can be analysed using both catchment and stand scales by launching just one simulation. Therefore, it becomes a more convenient procedure than calculating the local matrixes of the basic forest structures and then applying them to the study site. Hence, from now on this will be the approach used in the project.

This first approach has already been published as a scientific paper González-Sanchis et al 2019, where RESILIENTFORESTS has been part of it.

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