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Preventive irrigation for fire defence in Mediterranean wildland-urban interface areas based on the ecosystem water status

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Abstract

In highly anthropized Mediterranean environments, more intense and persistent droughts alter the characteristics of the soil substrate and consequently the water status of the vegetation. Causing an increase water stress of the forest stands implies an increase in dead fuel availability and fire risk. This situation together with the current trend of urbanisation in areas adjacent to forest areas, generating the wildland-urban interface (WUI) areas, represents a new field in the firefighting, which presents both regulatory and technical deficits. This paper presents a management model based on the water quantification of the soil-plant-atmosphere system that defines the optimal amount of irrigation needed to decrease fire intensity to a suppression stage in the WUI of La Vallesa forest in the Natural Park of Túria (Valencia, Spain). Mainly highlighted is the ability to manipulate the fire behaviour by intervening the water status of the system through prescribed irrigation. We report that by means of irrigation, the moisture content of the forest system can be increased by 5.49 ± 3.97 %, which translated to energy, implies an increase in the capacity of the system to absorb 14.24 ± 10.32 kJ/kg and this translates into a decrease in a potential flame length of 0.10 ± 0.26 m above its height.

1. Introduction

The tendency in the Mediterranean areas to urbanize in areas adjoining natural systems (mainly forests), has generated a territorial concept called the wildland-urban interface (WUI), which is susceptible to risk since it connects the territorial dynamics with the problem of forest fires (Martín, 2012). Therefore, a fire in a WUI has direct consequences on the adjacent population, which can translate into economic losses due to the burning of agricultural land, buildings, vehicles, etc., and even endangers the safety of the inhabitants.

Historically, social awareness of this problem has been lower to that of wildland fires, which may have influenced the lack of current legislation, technical methods, and experimental evidence to deal with this new situation (Vacca et al., 2020). One key aspect in this WUI context is the possibility to deploy irrigation-based protection systems (e.g. www.sideinfo.es).

This work aims to provide a vision based on eco-hydrology that addresses the problem of fires in WUI areas. The capacity to manipulate forest-water relationships and hence the hydration of the ecosystem can consequently reduce the risk and danger of fires. The main objectives considered are: i) relate irrigation dosage with the water status of the system and fire behaviour parameters and ii) quantify the effect of system hydration on fire behaviour.

Abbreviations

EHV	Eco-Hydro-Voxel	σ	surface-area-to-volume ratio (ft^2/ft^3)
RH	relative humidity (%)	σ_x	surface-area-to-volume ratio specific to each fuel size and fuel type (ft^2/ft^3)
1-h	dead fuel with a diameter of less than 0.6 cm	wo	oven-dry fuel load (lb/ft^2)
10-h	dead fuel with a diameter of between 0.6 and 2.5 cm	wo_x	oven-dry fuel load specific to each fuel size and fuel type (lb/ft^2)
100-h	dead fuel with a diameter of between 2.5 and 7.5 cm	δ	fuel bed depth (ft)

h	low heat content (btu/lb)	M_x	dead fuel moisture of extinction (%)
S_T	total mineral content (fraction)	M_f	moisture content (%)
S_e	effective mineral content (fraction)	Q_{ig}	heat of preignition (kJ/kg)
p_p	oven-dry particle density (lb/ft^3)	F_B	flame length (m)

2. Material

2.1. Study area

The study area is located in a private forest called La Vallesa, which is part of the Turia Natural Park in the province of Valencia (Spain). The climate is typically Mediterranean with a marked summer drought. The main land use is forestry with some abandoned agroforestry areas. However, there is also a strong anthropic influence, as the forest is surrounded by residential developments, with an estimated potential impact of 15,000 inhabitants in the event of a fire. Research plots were established in the forest in a representative area dominated by a *Pinus halepensis* stand and constituting a TU2 fuel model (Scott & Burgan, 2005).

2.2. Water status monitoring

The plots have a network of sensors that continuously measure the variables necessary to know the water status of the system. The quantification and therefore monitoring of the actual water status of the forest is done through the "Eco-Hydro-Voxel" (EHV) concept. The EHV is a typified volume of space based on the SPAC, which allows quantifying the amount of water stored in the different compartments or tanks of the volume along the SPAC. Tanks are defined according to the most representative compartments of the SPAC: saprolite/deep soil, surface soil, duff/litter, scrub, trunks, branches, canopy/living leaves and atmosphere.

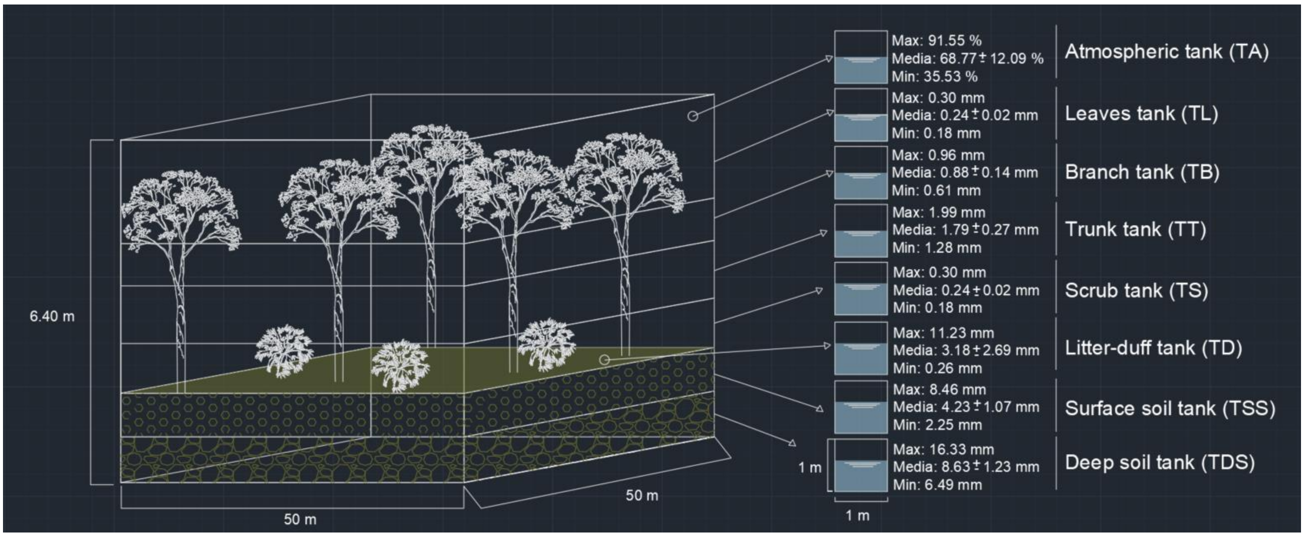

Figure 1- Schematization of the Eco-Hydro-Voxel (EHV) with its subdivisions or tanks. In addition, the basic statistics (maximum, mean ± standard deviation and minimum) of each water content of the tanks are presented.

For the present study, focusing on surface fire, duff/litter, scrub and atmospheric tanks have been used. Litter/duff tank moisture (%) is measured by soil moisture sensors installed between the litter layer and the decomposing organic horizon. Scrub tank moisture (%) is estimated by using an empirical model based on vapour pressure deficit, which was calibrated and trained with real measurements made in different sampling campaigns. Atmosphere tank moisture has the relative humidity (%) and vapour pressure deficit (kPa) as its main proxies for moisture content. These variables are measured by a weather station installed 2 m above the canopy, which also measures the wind speed (m/s) and the temperature (ºC).

Based on the EHV, the calculation of the moisture content (M_f, %) parameter is made, which is a measure of the amount of water in an environment available to a fire. Therefore, this parameter will be the link between the water status of the system and the energy of the fire. Classically this measure of M_f was composed of dead fuels (1-h, 10-h and 100h) and live fuels (herbaceous and woody). Specifically, 1h-moisture was estimated through the moisture content of litter/duff and the atmospheric tank (Rakhmatulina et al., 2021), and in this study it has been considered that each tank represents 50 % of the total moisture content. The moisture of litter/duff tank that represents this 50 % was included without transformation, however, for the value of the atmosphere tanks, relative humidity and temperature were selected and these two variables were combined using the Baksic et al. (2017) procedure, thus obtaining the value that will represent the other 50% of the humidity of 1h. On the other hand, 10-h and 100-h moisture content dynamics were obtained following Balaguer-Romano et al. (2020). These authors consider constant proportions between the different dead moisture contents; thus, we follow this approach to calculate 10-h and 100-h moisture contents as a function of the 1-h moisture content. Finally, the moisture content of the live woody material is taken directly from the moisture content of the scrub tank.

2.3. Effect of irrigation on fire behaviour

The design of preventive (prescribed) irrigations is based on two fundamental objectives: i) to increase the operational capacity of the system and ii) to reduce the danger and potential risk of a fire. Operational capacity refers to the energy absorption capacity of the system through its moisture content. This concept has been studied through the heat of preignition (Q_{ig}, Rothermel, 1972), which is the energy required for one unit of fuel to reach ignition and it is directly related to its moisture content. Fire danger is represented by the flame length (F_B, Byram, 1959) i.e., the distance measured from the tip of the average flame to the center of the flame zone at the base of the fire, and has been considered as potentially dangerous when it exceeds 1.2 m. It is calculated as a function of fire intensity (I_B). For the inputs related to the fuel particle properties, we used standard values: h = 8,000 Btu/lb, S_T = 0.0555 lb minerals/lb wood, S_e = 0.010 (lb minerals – lb silica)/lb wood and p_p = 32 lb/ft3. Some fuel array properties were calculate based on weight method, where σ = 1813.42 ft2/ft3 [σ_{1h} = 2000; σ_{10h} = 109; σ_{100h} = 30] and *wo* = 0.22 lb/ft2 [wo_{1h} = 0.06; σ_{10h} = 0.10; σ_{100h} = 0.05; σ_{1h} = 0.01], the parameter δ was measured (0.33 ft or 10 cm), and the M_x = 30 % (TU2 model as in Scott & Burgan, 2005). Finally, the environmental parameters correspond to real measurements carried out in the experimental plots (weighted moisture content and wind velocity at midflame height). As the plot is very flat, a value of slope = 2.5 % is considered.

3. Results

Detailed quantification of the EHV water reservoirs has shown a clear response of fire behaviour to water input as related to seasonality. With the onset of dry season, the tanks had low moisture content values and Q_{ig} is low and therefore the F_B is high (Figure 2). The accumulated water input (precipitation) in this dry period (dehydrated system) was 60 mm; and the average M_f was 11.63 ± 3.17 %, (average litter/duff humidity of 4.63 ± 3.90 %, scrub humidity of 75.50 ± 7.35 % and atmospheric humidity of 68.33 ± 12.12 %), resulting in an average Q_{ig} of 611.69 ± 8.23 kJ/kg and F_B of 0.84 ± 0.16 m. However, in the humid period (hydrated system), there was a total precipitation of 320 mm, the mean M_f increased to 19.34 ± 3.86 % (litter/duff with 13.75 ± 3.84 %, scrub with 89.02 ± 4.57 % and atmospheric with 74.43 ± 15.26 %), Q_{ig} increased to 631.71 ± 10.02 kJ/kg and F_B decreased to 0.75 ± 0.29 m.

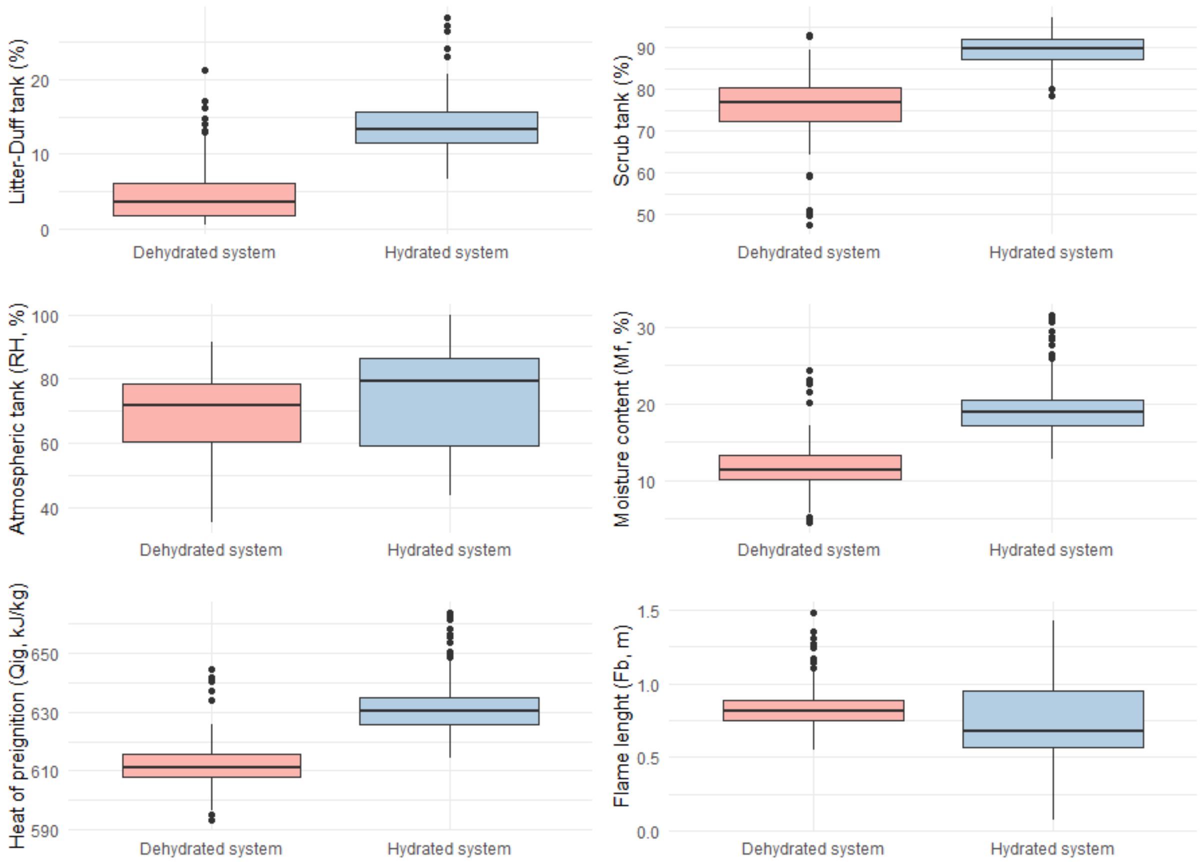

Figure 2- Comparison of the parameters studied in relation to a period of hydration and dehydration.

Regardless of the amount of precipitation and the previous hydration status of the system, the variation observed in M_f between the day before (dry condition) and the day of the water input suffered an increase of 5.49 ± 3.97 %, specifically the moisture content of the litter/duff increased 2.00 ± 3.87 %, the scrub 7.76 ± 7.21 % and the atmosphere 7.47 ± 8.57 %, this translates into a change in fire behaviour of an increase in Q_{ig} of 14.24 ± 10.32 kJ/kg and a decrease in F_B of 0.10 ± 0.26 m. In a particular case where a rainfall of 3 mm occurred (wind speed remained comparable, 1.24 m/s the day before and 1.06 m/s the day of the rain), the system in the day before had a litter/duff tank moisture content of 4.62 %, the scrub tank of 75.10 % and the atmospheric of 49.94 %, being a total M_f of 10.62 %, which makes its potential fire behaviour a Q_{ig} of 609.08 kJ/kg and an F_B of 0.90 m. However, after the occurrence of this precipitation, the system elevated its hydric status to a litter/duff moisture content of 5.82 %, 79.90 % in the scrub tank and 72.72 % in the atmospheric tank, with a total M_f of 12.81 %, implying an increase in Q_{ig} to 614.76 kJ/kg and a reduction in F_B , which became 0.80 m (Figura 3).

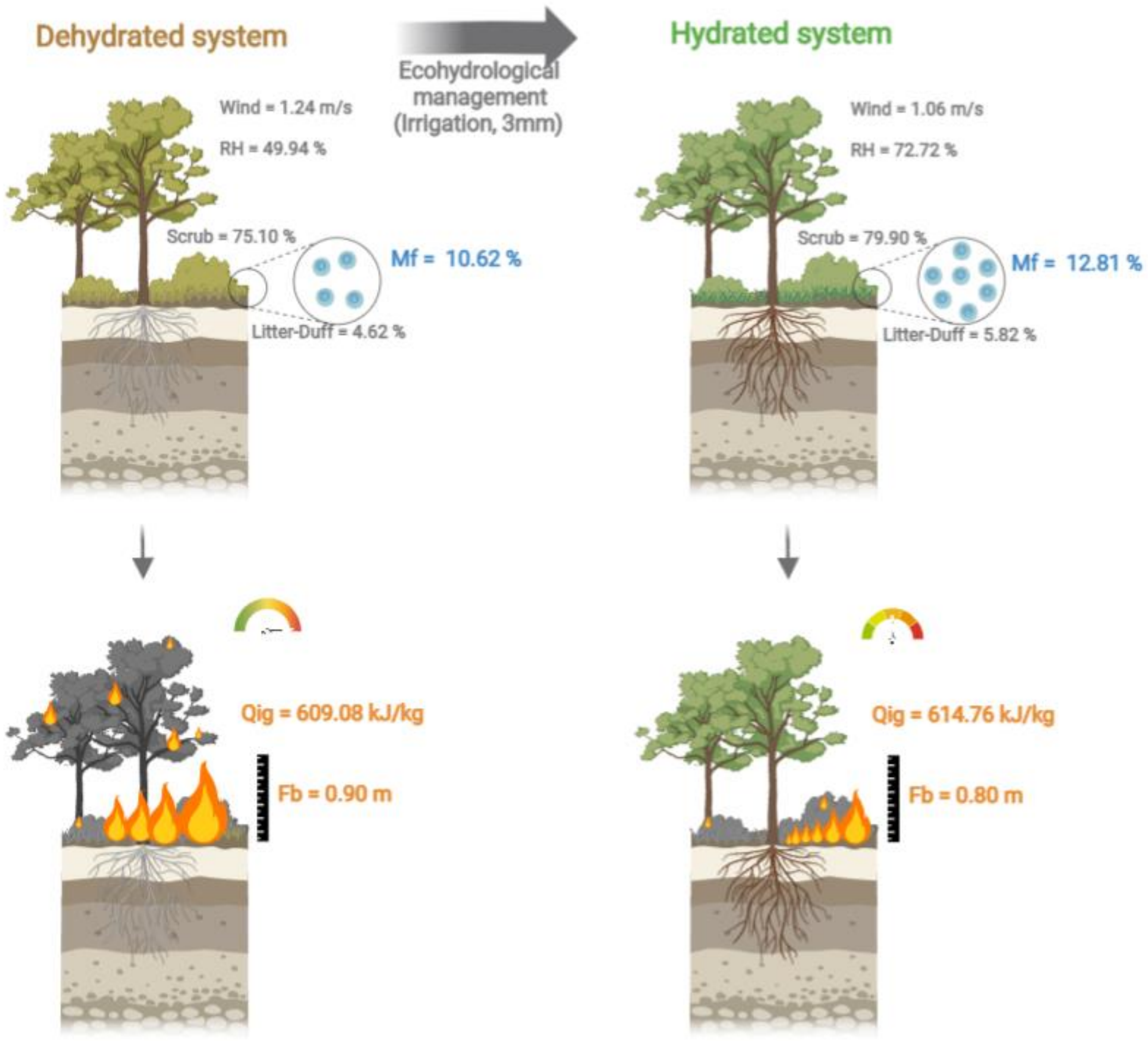

Figure 3- Case study of the change in moisture content (Mf), the EHV tanks used for its estimation (atmospheric or RH, scrub and litter-duff) and associated fire behaviour (flame length (Fb) and heat of preignition (Qig)) of the same system after a 3 mm rainfall.

4. Discussion

The EHV concept, through which the hydric state of the system has been quantified, has been a key point to study the irrigation-system-fire relationship. The main nexus of this relationship has been the transformation of system hydration into fire terms, i.e. the estimation of M_f (input for fire behaviour calculation) through the quantification of the EHV tanks (litter/duff, scrub and atmosphere). Furthermore, eco-hydrological monitoring of the system has allowed us to know the capacity and the real manipulation range of the hydration of the system through irrigation and thus the potential for the variation of fire behaviour.

The quantification of water and fire behaviour relationships is useful in fire-prone areas as it provides key information related to fire risk, availability of fuels, capacity for fire suppression, threats and danger to inhabitants as in the case of WUI areas. In this study it has been seen that through irrigation it is possible to increase the operational capacity of the system by 14.24 ± 10.32 kJ/kg on average, making a fire have to consume this additional heat amount before spreading, even decreasing the potential flame length by 0.10 ± 0.26 m on average, thus reducing the potential danger of the fire and increasing the probability to put the fire out. In addition, this approach that relates irrigation-fire makes it possible to develop irrigation algorithms, which will have the objective of minimizing the water supplied to obtain the greatest benefit of the characteristics of the fire behaviour (Blanco-Cano et al., 2022).

The practicality of the approach of increasing water status through irrigation could be a problem in areas affected by droughts, as water availability is low. This situation can be solved through: i) Use of reclaimed water, ii) eco-hydrological management: thinning and planting of green firebreaks. In reference to the use of reclaimed water the GUARDIAN project (https://proyectoguardian.com/) is a real-life solution and is currently installed in a semi-arid Mediterranean area. On the other hand, thinning, beyond reducing fuel load (which is the classic view in forest fire prevention), is known to increase the water status in the remaining trees (Del Campo et al., 2019; Manrique-Alba et al., 2020) and it should be included in the design of such treatments. Finally, the planting of green firebreaks consists of planting vegetation with low flammability and water retention mechanisms that allow them to have a relatively higher water content. In addition, these firebreaks can generate more humid and shaded areas, which allows for better water retention (Cui et al., 2019). This vision of hydric manipulation through eco-hydrological management for areas where water limitation is a critical factor in water supply through irrigation.

It can be concluded that fire management in WUI zones must bet on taking a pyro-eco-hydrological approach, understanding that the moisture content of the system can be modified and manipulated within certain ranges and that these modifications will have direct changes in the fire behaviour.

5. Acknowledgements

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