Post-fire soil Dynamics:
Influence of Consequent Wildfires, regrowing Plant Species, and Management on Soil Water Repellency, Carmel Mt., Israel

MSc Thesis by

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Date: September 2011

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Master thesis Land Degradation and Development Group submitted in partial fulfillment of the degree of Master of Science in International Land and Water Management at Wageningen University, the Netherlands

Study program:
MSc International Land and Water Management (MIL)

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Date: September 2011

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Acknowledgment

While working in the Carmel National Park I learnt what cannot be learnt out of the books. Learning about complex natural processes in the fields is something that can be achieved with perseverance and with the right help. I’m deeply grateful to who let this happen and to who gave me the chance and the opportunity to live this experience. The department of Geography of the University of Haifa gave me the chance to taste what is the meaning of doing in depth field-work and to look at processes as a whole complicated bundle made of many threads deeply interconnected between each other; thanks for that. Lea Wittenberg and Dan Malkinson were my guides through my permanence in Israel and help in difficult moments. A special thanks goes to Lea for hosting me in her house in moments of emergency as a wildfire approached the evacuated university campus. I felt at home and I will be always grateful for the feeling of safety and excitement that I faced in those days. Naama Tessler has provided me with precious help and hints throughout the whole study. That made the process a little bit easier, thanks. I cannot forget to acknowledge the university of Wageningen that hosted me and make me grow in these wonderful years. Thank you Saskia Keesstra, for the support, the ideas and the moral help that you always provided me. I will not forget the moments that despite the difficulties you helped me to overcome. I want to acknowledge my family that made this dream come through and are by my side in every moment. “Grazie mamma e babbo, grazie fratelli, grazie Gigi e Vanda, grazie nonni Samba". Thank you Pia, for the support, the patience and the constant presence. And thank you all my friends for being always there, for being sympathetic when I was worried, for always giving a hand when needed.

Abstract

In a highly anthropomorphised environment like the Mediterranean basin, wildfires have been a constant presence and in the past years their occurrence has increased. Israel makes no exception to the rule and shows a remarkable increase in number of wildfires, in the burnt areal and in its severity. Among the effects caused by fires is Soil Water Repellency that can seal the soil surface and influence bigger scale watershed processes. Water repellency is believed to be induced by fires, but also by various biotic factors as vegetation, soil microorganisms and organic material. The interaction between these factors has been analysed by means of the Water Drop Penetration Time tests in a detailed temporal and spatial scale, five years after the most recent fire. A particular importance has been given to the influence of plants, post-fire management and fire history. The results showed that, five years after a fire, the biotic factors prevail on the direct effect of fire in inducing Water Repellency. In facts, the non-burnt area showed a higher hydrophobicity than the burnt experimental plots. Furthermore, plants like *Pinus halepensis* seems to have an influence on WR only in a mature ecological stage in which the pine litter is thicker and plays a fundamental role in inducing hydrophobicity.

Keywords: Water repellency, WDPT, Carmel, Wildfire, Fire effects, Vegetation recovery, post-fire management.

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List of Abbreviations

CNP: Carmel National park
WR: Water Repellency
WDPT: Water Drop Penetration Time
OM: Organic Material
EC: Electro-conductivity
I: Single fire
II: Double fire
X: Control plot
C: Clear-cut
N: Natural regrowth
Spp: species

1. Introduction

a. Wildfires: Global occurrence, Mediterranean incidence, and Consequences on the ecosystem

In recent years, wildfire occurrence has been a subject of increasing media attention due to the boosting appearance of so-called Mega-fires. Events like the 2007 wildfires in Greece and the 2010 wildfires in Russia and Israel showed how wildfires still can be a natural power beyond human control (Williams et al., 2011). In a global scenario, the most common cause of wildfire is human negligence and arson. Mankind causes around 90% of the wildfires, which rarely occur spontaneously (UNEP, 2004). In the Mediterranean basin due to the high demographic pressure and favorable conditions, the natural fires represent only 1-5 % (FAO, 2001). Despite the global occurrence, wildfires are particularly common in ecosystems characterized by a long and dry summer. In fact, Chaparral, Mediterranean and Coniferous forests are often hit by recurrent blazes (Liu et al., 2010). It has been demonstrated that since the 1960s the number of wildfires in the Mediterranean increased; in particular in the Iberian, Italian and Greek peninsulas (Pausas and Vallejo, 1999). In Israel, like in its neighboring countries, wildfires occur annually. In the five years span of 2003-2007, an average of 1000 ha of forests burnt every year in Israel alone (FAO, 2010). In the period 1978-2006 the Haifa City Fire Department registered 9 major fires that destroyed areas of 80-530 ha each. Around 350 smaller fires were recorded in the same period (Tessler et al., 2008). Among the fires that hit the Carmel National Park (CNP), two events that occurred in 1989 and 2005 arrived to touch the areas close to the University of Haifa. The management of the fire aftermath consisted in clearing out the remains of the charred trunks and in few cases the vegetation was left to grow back naturally.

Apart from the often-dramatic impact on human activities, wildfires are also regarded as a vital and constantly present element of agro-ecosystems (Agee, 1996). Forest fires in the Mediterranean region commonly occur and induce multiple changes in the vegetation cycles, in the soil, and in the hydrological properties of the affected area (Shakesby and Doerr, 2006). Consequently, it helped in selecting and in promoting the most fire-resilient plants among other species. Buhk et al. (2007) demonstrate that the long fire history in the region has been a selective force for flora adaptation to fires. This way, it helped to define the global biome and to maintain the structure of communities resilient to fire (Bond and Keeley, 2005; Keeley, 1986). The role of fire in shaping ecosystems dates back to the beginning of the quaternary and the vegetation subsequently adapted to different fire regimes (Pausas et al., 2008), as is the case in the Carmel National Park. As consequence of the fire disturbances and the long historical human husbandry, degrading and regenerating patches of plant communities characterize this area. Its variety ranges from rich grasslands and woodlands to depleted dwarf-shrub communities, to denuded rocky areas (Naveh and Carmel, 2003).

The fire provokes not only the combustion of the vegetation, but it also causes the charring of the organic matter present in the litter and in the uppermost layer of the soil. The depletion of organic material has profound effects on soil properties such as soil structure and soil permeability (García-Corona et al., 2004). Furthermore, nutrient cycles are overturned and chemical properties mutated (Certini, 2005; DeBano, 1991). The freshly burnt ashes enrich the soil and cause a pH increase, but due to the highly

soluble nature of the nutrients released, the effect usually do not persist the wet season (Ulery et al., 1993).
The heating effect of fire may change the structure of the soil by affecting either the clay component or the organic material content. The organic material is predominant in the top layer; it is easily oxidized at relatively low temperature and has an important role in binding particles and in consolidating soil aggregates. When a wildfire happens, the downward moving heat directly influences the organic layer and as a consequence its binding characteristics are disrupted (Úbeda and Outeiro, 2009). Furthermore, higher temperatures are needed to alter the clay minerals in the soil. DeBano (1998) showed that a temperature of 400°C is needed to cause significant alterations and to remove the group –OH from the clays (DeBano, 1998). It follows that the depletion of OM occurs in an earlier stage and has a stronger influence on structure than the effect of fire on mineral soil.

b. Fire induced water repellency (WR)

After a fire, a water repellent layer is commonly found on the surface of the soil or a few centimeters beneath it. This hydrophobic layer is believed to be a response to moderate heating of organic matter. The volatilized OM moves downward following a heat gradient and binds to the soil particles or to the spaces in between (Certini, 2005). In this process, the temperature of the fire plays a key role in determining hydrophobicity. Laboratory tests have shown that between 175°C and 270°C hydrophobicity increases, whereas between 270°C and 400°C it is again destroyed (Doerr et al., 2009). Other studies have classified the hydrophobic organic compounds into two main groups: aliphatic hydrocarbons and amphiphilic structured hydrocarbon chains. Both groups have the peculiar characteristic of having a chained morphology with at least one of the two ends being hydrophobic. This characteristic makes the bond with soil substrata particularly resistant to the influence and attraction caused by the dipolar properties of water (Doerr et al., 2000). However, due to the complexity and variety of the organic materials present in the soil, a clear identification of the hydro-repellent substances is far to be complete (DeBano, 2000). The interaction between water and the hydro-repellent layer is therefore characterized by a decreased number of bonds that causes the water droplets to ball up and stand on the soil surface for prolonged time. This mechanism is associated with the water-solid contact angle. The water infiltrates in a soil if the contact angle is lower than 90 degrees (figure 1). Whereas when the contact angle is equal or greater than 90 degrees the drops tend to ball up and to resist infiltration. The fact that the droplet will eventually infiltrate indicates that the contact angle changes and that it decreases under the 90 degrees threshold (Letey, 2001).

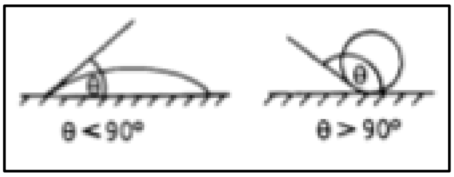

***Figure 1**: The drop in the first illustration creates binds with the soil causing a contact angle (**θ**) smaller than 90°. In the second illustration, the behavior of a drop on an hydro-repellent soil is showed (Tschapek, 1984).*

Furthermore, different and sometimes opposite soil behaviors in reaction to wildfire have been documented. The burn severity often shows a spatially differing distribution due to the non-homogenous behavior of the fire (Hubbert et al., 2006). This variability is likely to be a consequence of the fire characteristics and the pre-fire vegetation conditions, or soil properties (Doerr et al., 2009; Robichaud and Miller, 1999) and often results in a heterogeneous water repellent (Hubbert et al., 2006).

Soils tend to become less water repellent as the soil moisture increases. After a fire, water repellency tends to diminish and to get closer to pre-fire values or to settle towards a new balance influenced by the re-growing vegetation (figure 2) (Doerr et al., 2009). When a certain soil moisture value, called critical threshold, is reached the soil becomes wettable again. This threshold spans from as little as 5% for sandy soils to more than 30% for finer soils (Doerr et al., 2009). As the soil dries out the WR repellency tends to be restored (Doerr et al., 2009). WR can be assumed to be absent as long as the moisture is above the critical value. The factors influencing the restoration might be of biological nature coupled with the soil water content (Doerr and Thomas, 2000). The effect of factors other than moisture needs to be investigated to understand the correlation between WR and the surrounding environment.

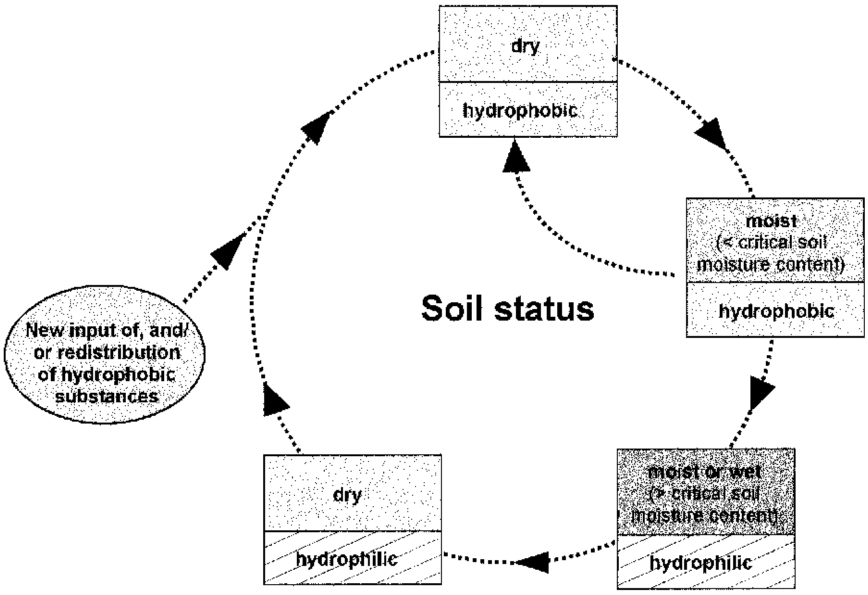

Figure 2: *Drying cycles with hydrophobicity variation in a freshly burnt soil. The Water Repellency is believed to vary its presence according to the soil moisture. (Figure adapted from Doerr and Thomas, 2000)*

Nevertheless, water repellency can be also naturally induced by various factors other than wildfires (Doer et al., 2000). This fact leads to the scientific problem of understanding when WR dynamics in a long run scenario are influenced by the fire effects and when from other natural processes like biological activity, soil type and OM content. This is especially true in an inter-annual scenario. According to the work of Malkinson and Wittenberg (2010) the often-reported increase of WR after a fire event is followed by a sharp decrease in its value. Subsequently the OM augmentation and the recovered soil biotic activity characterize the soil that shows a newly increased hydrophobicity. Their hypothesis was tested in a study that addressed a burnt areal where consequent fires occurred. The control areas showed the highest degree of WR followed by the area burnt 16 years in advanced and by the area that burnt 2,6 and 7 years earlier. This suggests a biological contribution to the restoration of hydrophobicity to levels similar to the one in control-natural conditions.

The intra annual, short-term variations in WR are mainly driven by change in soil moisture. When a critical soil moisture threshold is reached, the soil become wettable again. As it dries out WR tends to be reestablished. On the other hand, inter annual variations are mainly influenced by a complex matrix of factors involving chemical and biological processes (Doerr et al. 2009). It should be noted that 5 years after a fire most of the studies identified a decrease in fire induced WR, only in few cases the effects were seen for longer times (Doerr et al, 2010).

c. and challenges

The current literature is mainly focused on the changes in soils right after a single fire event (Wittenberg and Inbar, 2009). Some studies concentrate on the geomorphological action of fire. For instance, Inbar (1998) shows that the watershed response to a single fire changes its behavior over a five years time span, after which it goes back to sediment yields similar to pre-fire conditions (Inbar et al., 1998). Furthermore, Wittenberg and Inbar (2009) study the increased erosion rate and the sediment yields that occur when there is a succession of multiple wildfires. Nevertheless, present studies on water repellency are lacking a deeper understanding of the mechanisms underlying beneath the recovery of the soil hit by recurrent fires in a decadal long term perspective (Malkinson et al., 2010).

There are publications on water repellency pinpointing the influence of the burnt vegetation in micro-scales. Arcenegui et al (2007) demonstrates that soil texture, the presence and typology of charred litter influence water repellency. Other studies focus on the effect of vegetation on WR in not-disturbed conditions (Mataix-Solera et al., 2007). Nevertheless, the linkage between fire-induced water repellency and plants-induced water repellency is poorly investigated. The scarcity of literature about long-term factors influencing WR is explained with (Doerr et al., 2009):

(i) The paucity of long term studies
(ii) The large variability of the results
(iii) The different interpretation of water repellency used by different scholars
(iv) The obstacle of isolating the different processes influencing WR in the long run

Furthermore, the most commonly used methodology is based on experiments in controlled conditions. The samples are brought to the lab, sieved, dried and then used for the Water Drop Penetration Time test (WDPT) (Mataix-Solera et al., 2007; Novak et al., 2009; Arcenegui et al., 2007; García-Corona et al., 2004). This procedure is likely to disturb the natural characteristics of the soil (Graber et al., 2006). Doerr (2004) states that to better understand WR and all the involved processes, scientists should broaden the spectrum of the research because biotic and hydrological processes are connected in a non-linear way and cause non-linearity in WR. In order to tackle the high spatial and temporal variability it is therefore necessary to perform detailed studies of the small-scale processes in order to better explain the non-linear variability of this phenomenon and of consequent larger scale phenomena (Doerr and Moody, 2004). In other words, it is necessary to look at the single factors and their interactions to understand the overall process.

This study looks at soil water repellency as a process resultant of multiple, interacting factors. Fire history, regrowing plants and post-fire management are critically investigated as determining factors in a time dependent system (Figure 3). The complexity of the process is addressed by attempting to minimize disturbance to the samples by working in natural field conditions, *in situ*.

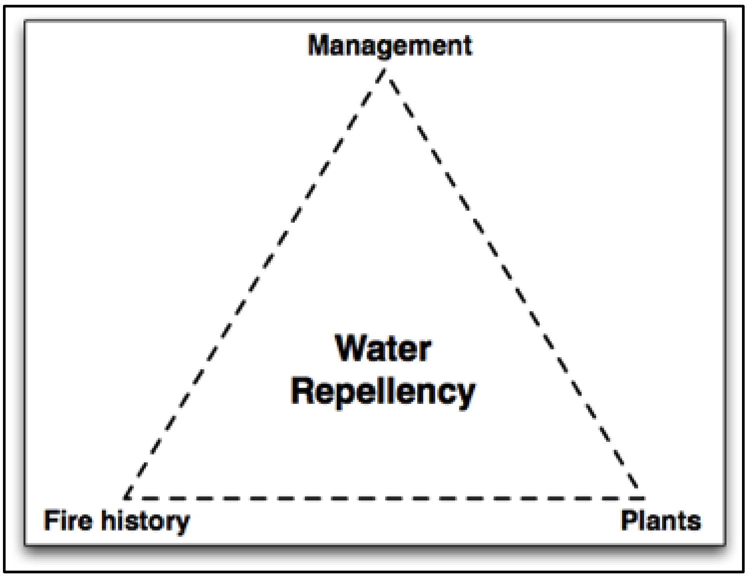

Figure 3*: Scheme of the study concept, underlining the main factors analyzed and influencing WR (Source: Sambalino 2011)*

2. Objective and Research Questions

a. Objective

The objective of this study is to investigate the dynamics of water repellency on fire-damaged soils and its relation with different management practices and vegetation regrowth patterns. A particular focus will be on the role of the micro-scale distribution of the vegetation, the fire history and their influence on the rehabilitation processes. Water repellency (WR) will be analyzed in a detailed temporal scale to clarify its dynamics following rainstorms, five years after the most recent wildfire.

b. Research Questions & sub-questions

- Does water repellency occur, and what are its properties in a long-term (decadal) post-fire scenario?

  a. Under what conditions does it occur?
  b. What is the magnitude and its variation in a short time scale analysis?

- Does <u>fire history</u> influence water repellency?

  a. How does it affect the WR response to rainfall events and to the following drying cycles?
  b. Does the WR reappear shortly after the rainfall event?
  c. What influence does fire history have on other soil parameters (pH and EC)?

- Does the regrowing vegetation influence water repellency?

  a. How does it affect the WR response to rainfall events and to the following drying cycles?
  a. Is there a correlation between vegetation type and water repellency?
  b. Is there any biota related WR?
  c. Which species influence WR most?

- Do post-fire management practices affect WR?

  a. How does it affect the WR response to rainfall events and to the following drying cycles?
  b. What is the influence of clear-cut and natural regrowth on WR?

3. Study area

The study area is situated on the Carmel mountain range, in the Israeli northwest coastal region. The soil is characterized as brown or grey rendzina, rich in chalk and limestone (Tessler et al., 2008). The experiments took place on the northern slopes of the range that have been subject to wildfires in 1989 and 2005 (Kutiel, 1994; Inbar et al., 1997; Ne'eman, 1997; Tessler et al., 2008). In this area, the lithology and the topography are homogeneous. A typical Mediterranean maquis covers the Carmel and is characterized by a blend of high-standing plants, shrubs and trees. Shrubs as *Pistacia lentiscus*, *Cistus salviifolius* are growing alongside with tree species such as *Quercus calliprinos*, *Arbutus andrachne* and *Pinus halepensis*. The flora adapted to recurring wildfire with different strategies (Naveh and Carmel, 2003):

1. *Pinus halepensis* is an obligatory seeds regenerator implying that its regrowth relies on the production of seeds. The heat triggers their spread that opens the otherwise closed cones.
2. Other plants such as *Pistacia lentiscus* are obligatory roots-resprouters, which are more resistant to fire damage. They re-sprout in the following season taking advantage of the rich starch reserves located in their root systems.
3. *Cistus salviifolius* is an example of facultative root resprouter that can either regrow from the roots crown or can re-germinate from seeds.

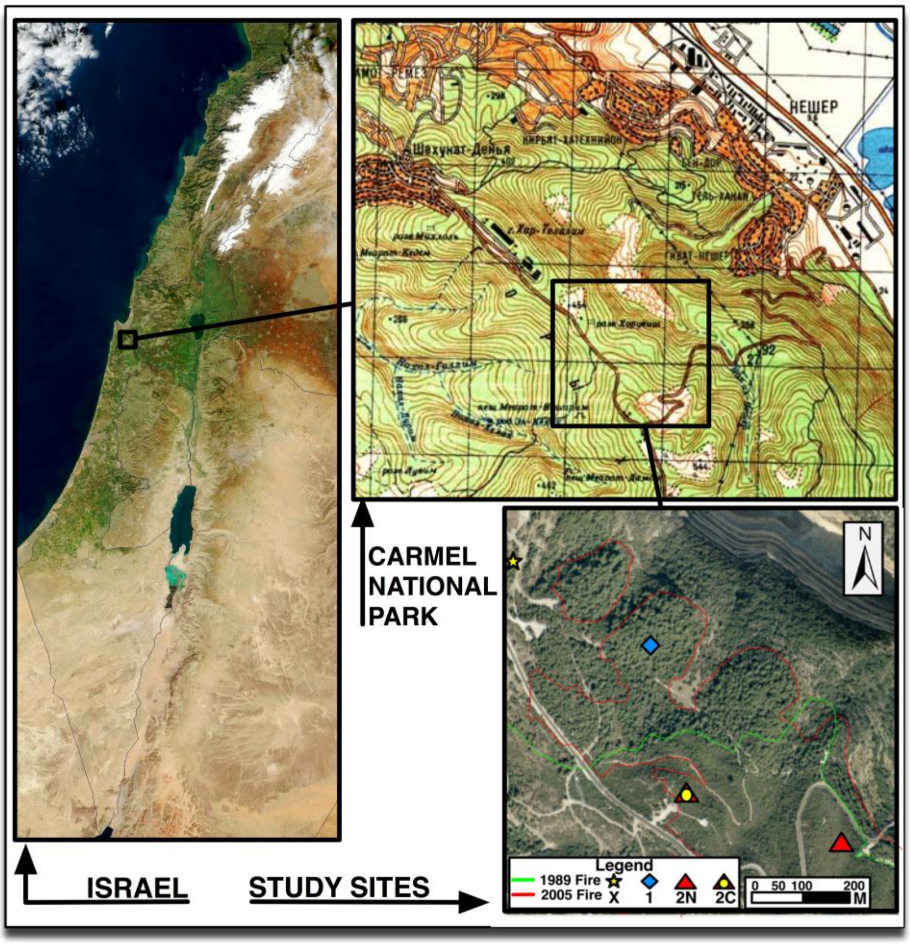

Figure 4: *Location of the research project. From the left: Israel, Carmel national park near Haifa university, and finally the study sites.*

After the 1989/2005 wildfire, two types of management practices were executed. The most common practice in the region was the total removal of all burned vegetation ('Clear-cut'), which was performed with heavy machinery. A small portion of the area was left untouched and the vegetation has regrown naturally without human intervention. Most of the trees were logged to avoid the accumulation of potential fire fuel and also because *Pinus halepensis* is an obligate seeder and it has a high germination rate that allows it to regrow even when all the charred plants are removed (Inbar et al., 1997). Furthermore, there were not any negative correlations between post-fire management, species distribution, and vegetation cover that refrain from the clear-cut practice (Ne'eman, 1997).

4. Methods

A detailed analysis of WR repellency was performed to assess what are the effects of wildfires on a mediterranean setting, 5 years after the most recent fire. Water Drop Penetration Time test (WDPT) was reiterated weekly in order to compare between the effects of different plant species, fire history and post-fire management on water repellency, with a detailed temporal resolution. On the same day of the field experiments, soil samples were collected in every plot in order to test soil parameters in the laboratory like water moisture, organic matter and texture. Statistical analysis was used to interpret the data, to unveil important trends and to draw conclusions.

a. Experimental design

In the northern slopes of the Carmel mountain ranges, we identified areas (figure 4) that were subject to fire once (I) or twice (II). The 2005 wildfire affected both areas, while the 1989 fire blazed only the area burnt twice. Furthermore, we identified areas where the post-fire management differed. Clear-cut and natural regrowth are the practices used in the region. In the study locations, we also chose tree species being widely present and representative of the local vegetation (table 1). *Pinus halepensis, Cistus salviifolius, and Pistacia lentiscus* were chosen according to these characteristics.
Every week, in each of the identified plots, three plants per species were randomly chosen (figure 6). Around every plant, the water drop penetration time test (WDPT) was repeated five times. In the control plot we analyzed only *Pinus* and *Pistacia* because *Cistus* were not present. This is explained by the fact that it is a pioneer plant that commonly grows after a disturbance event and in earlier ecological stages than in the mature maquis present in the control area (Guzmán and Vargas, 2005).

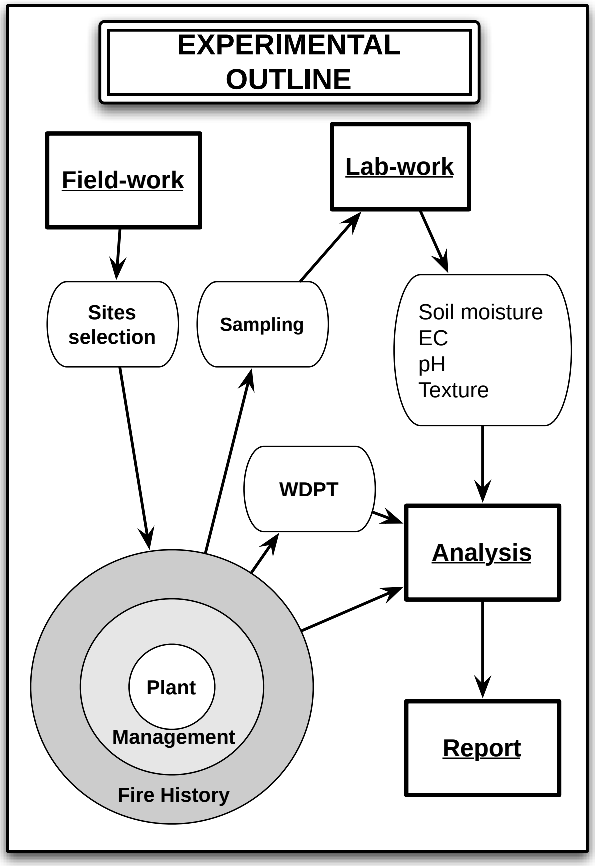

***Figure 5**: Experimental outline showing the different phases of the study. It is divided in four main stages: Fieldwork, lab-work, analysis and report.*

In an advanced stage of the experiments, the area assumed to be regrowing naturally, in the once-burnt zone, revealed to be clear-cut. Consequently, the once-burnt plots were lumped and treated together as clear-cut.

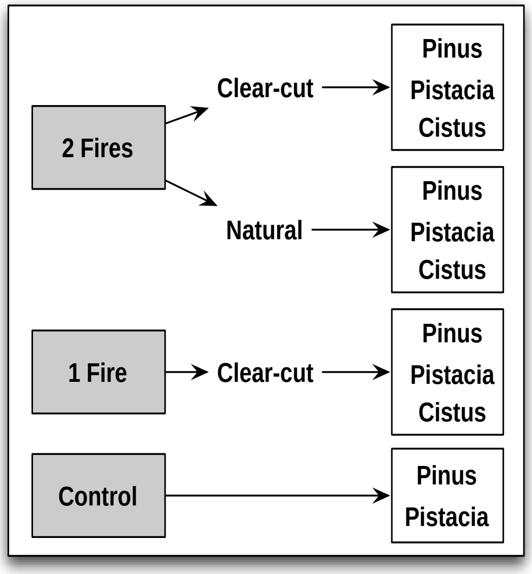

***Figure 6**: Features considered for the study sites selection. From right to left: fire-history, management and plant spp.*

Throughout the whole experiments a specific coding system was used in order to define the features of every location where the WDPTs and following laboratory tests. The coding system is explained in table 1.

***Table 1:** Coding system used throughout the study. In parenthesis is the code used to represent the given aspect. For the plants spp, no code has been used.*

Fire history	**Management**	**Plant spp.**	**Code**
Control (X)	--	*Pinus*	XPinus
Control (X)	--	*Pistacia*	Xpistacia
1 Fire (1)	Clear-cut (C)	*Cistus*	1CCistus
1 Fire (1)	Clear-cut (C)	*Pinus*	1CPinus
1 Fire (1)	Clear-cut (C)	*Pistacia*	1CPistacia
2 Fire (2)	Natural (N)	*Cistus*	2NCistus
2 Fire (2)	Natural (N)	*Pinus*	2NPinus
2 Fire (2)	Natural (N)	*Pistacia*	2NPistacia
2 Fire (2)	Clear-cut (C)	*Cistus*	2CCistus
2 Fire (2)	Clear-cut (C)	*Pinus*	2CPinus
2 Fire (2)	Clear-cut (C)	*Pistacia*	2CPistacia

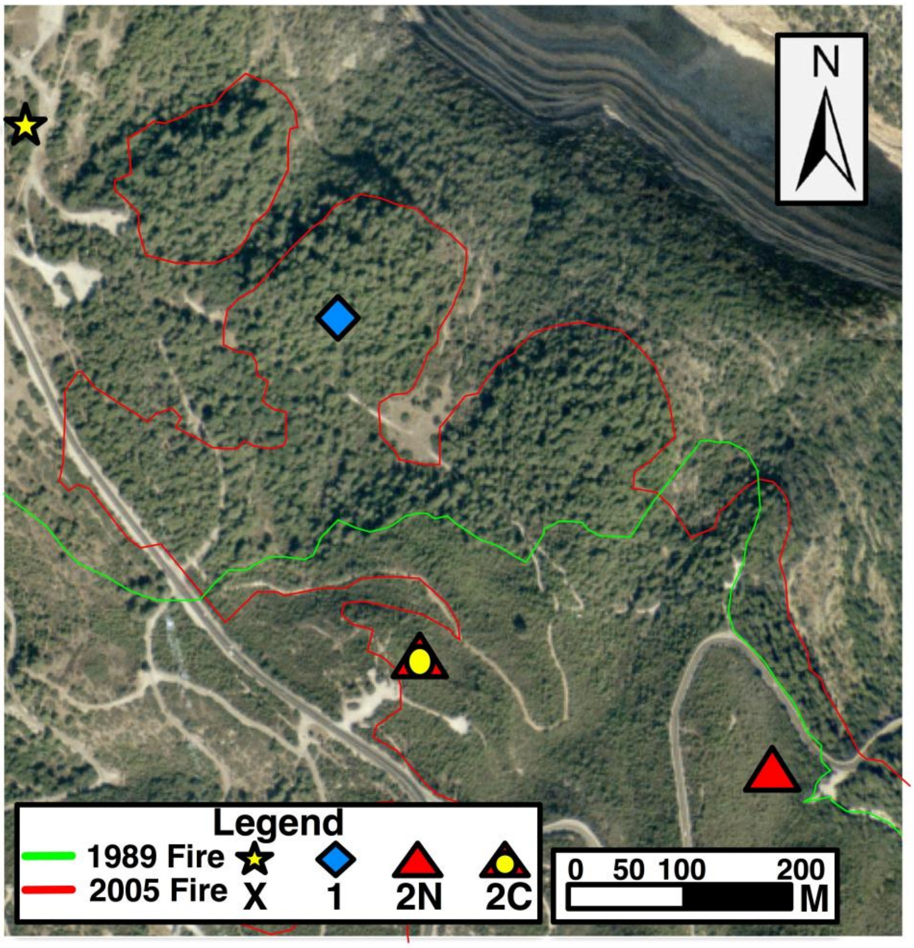

Figure 7: *Experimental plot sites selected for the study. The four locations were chosen because similar: similar vegetation and topography, but different fire history. The symbols represent the different plots and are characterized by fire history and management.*

b. Field measurements and sampling

Prior to the WDPTs, the micro-zone right next and under the plant has been cleared of litter and stones in order to apply the droplets on the mineral soil and not on the recently formed organic layer.

The experiment was executed with a pipette by placing drops on the soil surface from a close distance to avoid the splashing effect created by the kinetic energy of the liquid (DeBano, 1981; Letey, 1968). The temporal interval was measured to assess how long it took for each drop to infiltrate. The removed litter was then carefully replaced in its initial position to restore the natural conditions.

For every combination of plant/fire-history/management a sample of around 500 grams was collected for further analysis in the laboratory. Eleven samples were therefore examined weekly in the laboratory (Xpinus, XCistus, IICPinus, IICPistacia, IICCistus, IINPinus, IINPistacia, IINCistus, IPinus, IPistacia, ICistus).

c. Measurements in the laboratory

After every round of weekly measurements further tests were performed in the laboratory. On the same day of the fieldwork, gravimetric soil moisture was measured. First, the samples were prepared by crunching the soil aggregates with a mortar and a pestle. Second, the visibly big stones and organic material were manually removed. Third, the samples were sorted through a 0.5 mm sieve. The obtained specimen was then transferred in a previously weighted 20/50 mL beaker. After taking notes of the weight of the glass and the weight of the glass plus the soil specimen, we put it in a soil oven (104°C) for 24 hours. The soil moisture (u) value was obtained using equation 1.

$$u = \frac{m_{\text{wet}} - m_{\text{dry}}}{m_{\text{wet}}} \qquad \text{(Equation 1)}$$

$$m_{wet} = wet\ mass \quad m_{dry} = dry\ mass$$

Afterwards, a 1:1 solution of soil and distilled water was prepared to measure the pH and electro-conductivity (EC) of the samples. The measurements were carried out at a constant temperature of 22°C (+-1.5).

d. Statistical analysis

Data analyses were conducted using SPSS (PASW Statistics 18). Non-parametric tests were used because the data were not normally distributed. These tests use ranked or ordinal datasets rather than metric data utilized in parametric tests. Non-parametric tests are less powerful tools when dealing with normal populations, but when dealing with non-normal populations, they are more powerful (Davis and Sampson, 1973). This fact is logic because instead of using the real magnitude of the data it makes use of their relative magnitude (ranks). Moreover, outliers that characterize non-normal distribution (Lyman ott and Longnecker, 2001) do not influence it. In the present research, the Kruskal-Wallis and Mann-Whitney tests were preferred among other possible tools.
The confidence interval used throughout the analysis was of 95% (C=0.95).
The weekly sample size was n=210. The total sample size was n=1890.

The **Kruskal-Wallis** test was used to compare data sets with more than two samples. For this tests the assumptions about the data production are more relaxed compared to the analogue parametric test (ANOVA). In fact, Kruskal-Wallis, like the ANOVA, compares several populations, but instead of analyzing their means, it assesses the median values and the distribution of the ranked datasets around them. Moreover, for Kruskal-Wallis the distribution does not have to be normal and the dataset just need to have a similar distribution shape. The null hypothesis is that every population *n* has the same median. Consequently, the alternative hypothesis is that not all the medians are equal and that at least one is different (Moore et al., 2009).

The **Mann-Whitney** test was used when a Kruskal-Wallis test resulted in a rejection of the null hypothesis and we wanted to investigate which populations were causing the significant variation. It acts as a non-parametric substitute of the t-test and like the Kruskal Wallis test it considers the position of the median of the ranked populations. The null hypothesis and the alternative hypothesis are the same as in the case of Kruskal-Wallis, but limited to the comparisons of 2 populations instead of *i* populations.

The tests were performed following a scheme (table 2) that was specifically designed to partition the influence of plants, management and fire history on water repellency. These factors are considered as independent variables that affect WR. In every round a set of different variables are tested using one or more iterations. The final idea was to isolate the factors that might influence WR.

Table 2: *Outline of the hypothesis test statistical analysis. The different factors (fire history, plants and management) are coupled to test different combinations. The analysis is divided in eight rounds.*

Round	**Variable 1**	**Variable 2**	**Variable 3**	**Sig. level (α)**
1	Fire history			0.05
2	Plants			0.05
3	Plants	Control		0.05
4	Plants	1 Fire		0.05
5	Plants	2 Fires		0.05
6	Management	2 Fires		0.05
7	Plants	2 Fires	Clear-cut	0.05
8	Plants	2 Fires	Natural regrowth	0.05

To decrease the risk of type one error due to consequent tests in the same round, the α was modified using the Bonferroni correction (equation 2). The type I error implies the rejection of the null hypothesis even-though is true. The modified α_m was used for every test in the round. The sum of the α_m within one round gives back the original value of α (i.e. 0.05).

$$\alpha_m = \frac{\alpha}{n}$$ *(Equation 2)*

5. Results

a. Rainfall distribution

During the study, the rainfall occurred mainly in the month of December with a long dry period in October and November (Fig. 8). The dry spell allowed comparing the behavior of water repellency in these two opposite conditions and in the period in between. A more detailed profile of the rainfall distribution can be found in appendix 1.

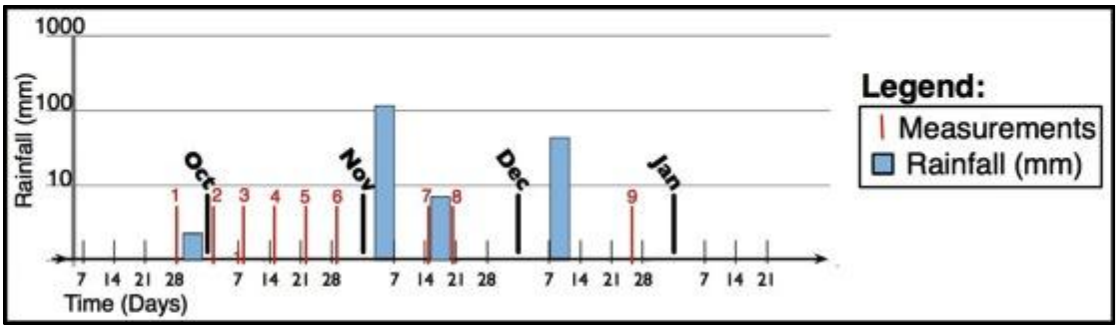

Figure 8: *Timeline of the experiment. On the x axis the time span is shown, divided in months and days. On the y-axis the rainfall height is represented. The blue bars depict the cumulative rainfall fallen in between two adjacent measurements.*

Measurements showed a sharp increase in soil moisture at the seventh measurement, which coincides with the first heavy rainfalls in December. Therefore, the graph can be divided in two parts as shown in Fig.9, a dry and a wet part.

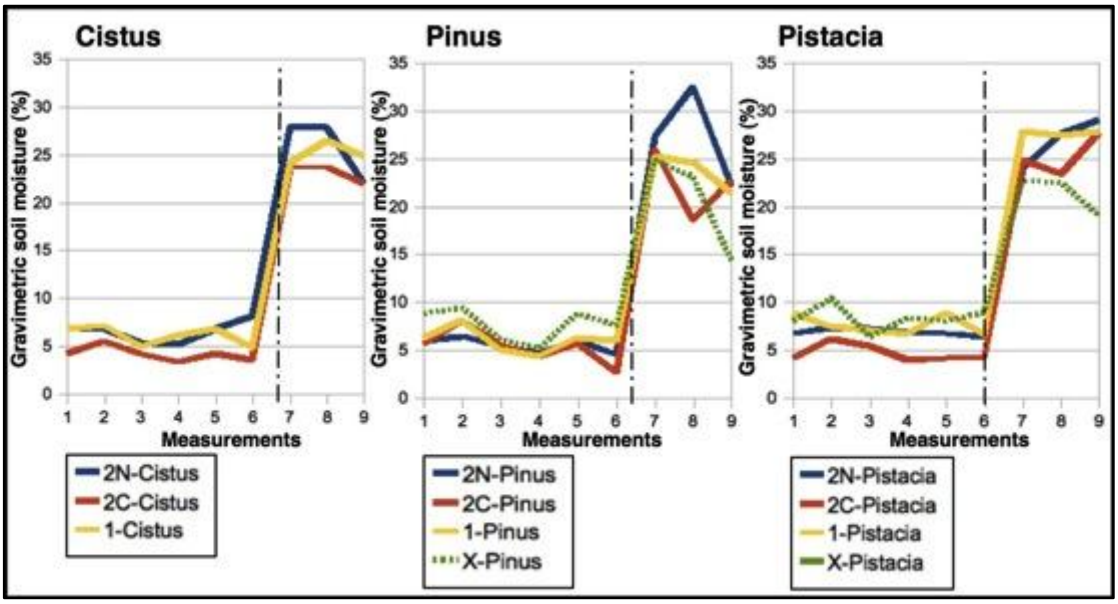

Figure 9*: Soil moisture (Y) fluctuations in time (X) grouped according to plant spp.. The spot-and-dot vertical line draws an ideal division between a dry part on its left and a wet part on its right side.*

In the dry period, the water content never rose above 10% and showed slight fluctuations. In the wet period, a slight moisture decrease after the seventh measurements was measured for *Pinus*, *Cistus* and the control sites. However, for *Pistacia* there is an increase in soil moisture for all the cases except for the control. The control trend-lines show a divergent behavior. They show higher moisture in the dry part of the graph whereas they show lower moisture in the wet part. The 2C and 2N areas exhibit different soil moisture patterns, being the natural regrowth always in a higher position than the Clear-cut.

b. Water repellency occurrence

Water repellency is found throughout the experimental area with changing magnitude and different behaviors linked to different conditions. Its presence varies greatly with differing conditions suggesting that the complexity of the process is influenced by numerous factors. Right after a wildfire on Mt. Carmel, Tessler et al. (Tessler et al., 2008) found that 96% of WDPTs revealed the presence of WR with values ranging from 30 seconds to more than 300 seconds. Furthermore, 22% of the measurements had a WR with values above 300 seconds. Five years after the same wildfire every area showed water repellency to a certain extent. As shown in figure 10, it is clear that WR was manifested in every measurement in a varying pattern, but in all the cases, the fraction that did not show any WR was still predominant. The soil was found to be wettable in 43-60% of the cases in dry conditions and in 95% of the cases in wet conditions. On the other hand, the area showed a certain degree of WR in every measurement, ranging from 40-60% in dry conditions and to 5% in wet conditions. Water repellency appeared in every experimental plot in a pattern that varies according to the different growing plant species, with the different amount of soil moisture, and with the different post-fire management techniques.

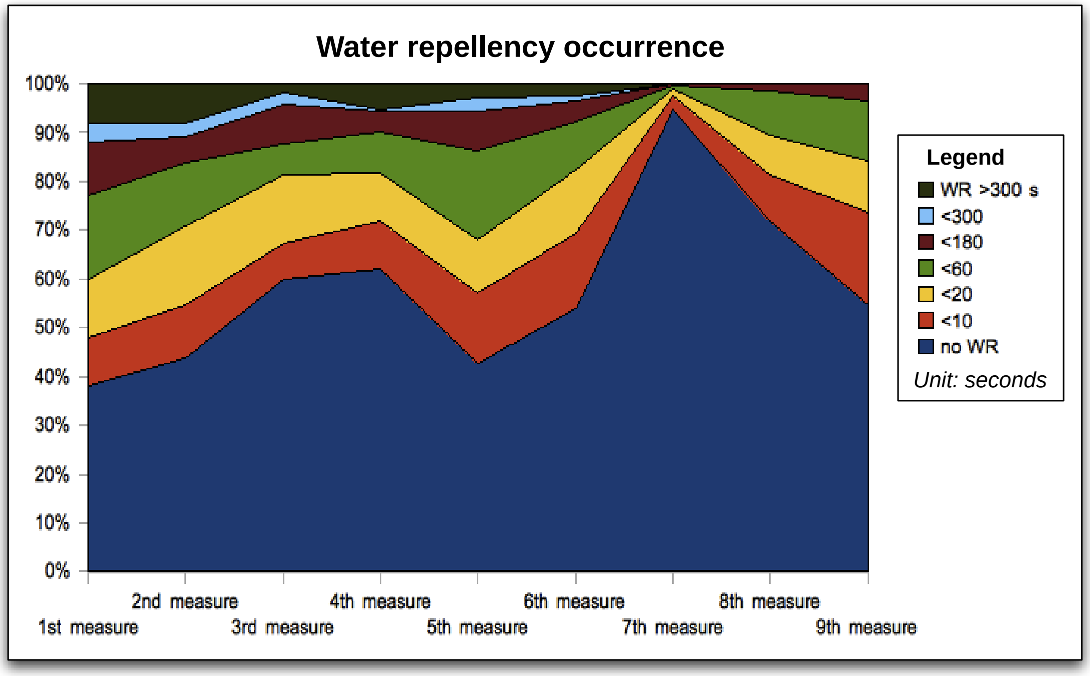

Figure 10: *Water repellency occurrence (%) among the 9 measurements performed. WR intensity is showed by different colors. The heavy December rainfall events coincide with the 7th measurement.*

c. Water repellency in time

All the gathered data were organized and analyzed in different steps according to the factor that were under investigation (fire history, vegetation type and management practice). The first result is a prospect (figure 11) that shows the occurrence, average and median of WR according to fire history, plant species and post-fire management. Both the average WDPT and the median WDPT where considered to include in the calculation all the extreme values of the data-points (average) or to avoid the excessive variation of the data-points that stretched the trend-line (median). However, the median and the average showed a similar trend.

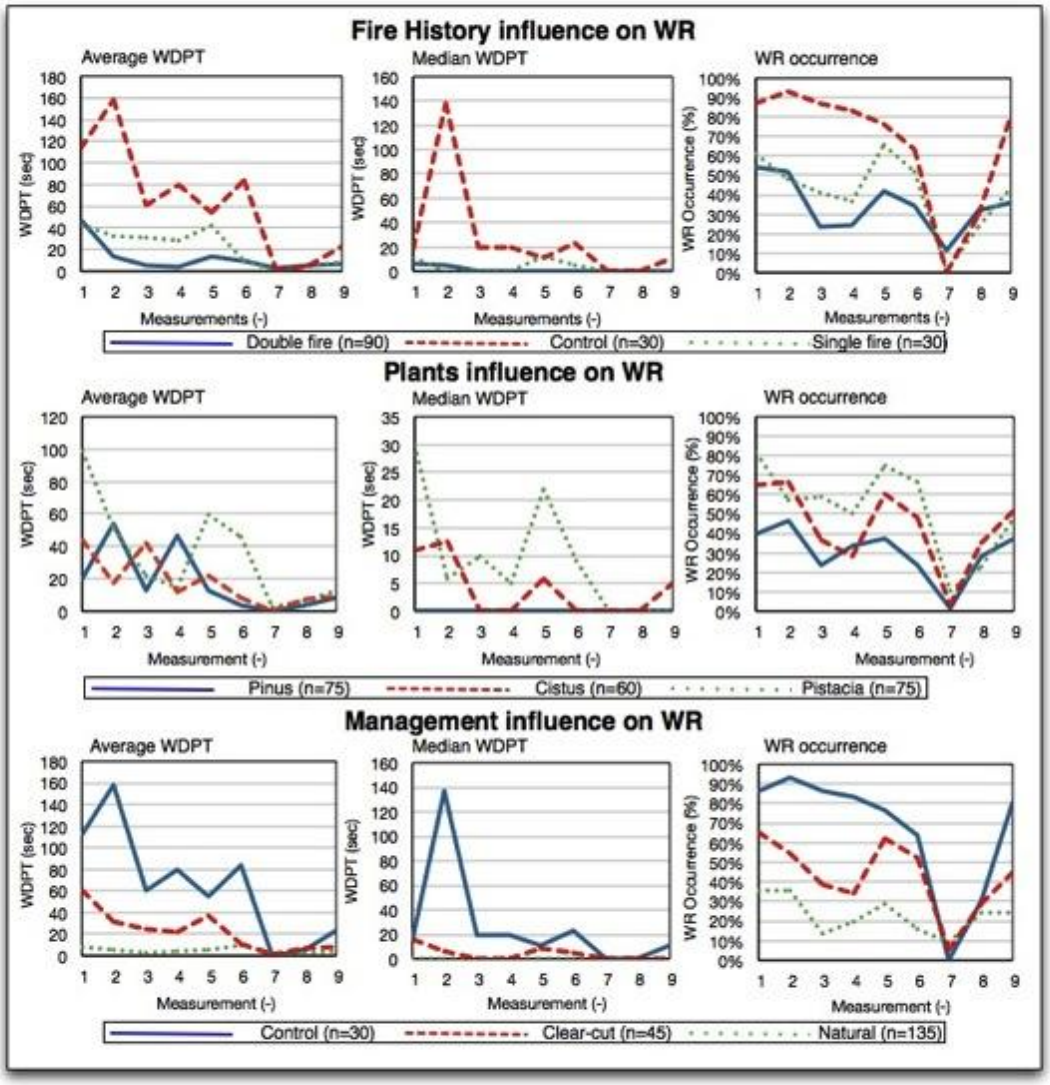

Figure 11: *Water repellency evolution throughout the study according to the main analyzed factors. The median, average and occurrence (%) are displayed.*

The fire history graphs reveal that the control plot always has higher water repellency, whereas double fire has lower values and single fire has intermediate values.

Also for the effect of plants on water repellency, a clear and homogenous behavior can be distinguished. The *Pistacia* has higher values while *Cistus* has intermediate values. *Pinus* has a similar behavior as *Cistus* in the average graph, but the median trends are not similar as indicated in the graph where *Pinus* has lower WR values. In the occurrence graph *Pistacia* has the highest WR values followed by *Cistus* and *Pinus*.

When looking at the effect of management practices, another clear trend can be seen. The control always showed higher WR while the Clear-cut plot has intermediate values and Natural has the lowest.

Single fire

The first important trend observed is the sharp decrease of water repellency in coincidence with high soil moisture values (figure 12). After the rain, when still present, the WDPT values are low. After this drop, the WR increases and shows longer drop penetration times. In the dry period, water repellency has higher values but with big fluctuations in its mean values.

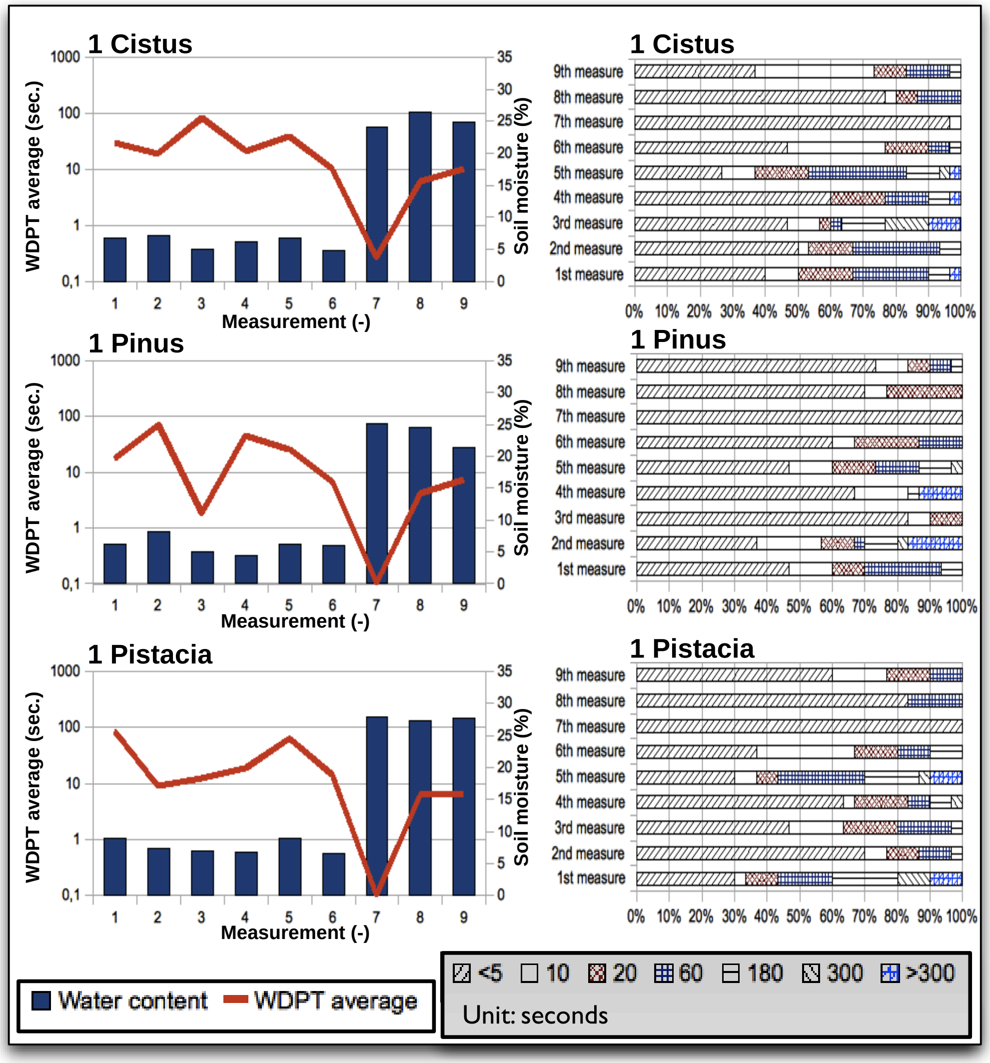

Figure 12: WDPT characterization according to different plants in areas burnt once. In the graphs on the left, Soil moisture bars (%) are drawn together with a trend representing WDPT average (sec). The graphs on the right side show the percentage of water repellency

per measurement. It also describes the magnitude of the phenomenon dividing it in 6 classes according to the different infiltration times.

Double fire

In the areas burnt twice, we observed substantial differences between the different species and their effect on water repellency. In the plots (2N) with *Pinus*, WR was absent in most of the measurements, or it was manifested for few seconds in only few cases (figure 13). Surprisingly there was slightly more repellency after the big December precipitations instead of during the long lasting dry spell of October-November. This trend is visible in both the natural regrowth area and in the clear-cut area.

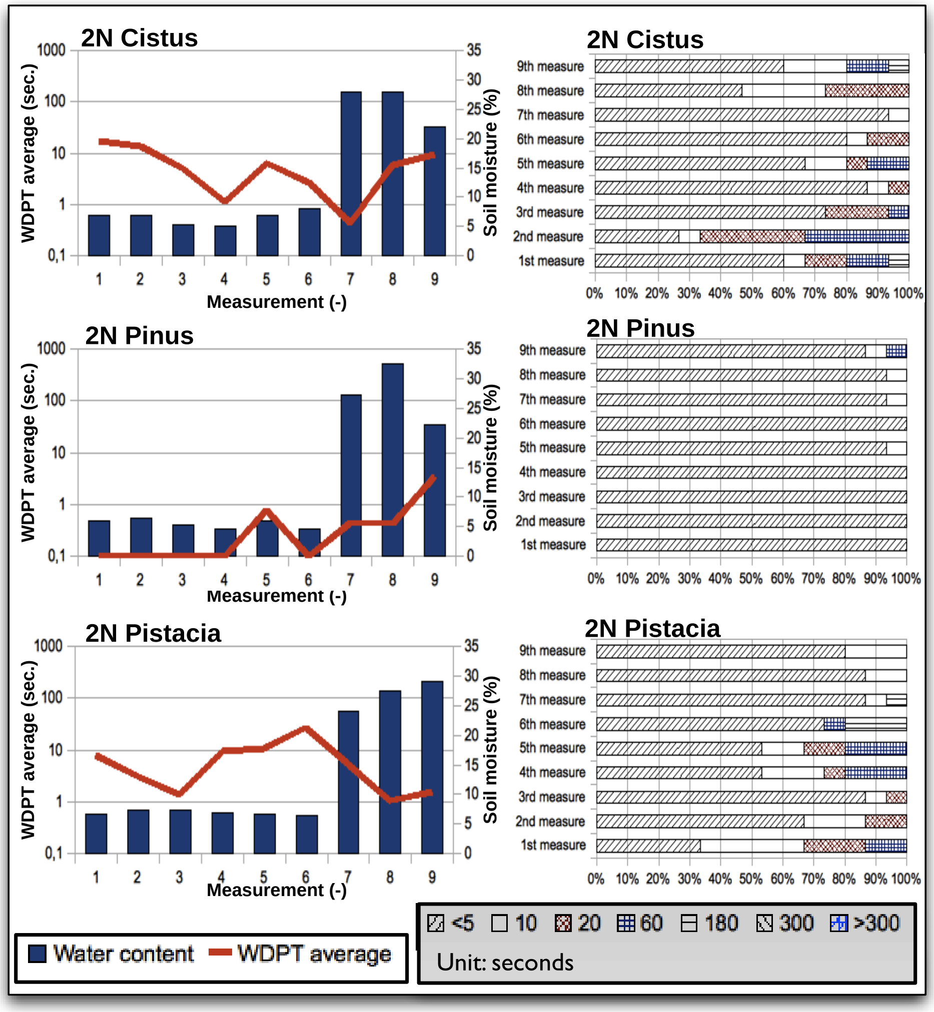

Figure 13: *WDPT characterization according to different plants in areas burnt twice with no post-fire management in place. In the graphs on the left, Soil moisture bars (%) are drawn together with a trend representing WDPT average (sec). The graphs on the right side show the percentage of water repellency per measurement. It also describes the magnitude of the phenomenon dividing it in 6 classes according to the different infiltration times.*

In the clear-cut area the *Pistacia* plots show a peculiar behavior. In fact the water repellency decreases after a rainfall event but it does not go to zero as in the other cases. To a lesser extent, this behavior can be also observed in the 2N. As a general trend, the *P.halepensis* reveals the lower mean WR values, whereas *C. salviifolius* and

P.lentiscus are more or less within the same range. *P.halepensis* has the highest WR after the big December rains as it also happened for 2N.
Comparing the two sets 2N and 2C we notice that in the clear-cut, WR is present in more measurements than in the natural regrowth showing values as high as 300 seconds.

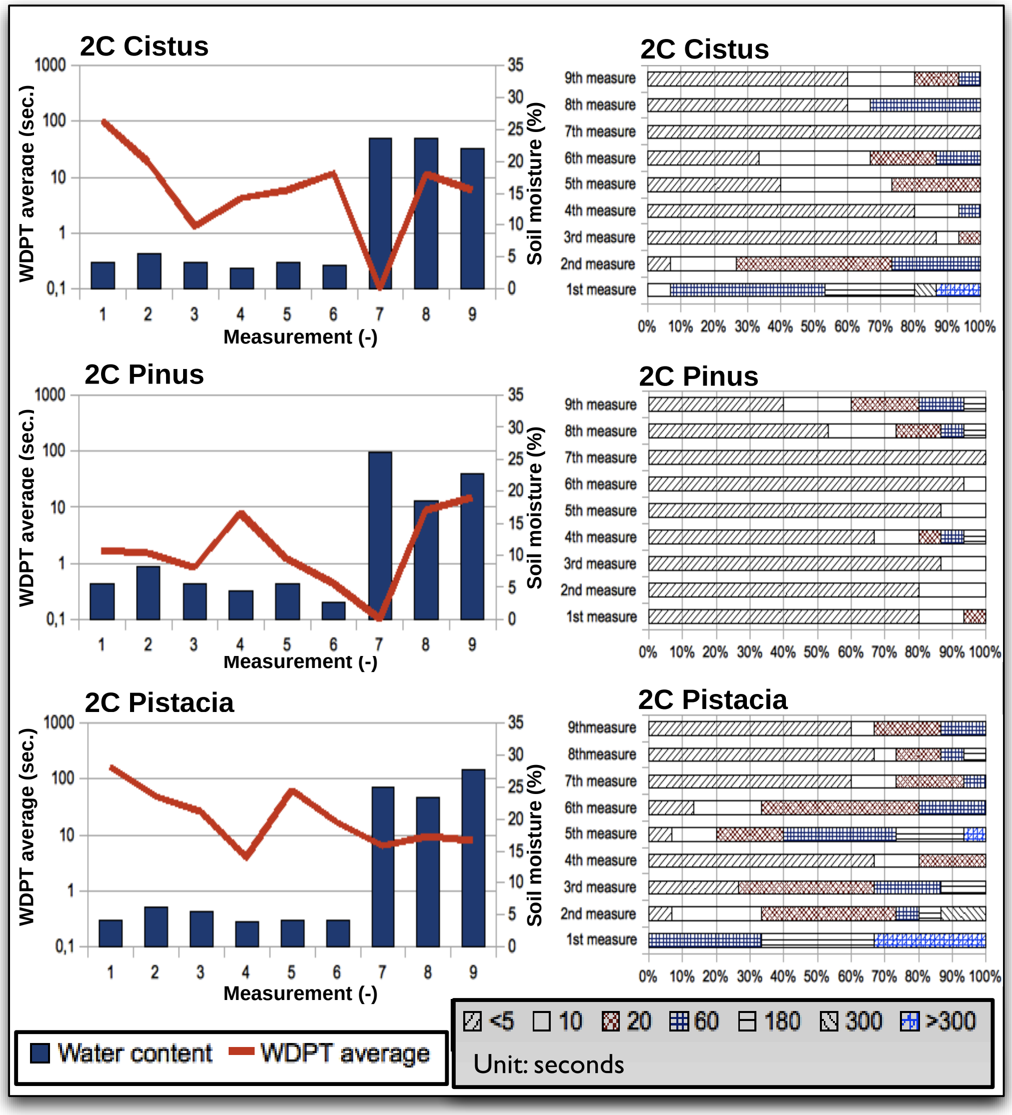

Figure 14: *WDPT characterization according to different plants in areas burnt twice with Clear-cut post-fire management. In the graphs on the left, Soil moisture bars (%) are drawn together with a trend representing WDPT average (sec). The graphs on the right side show the percentage of water repellency per measurement. It also describes the magnitude of the phenomenon dividing it in 6 classes according to the different infiltration times.*

<u>Control</u>

The control areas revealed higher water repellency. WR was present with both low values as little as 5 seconds (low WR) and with values going up to 300 seconds (severe WR). In the control areas, there is the expected decrease at the seventh measurement and the following increase can be seen. The average WR measured was often close to 100 seconds (strong WR) and showed in general higher values than the burnt areas.

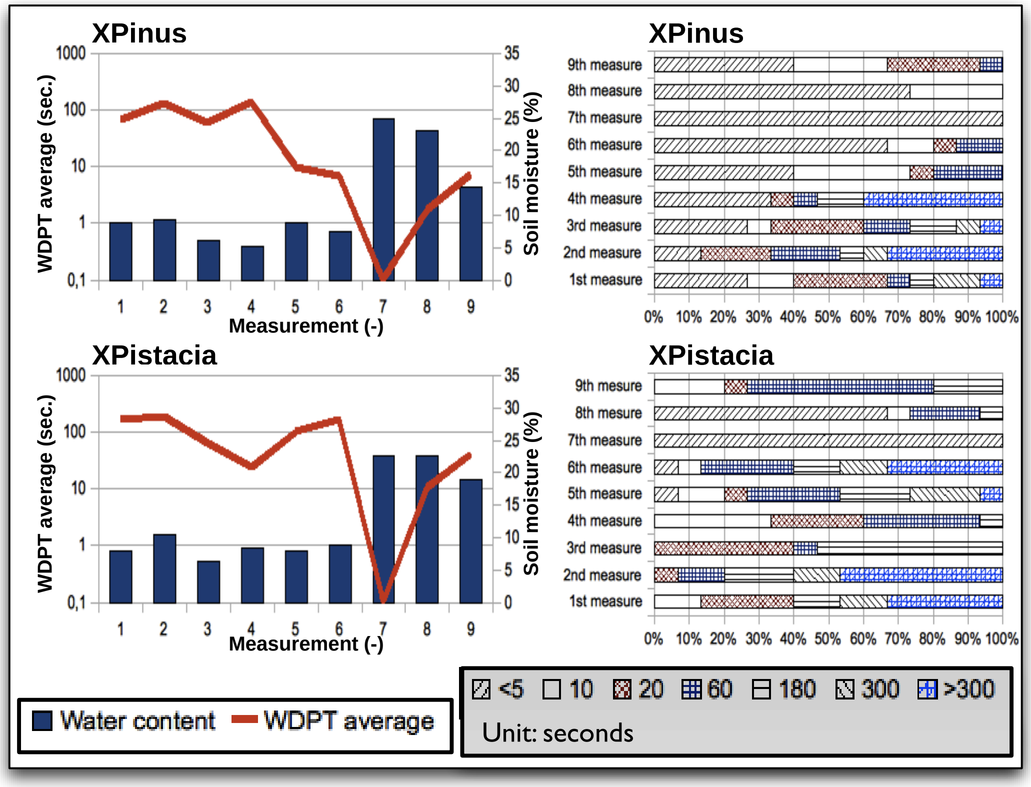

Figure 15: *WDPT characterization according to different plants in control areas. In the graphs on the left, Soil moisture bars (%) are drawn together with a trend representing WDPT average (sec). The graphs on the right side show the percentage of water repellency per measurement. It also describes the magnitude of the phenomenon dividing it in 6 classes according to the different infiltration times (sec).*

d. Soil moisture effects on Water repellency

The relation between average water repellency and soil moisture (figure 16) was low when all data-points were used for the analysis. However, when the graph was divided into two parts (clusters), around the value 15% of soil moisture we obtained two different graphs with a better R-squared. Even though the coefficient is still low, the distribution shows that high values of WR are always linked to low moisture (left side of the graph). Nevertheless, at low moisture values low values of WDPT are still present and predominant. On the other hand, when the soil moisture is high the water repellency is always low. In between 10% and 20% of soil water content there are only few WR measurements leaving a broad gap in between the two analyzed clusters.

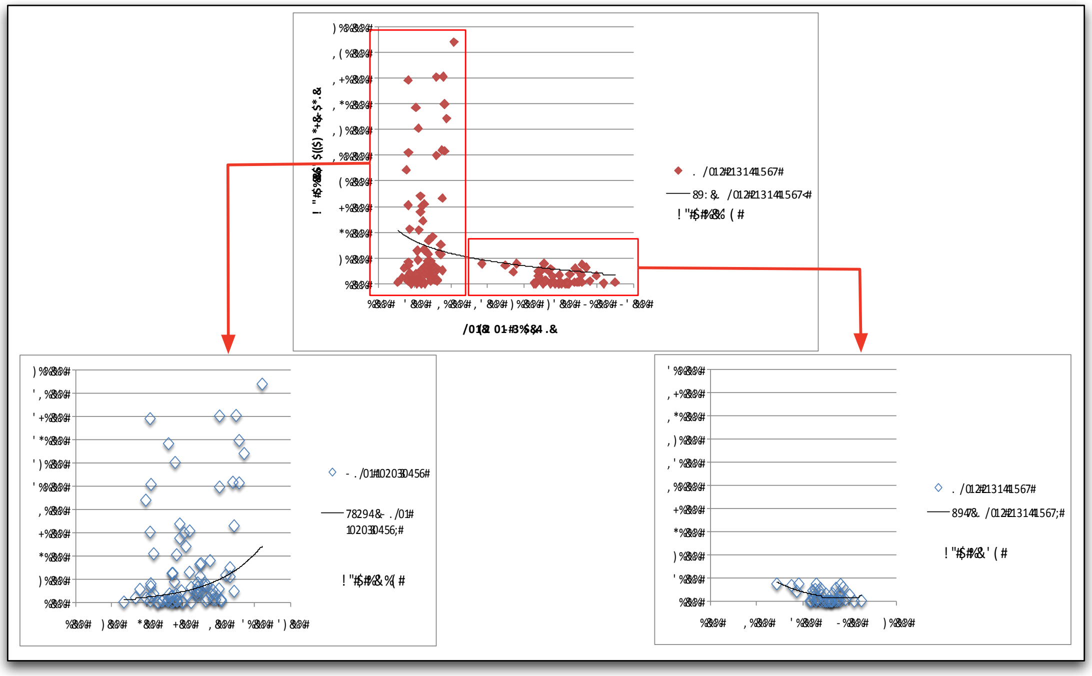

***Figure 16**: In red is the scatter plot of average WDPT values (sec) against soil moisture (%).The underlying blue scatter plots show the behavior of WR for low soil moisture (on the left) and for high values (on the right side).*

When the same procedure is used dividing the data according to the fire history the results are different (see figure 17). There is an evident difference between the twice-burnt areas that have a lower correlation (R-squared = 0.051) than in the single fire (R-squared = 0.346) and in the control area (R-squared = 0.60). From figure 17 it appears that under dry conditions WR is present in every point, except than in few cases. When looking at the burnt fields the difference is pronounced. In the single fire site WR repellency was often absent in dry conditions. This trend is confirmed and accentuated in the plot that was subject to consequent fires.

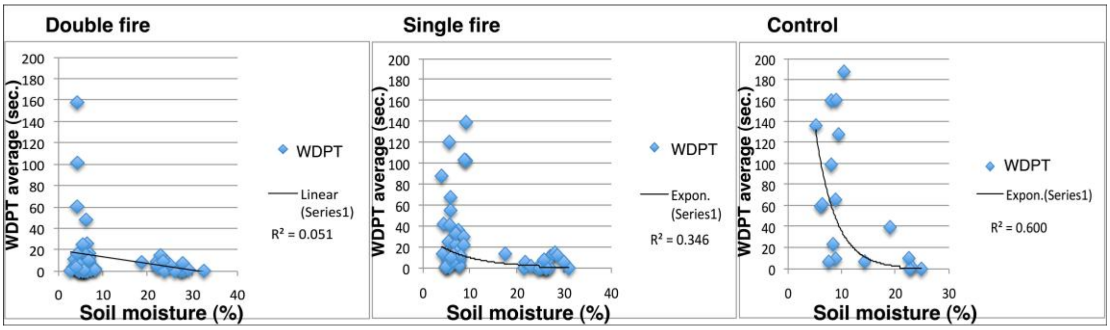

***Figure 17**: Scatter plots of WDPT averages against soil moisture, subdivided according to the fire history.*

e. Hypothesis testing:

Assessed that the dataset does not have a normal distribution, non-parametric tests were conducted. In order to compare more than two samples in one run we opted for the Kruskal-Wallis test. As mentioned in the methodology, for this test the null hypothesis (H_0) is that the samples have the same distribution around the median value. In case of rejection is important to perform further post-hoc tests to understand which sample is different from the others. For this purpose, Mann-Whitney test is used. Therefore, when Kruskal Wallis was used on three populations and it gave a rejection, it was followed by a sequence of three Mann-Whitney tests. For both tests, the overall confidence level used is of 95% with a two-tailed significance level (α) of 0.05. Therefore, the null hypothesis must be rejected in case of a α bigger than 0.05. Nevertheless, when the Kruskal Wallis test was followed by post-hoc Mann-Whitney tests, the α had to be adapted to decrease the occurrence of type 1 error caused by the use of a sequence of tests. The Bonferroni correction was applied and resulted in a lower α (equation 2). In all the rounds except for three, four and six, the α value was reduced by dividing the desired significance level (α=0,05) by the number of test in the round (i.e. 4). The resulting α_m has therefore a value of 0.0125 (equation 3). In the same round, the sum of the α_m would always be 0.005 and therefore equal to the initial α.

$$\alpha_m = \frac{0.05}{4} = 0.0125 \qquad \text{(Equation 3)}$$

All the results are summarized in table 3 where the different rounds are showed with the yielded significance levels and mean ranks.

1. Fire influence (α_m=0.0125; α=0.05)

To understand the impact of fire history on WR, the whole dataset was grouped according to the different fire history (i.e. 1,2,X). First the three obtained groups where tested with Kruskal-Wallis, that gave a rejection (α<<0.0125, χ^2=124.623) and denoted a significant difference among the different groups. Subsequently, the Mann-Whitney test was used and it gave three further rejections (α<<0.0125) denoting that the populations grouped by fire history are all different from each other.

2. Plants (α_m=0.0125; α=0.05)

The plant species were used as a grouping variable leading to three groups (*P. halepensis*, *P. lentiscus*, *C. salviifolius*). The three groups were tested with Kruskal-Wallis that lead to the rejection of the H_0 (α<<0.0125, χ^2=79.537) denoting significant differences among the groups. Among the three groups, Mann-Whitney gave three further rejections (α<<0.125) showing that all the groups are significantly different from each other.

3. Plants in the control area (α=0.05)

When grouping the dataset according to plant species within the control area (XPinus and XPistacia), the performed Mann-Whitney test brought a further rejection between the *Pistacia* and *Pinus* sampling area ($\alpha << 0.05$).

4. Plants in the area burnt once ($\alpha_m = 0.0125$; $\alpha = 0.05$)

When plant spp. was the grouping variable within the area burnt once, Kruskal-Wallis gave an $\alpha = 0.014$ that is lower than $\alpha = 0.05$ and would lead to the rejection of the H_0. When performing the following Kruskal-Wallis tests the α should be modified to $\alpha_m = 0.0125$ and it would consequently suggest the acceptance of H_0 ($0.014 > 0.0125$) and it would suggest similarity among the three subgroups. Moreover, if the H_0 is not rejected there is no need of further tests and consequently for a modified α_m that was the reason for H_0 to be not rejected. Assuming that the H_0 is rejected, the Mann-Whitney test was performed three times to see which plant is differing from the others. This test suggest that *Cistus* and *Pistacia* have a similar dataset ($\alpha = 0.488$) while *Pinus* is differing from *Cistus* ($\alpha < 0.05$ and/or $\alpha < 0.0125$) but is similar to *Pistacia* that has an $\alpha = 0.038$ ($\alpha > 0.0125$).

5. Plants in the area burnt twice ($\alpha_m = 0.0125$; $\alpha = 0.05$)

Plants were used to group the data of the area burnt twice without giving importance to post-fire management. Kruskal-Wallis gave a rejection of the null hypothesis ($\alpha << 0.05$) suggesting that one or more groups are different. When checking which plant was causing the significant difference, Mann-Whitney tests gave rejections ($\alpha << 0.05$) denoting that every group is different from the rest.

6. Management in the area burnt twice ($\alpha = 0.05$)

To look at the different management techniques effects on the area burnt twice, two groups were created (Clear-cut and natural regrowth). Subsequently the groups were tested directly with Mann-Whitney that gave a rejection of the H_0 ($\alpha << 0.05$). The result reveals that the areas under the two management techniques have a significantly different WR.

7. Twice burnt, Clear-cut and Plants ($\alpha_m = 0.0125$; $\alpha = 0.05$)

The effects of the plant spp. on water repellency were tested for the area burnt twice and subject to clear-cut. The grouping variable was the plant spp. (IICPinus, IICPistacia, ICCistus). Kruskal-Wallis, with a rejection ($\alpha << 0.0125$), denotes that at least one group is differing from the rest ($\alpha << 0.05$). The consequent Mann-Whitney gave three further rejections ($\alpha << 0.0125$), which denote a difference present between each group.

8. Twice burnt, natural regrowth and Plants ($\alpha_m = 0.0125$; $\alpha = 0.05$)

The effects of the plant species on water repellency were tested for the area 2N. The grouping variable was the plant spp. (IINPinus, IINPistacia, IINCistus). The Kruskal-Wallis analysis, yielded an $\alpha << 0.0125$ denoting that at least one group is differing from the rest. The subsequent Mann-Whitney tests gave two further rejections ($\alpha << 0.0125$) when *Pinus* was tested against *Cistus* and when it was tested against

Pistacia. However, when *Pistacia* was tested against *Cistus* the H_0 was not rejected. The result shows that *Pistacia* and *Cistus* have similar WR (α>0.125), while the WR under *Pinus* is differing from both *Pistacia* and *Cistus* (α<0.125).

Table 3: *Results of the hypothesis testing phase in which 8 rounds of tests have been performed. The resulting significance level (sig.) and Z-value are reported.*

Round	Kruskal-Wallis	Sig.	Mean rank	Mann-Whitney	Mean rank	Sig.	Z
1	X-I-II	0.000	X:1237	X-I	X: 668 I: 497	0.000	-8.411
			I:939	X-II	X: 704 II: 485	0.000	-11.116
			II:854	I-II	I: 847 II: 773	0.000	-3.604
2	Cistus-Pinus-Pistacia	0.000	C: 950	Cistus-Pinus	CIS:654 PIN:570	0.000	-4.821
			PIN: 824	Cistus-Pistacia	CIS: 565 PIS: 641	0.000	-4.029
			PIS: 1062	Pinus-Pistacia	PIN: 592 PIS: 758	0.000	-8.787
3				XPinus-XCistus	PIN: 111 CIS: 159	0.000	-5.099
4	ICistus-IPinus-IPistacia	0.014	ICIS: 426	ICistus-IPinus	CIS: 287 PIN: 253	0.004	-2.805
			IPIN: 376	ICistus-IPistacia	CIS: 274 PIS: 266	0.488	-0.693
			IPIS: 413	IPinus-IPistacia	PIN: 258 PIS: 282	0.038	-2.071
5	IICistus-IIPinus-IIPistacia	0.000	IICIS: 431	IICistus-IIPinus	CIS: 309 PIN: 231	0.000	-7.404
			IIPIN: 316	IICistus-IIPistacia	CIS: 257 PIS: 283	0.000	-2.072
			IIPIS: 468	IIPinus-IIPistacia	PIN: 220 PIS: 320	0.000	-9.111
6				IIC-IIN	N: 354 C: 456	0.000	-7.273
7	IICCistus-IICPinus-IICPistacia	0.000	IICCIS: 206	IICCistus-IICPinus	CIS: 154 PIN: 116	0.000	-4.582
			IICPIN: 150	IICCistus-IICPistacia	CIS: 120 PIS: 150	0.001	-3.379
			IICPIS:	IICPinus-	PIN: 102	0.000	-7.706

Round	Kruskal-Wallis	Sig.	Mean rank	Mann-Whitney	Mean rank	Sig.	Z
			251	IICPistacia	PIS: 168		
8	IINCistus-IINPinus-IINPistacia	0.000	IINCIS: 226	IINCistus-IINPinus	CIS: 156	0.000	-6.403
					PIN: 114		
			IINPIN: 163	IINCistus-IINPistacia	CIS: 138	0.511	-0.657
					PIS: 132		
			IINPIS: 219	IINPinus-IINPistacia	PIN: 116	0.000	-5.944
					PIS: 154		

6. Discussion

a. Effects of soil moisture fluctuations

The gravimetric soil moisture content has a remarkable effect on hydrophobicity. Unavoidably, soil moisture is linked to the rainfall events, its amount and timing. As shown in figure 9, soil moisture is present in different patterns according to the characteristics of the experimental plot. The soil moisture of 2N showed higher values (up to 29-32 sec) than 2C (up to 25-27 sec) suggesting that less disturbed areas are able to retain water to a higher extent. Moreover, the control plot exhibits the highest soil moisture (min: 5-8 sec) in the dry period and the lowest in the wet period (max: 22-24) (fig 9). This aspect suggests that the natural conditions of the area favor both retention and drainage according to the wetting conditions. The trees in the control areas shade the soil with their branches and thick litter causing a slower drying phase and intercepting parts of the rainfall and decreasing the amount of water reaching the soil. Debano (1981) speculate that this phenomenon might be also a result of water repellency that decreases the amount of water that is lost through evaporation. In this case the capillarity movement of water to the surface is decreased due to the fewer bonds that are created between the soil particles and the fluid.

In every plot, the rainy spell resulted in a substantial decrease of water repellency linked to higher soil moisture present in the soil. However, during the dry spell, WR is subject to fluctuations that might be caused by recurrent morning fogs and by the spatial variability of hydrophobicity. After the low peak, WR tends to increase even though soil moisture is still high. This is the case in most of the situations except than for *Pistacia* in areas burnt twice. In addition, when the relationship between moisture and WR was explored (figure 16), the resulting scatterplot showed that all the high WR data-points are present only in presence of low soil moisture content. On the other hand, the average data-points with high moisture content never showed high WR. Even though the resulting correlation (R^2) was very poor, the visible trend has to be taken into account, because it shows a clear pattern in the two extremes of the moisture span (Dry-wet). Moreover, the low correlation is likely to be influenced by the numerous data-points that show lower WR in the wet phase and by the absence of data-points when the soil moisture was 10-20%. The absence of these points might be caused by the simple absence of measurements in such conditions or by the unpredictable drying-wetting behavior of soils (hysteresis).

The behavior of WR shows therefore a constant response to rainfall/moisture. The WR disappears with high soil moisture, but it has varying behaviors in the dry phase and in the wet phase. It is surprising to see how WR is increasing right after the major rainfall event even though soil moisture is still high. In this phase other factors than soil moisture might play a bigger role in influencing water repellency. Doerr suggests that in some cases to restore hydrophobicity a new input of hydrophobic substances is needed (Doerr et al., 2000). Therefore, a possible explanation is the increase of soil biological activity sparked by increased soil water content. However, in this study this was not assessed.
Soil moisture influences WR in both control and burnt conditions. However the most disturbed soils appear to have bigger fluctuations and a more direct correlation to changing water content. The OM and litter present in the control plot decrease the evaporation and the amount of rain that reaches the soil. Furthermore the higher soil moisture appears to cause an increase of WR in the control area, probably triggered by an increased biotic activity.

b. Effects of vegetation

The presence of different plant species together with the ecological stage of the local micro-ecosystem are factors that influence the dynamics and fluctuations of WR (Doerr et al., 2000). Every experimental plot, that was subject to fire disturbance, showed a lower WR than the control plot (figure 12-13-14-15). This result can lead to a series of plausible hypothesis. The complexity and maturity of the control ecosystem, has probably led to the establishment of a complex network of interactions between soil, microorganisms, fungi and plants. The role of these factors in determining hydro-repellency is far from being clear, but suggests that after a certain time the effects of fires are overcome by the ecosystem complexity. Being the main difference between the control plot and the other areas the absence of fires in recent years, it is plausible to address other factors as the cause of water repellency.

The effect of *Pinus*, *Cistus* and *Pistacia* on WR showed that experiments carried out under *P. halepensis* plants have a lower WDPT mean (figure 11). These results are in contrast and opposite to the present literature in which *Pinus* is usually inferred as a potential cause of WR in Mediterranean environments (Jaramillo et al., 2000; Doerr et al., 2000). As mentioned by Reeder and McGhie (in Doerr et al., 2000) one cause might be the litter. In fact, in most of the experimental areas under the pine trees, the litter covering the soil was sparse and thin, with ample zones free of any sort of debris. With this in mind it is possible to suggest the potential influence of litter on water repellency. In fact pine stands might be not able to generate water repellency until a later, more mature phase in which a more consistent layer of organic matter is created on the soil surface. This explanation is reinforced by the data showing high water repellency average in the control area, which is very rich in pine tree litter.

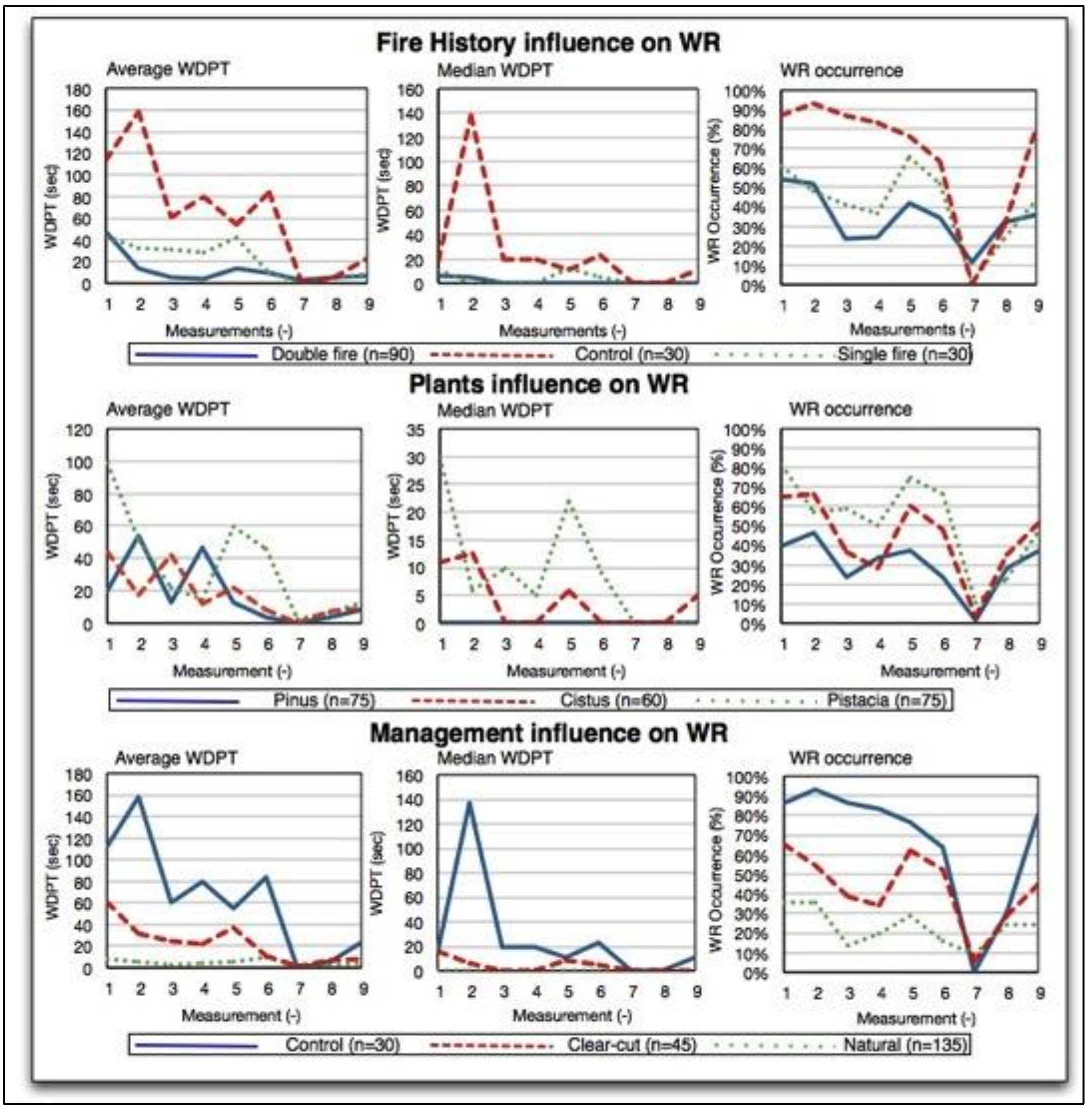

Figure 11

The results can help to better understand these postulations. The rejection of the null hypothesis indicates that populations are differing from each other significantly, but without discerning, which dataset is different. This fact simply tells that there are inherent factors of the process that are not being isolated and identified. A possible interpretation is that plants, management and fire history have an influence on water repellency, but the factors in the game are connected with other processes or they are not independent from each other. In other words this result underlines the complexity of soil processes, with water repellency making no exception. These results confirm the above-cited statement of Doerr that addresses the difficulty in isolating the different determining factors (Doerr et al., 2009). Only in the case of 2N and the differing variable was clearly pinpointed and isolated. In fact, pine stands in the fourth and eight sampling round are differing from the other species stands, while *Pistacia* and *Cistus* yield similar values of water repellency. This fact indicates that in the 2N field and in the field burnt once there is a clear difference between the areas with different plant covers, with pine plots having a statistically lower WR (table 3, figure 11).

Nevertheless when using descriptive statistics it is clear the difference between groups. Pine plots always yield lower WR except than in the case of the control.
When looking at figure 11 it is straightforward that *Cistus* and pines have a similar behavior, but when looking at the median values pines show lower values. This fact suggests that the variation is a mere statistical discrepancy, while in fact the median, which is not influenced by the extreme values, shows that pines have lower WR. The same trend is also demonstrated by the occurrence graph in which *Pinus* always has lower hydrophobicity.

c. Effects of Fire History

The statistical analysis did not isolate fire history as an independent factor influencing WR. Nevertheless, important trends can be seen and discussed. When looking at figure 11, it is clear that consequent fires did show a different behavior.
It is interesting to see how the average WR is higher in the control plot, it has an intermediate value in the once-burnt area and it is lower in the twice-burnt area. The natural conditions of the control area seem to favor WR. It is interesting to see how two consequent fires have an impact on WR. Even though the plots were both burnt by the most recent fire, it is possible to see how the disturbance caused by the 1989 fire still has an influence on the twice-burnt plots. The recurrent fires, with an interval of 15 years have probably caused some stronger damage to the soil or had an indirect influence on other factors like the organic matter. The occurrence of two fires in a short time interval might inhibit vegetation regeneration and consequently soil biotic activity.
When looking at the fire history in the scatter plot (figure 17) that relates moisture and WR, the coefficient of determination varies greatly. It has the highest correlation indices in the control and the lowest in the twice-burnt area. This fact suggests that the control plot is more responsive to soil moisture as a catalyzer of WR, whereas in the disturbed plots the effect of moisture is less pronounced and directly correlated to WR. Consequently, it is possible to conclude that humidity is more strictly correlated to WR in the plots that were less disturbed. The action of soil moisture appears to trigger other processes involved in WR than fire disturbance.
According to Tessler et al. (2008), fire induced WR decreased sharply in the weeks following the fire event. In this study the control showed a high WR, suggesting that in a first phase fire is the main driving force of WR, while later on it hinder the built-up of natural WR as it was found in the control. Five years after the most recent fire, other factors have a bigger role in inducing WR than the fire effects (Malkinson and Wittenberg, 2010). As widely explained in the available literature, WR can be the result of wildfires, plants organic compounds, fungi and microorganisms, humus and organic matter. Furthermore WR is strictly interconnected with hydro-morphological processes, soil texture and clay content (Doerr et al., 2000b). The complexity of the process suggest that according to different conditions one factor might be predominant in determining the intensity of the occurring hydrophobicity. In a well-established ecosystem, as in the control plot, the biotic factor is likely to have a stronger influence. On the other hand in a freshly burnt field, the biotic activity is likely to be lower. In this case as showed in many studies WR repellency is directly linked to the fire characteristics (DeBano, 2000}.

d. Effects of post-fire management

The initial plan of the study was to check the effects of management on every plot. Some difficulties lead the experiment on a different path. As it happened, we managed to test the management effects only on the plots burnt twice. On the other hand we had to consider all the data-points collected in the once burnt field as managed with clear-cut. This fact lead to an unbalanced distribution of the population size, with natural management having only 45 data-points against 135 data-points of Clear-cut. Nevertheless, the control shows higher values than the other treatments and this fact is likely to be caused by the higher ecological complexity of the area. The difference between Clear-cut and Natural even-though not statistically significant can be detected. However, the natural regrowth showed a lower hydrophobicity than the Clear-cut. Due to the unfortunate development of the experiments it is hard to make some conclusions regarding the management effect on soil post-fire recovery. Different management techniques appear to influence WR, but further studies with a special focus on the effect of heavy machinery on the soil and on the effect of the removal of charred plants on the germination of the new sprouts are here suggested.

7. Conclusions

Water repellency in the Carmel mountain range is commonly found after wildfires. Its presence decreases in the months following the fire. With this study the effects of consequent fires on soil water repellency was carried out five years after the most recent wildfire. The results show hydrophobicity being present in most of the areas, but peculiar and differing values and dynamics were found. Plants, post-fire management practices, and fire history appear to influence the formation and persistence of WR. The fact that WR is present in the control area to a greater extent indicates that hydrophobicity is a naturally occurring process probably induced by biotic factors. It is interesting to see how the burnt plots always showed an average lower occurrence of WR. From these considerations, this study creates evidence in favor to the model developed by Malkinson and Wittenberg (2010). The model displays fire history of ecosystems as a cycle of recurring wildfires and restoring phases. If the fire initially provokes high repellency, in a second phase this property tends to decrease significantly. Afterward a new balance tends to be reached. This phase is thought to be controlled by a complex interaction of multiple factors such as plants, microorganisms, fungi, litter, moisture, and management.

From the evidences collected, the graph in figure 17 has been drawn according to the model presented by Malkinson and Wittenberg (2010). With this curve we consider the fire occurrence as a continuous cycle of wildfires and restoration periods. In the first phase (phase 1), when the wild fire occurs there is a sharp increase in WR repellency followed by a sharp drop that can take from few weeks to several months (phase 2). The following phase (phase 3) involves a growth in WR. In the end (phase 4) the soil is reaching a more or less stable phase in which the values of WR are steady.

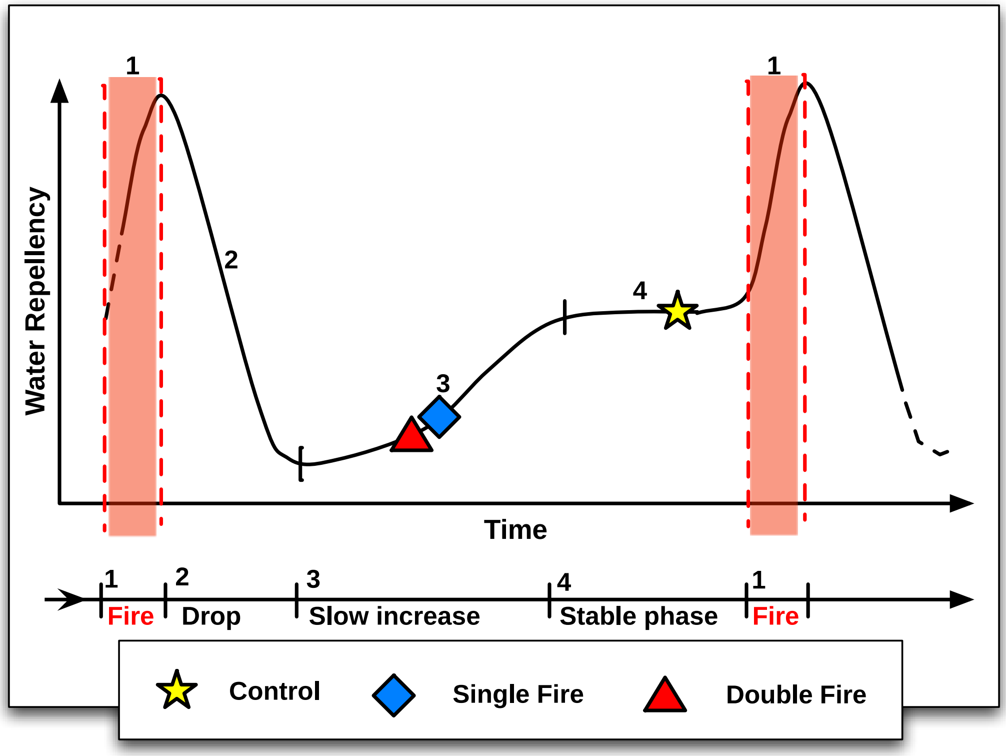

Figure 17: *Hypothetic behavior of WR in a regime of consequent wildfires. The curve is divided in 4 phases with the fire being the first.*

In the present research, we saw how the regenerating region is showing a certain degree of WR, but it is still lower than the mature control areas. From the results and following this model is possible to say that the burnt experimental plots are in the third phase, in which other factors than the fire are bringing the soil to a new balance in which water repellency is on a higher level. This new level (phase 4) of WR is likely to be similar to the values measured in the control plot. Moreover, the twice-burnt area appears to be slower in building up WR suggesting that consequent fires make the process (phase 3) slower or the more severe damage bring the second phase to reach an even lower value. Furthermore, plants effects also fit to this model. Plants that develop a thick layer of litter and favors retention of moisture seem to speed up this process.

8. References

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9. Appendix

Appendix 1: Rainfall events registered at Haifa university meteorological station:

Date (dd-mm)	mm	Month tot. (mm)	Season tot. (mm)
02-10	0.8	0.8	
30-Oct	0.9	1.7	1.7
05-Oct	2.5	2.5	4.2
07-Dec	2.8	5.3	7
10-Dec	7.1	12.4	14.1
11-Dec	49	61.4	63.1
12-Dec	49.3	110.7	112.4
13-Dec	0.9	111.6	113.3
17-Dec	0.2	111.8	113.5
18-Dec	1.5	113.3	115
31-Dec	4	117.3	119
4/5-Jan	31.7	31.7	150.7
8/9-Jan	10.7	42.4	161.4

Appendix 2: Laboratory instruments: in the upper pictures the portable ph-meter and ec meter; in the lower picture the soil oven.

Appendix 3: experimental outline together with the coding system used.

Table #: *Experimental outline. The columns describe from left to the right: the number of fires occurred, the post-fire management practice, the plant species object of the study, the number of plants per species (n), the code used for identification, the number of droplets applied per plant (k).*

Fire history (X,I,II)	**Management Practice (A,B,-)**	**Plant (Spp.)**	**(n)**	**Plot code**	**(k)**
Control **(X)**	None **(X-)**	Pinus	3	X-Pinus*n*	5
		Pistacia	3	X-Pistacia*n*	5
Burnt once **(I)**	Natural **(I-)**	Pinus	6	I-Pinus*n*	5
		Cistus	6	I-Cistus*n*	5
		Pistacia	6	I-Pistacia*n*	5
Burnt twice **(II)**	Natural **(IIA)**	Pinus	3	IIA-Pinus*n*	5
		Cistus	3	IIA-Cistus*n*	5
		Pistacia	3	IIA-Pistacia*n*	5
	Clearcut **(IIB)**	Pinus	3	IIB-Pinus*n*	5
		Cistus	3	IIB-Cistus*n*	5
		Pistacia	3	IIB-Pistacia*n*	5
	Total			**42 plots x 5 =**	**210**