

Ash unraveled:

A descriptive study about physical, chemical and spectral characteristics of ash and soil in a Mediterranean forest after a large wildfire

Mount Carmel area, Israel



MSc Thesis by Heike Vincentie

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Heike Vincentie

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Abstract

The presence of wildfires is a growing issue in Mediterranean areas. Defining a standardized method of assessing fire impact on soils is a challenging task due to high environmental heterogeneity. In this study an attempt is made to take up that challenge and see whether it is possible to combine traditional field and lab methods with modern hyperspectral analysis in the Carmel mountains, Israel (5 months after a large wildfire) in order to develop a tool with which wildfire effects on soil can be examined quickly.

In recent literature, a number of soil parameters are described as major soil characteristics that are influenced by wildfires. Soil moisture, water repellency, organic matter content and aggregate stability are a few of these parameters. The different top soils in a severely burnt area show that there is a relation between ash type and water repellency. White ash contains a relatively high percentage of silt and is either highly wettable (top soil) or strongly water repellent (subsurface soil). Black ash contains a high amount of organic matter (as expected because of the dark color) and bare soil is the least water repellent of the three.

PLSR (partial least square regression) examines the ability to predict each of these soil characteristics with spectral signatures. This seems possible for water repellency and soil organic matter content. Spectral analyses are surprising as this study shows that white is not always white. White ash gives significantly lower spectral signatures in both the visible (~400-700 μm) and the total spectrum (350-2500 μm).

Key words: Wildfire, Israel, Hyperspectral signatures, PLSR, Ash, Organic matter, Water repellency

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Abbreviations

MDI:	Mini Disk Infiltrometer
PLSR:	Partial Least Square Regression
ParLes:	Software for Partial Least Square regression suitable for soil spectrometry
SERS:	Soil Erosion Research Station (Ruppin, Israel)
SOM:	Soil Organic Matter
WDPT:	Water Drop Penetration Time
WR:	Water repellency

1 Introduction: wildfires, soil and ash

Wildfires

In Mediterranean forests wildfire frequency and wildfire hazards have remarkably increased during the past decades (Wittenberg & Malkinson, 2009). Wildfires are one of the mayor threats to Mediterranean forest ecosystems (Reyes Ruiz-Gallardo, et al., 2004). As large areas are affected by wildfires, the following questions arise: What are the effects of these fires on the forest ecology and (how) does an area recover from a large disturbance like this? The rate of recovery and response of the soil ecosystem depends on both internal and external factors. Internal factors like soil physical and chemical characteristics, topography, slope and external factors like the intensity and frequency of wildfires as well as rainstorms (Certini, 2005). In all of these parameters that affect the forest soils -and therefore influence recovery of the forest ecosystem- there is a great (spatial) heterogeneity which makes defining soil-wildfire relations complex.

This research will elaborate on the presence of a post-fire ash layer. The ash layer that covers the surface is a product of the available biofuel and fire characteristics and on its turn the ash layer has an effect on the soil and vegetation as well as soil and vegetation recovery process. The ash layer is spatially highly variable and has an impact on the soil depending on its chemical and physical characteristics.

Soil

Soil is the agent that provides nutrients and forms the basis for vegetation. The vegetation type and abundance depends on the properties of the soil. This means that when soil characteristics are altered after a wildfire this will affect the regrowth of vegetation in terms of abundance and species composition (Casady, et al., 2010). The pre-fire vegetation type and structure, soil type, heat input during fire and soil moisture define the magnitude of post-fire changes of the soil system (Neary, et al., 1999). Wildfires affect hydrological characteristics of soils and with that susceptibility to erosion (Bodi, et al., 2012).

On the other hand, vegetation influences soil formation as it provides the soil with biomass. Plant water uptake and evaporation regime affect the soil and vegetation also protects the soil physically during rainstorms by interception of precipitation and by making the soil less sensitive to erosion (Shakesby, 2011).

With respect to these relations the influence of slope and aspect of the slope are factors to be considered for explaining the complex post-fire soil system. South facing slopes receive higher sun intensity than north facing slopes as they are more exposed to the sun. In addition, raindrops have a bigger impact on the slopes that are facing the main wind direction, as the raindrops will fall perpendicular to the slope which causes the highest raindrop impact and splash erosion. Rainfall on the slopes facing the opposite direction is more or less parallel to the slope of rainfall, causing less erosion. This illustrates that even on a small catchment scale the variables affecting slope processes and thus post fire soil and vegetation recovery are highly heterogeneous. (Casady, et al., 2010, Pérez-Cabello, et al., 2006)

Forest Resilience

The impact severity of wildfires on the forest ecosystem varies according to the different factors described above. In some cases forest ecology resilience to wildfires is high, when after a fire event vegetation recolonizes and many properties are restored to their pre-fire level. This process is thought to be more rapid for vegetation (for example less than 5 years, (Wittenberg, et al., 2007)) than for soils, with for example changes in organic matter (quality and quantity) that last up to millennia (Certini, 2005). The rate of restoration varies for physical, chemical and biological soil properties. For example changes in nutrient availability

occur but are ephemeral while the quality of organic matter can be permanently altered (Certini, 2005).

Less is known about the long term effects of wildfires on for example water repellency (Wittenberg & Malkinson, 2009) and other physical and chemical characteristics of soils and soil layer interaction. A less severe burn can support the growth of healthy forests while severe burning could result in lower plant available nutrients, changes in soil properties and species composition (Neary, et al., 1999). There are also examples of soil ecosystems that are exposed to recurring fires followed by heavy rainfall events, causing erosion and contributing to an irreversible land degradation process (Doerr & Cerdà, 2005).

Among the factors that determine soil resilience is the depth of the topsoil, as this is often relatively thin in Mediterranean areas (Pardini, et al., 2004) (Shakesby, 2011). The vulnerability of the topsoil to erosion or degradation due to nutrient loss can be an important factor in defining recovery possibilities for forest ecosystems. Pérez-Cabello et al (2010) have found that the most important fire-induced changes in soil properties were “the decrease in thickness of the O horizon, in carbonates, in the size of aggregates and in organic matter, and the increase in silt percentages” and they also observed a general increase in soil homogeneity of these properties.

Arianoutsou et al (2011) use vegetation cover as an input for evaluating post-fire resilience of forest ecosystems. They find that important factors for the sensitivity analyses they conducted are history of fire, parent rock type and slope. Using multiple criteria makes it possible to consider many factors but produce a single index that can be used for post-fire management measures.

Ash layer

Ash is thought to be a useful indicator for fire intensity and is therefore an important part of the soil system that needs to be studied (Bodí, et al., 2011). Úbeda et al (2009) studied the effects of temperature gradient on the ash properties and found relationships between temperatures and physical properties of ash such as aggregate stability as well as chemical properties as cation concentrations. It appears that low intensity fires do not have a large negative effect on the soil but this negative effect on physical and chemical soil properties increases with higher fire temperatures.

The ash layer can change the hydraulic properties of soils in terms of the creation of a water repellent layer in the subsurface and infiltration rates change with the presence of ash in the soil profile. The water retention capacity can increase due to the presence of ash and a water repellent layer will decrease this capacity, which illustrates the complex relations of ash and soil (Moody, et al., 2009).



Figure 1.1. Field examples of (from left to right) white ash, black ash and (baked) soil without ash cover.

There is a small amount of knowledge on the physical and chemical characteristics of the ash layer after wildfires in Mediterranean forests and although this layer is very prominently present there is no widely accepted definition of wildfire ash (Bodí, et al., 2011). Ash color is used as a common indicator of fire severity and ash classification (Parsons, et al., 2010). The

top soil layer after wildfires is generally divided into three classes: white ash, black ash or no ash (soil) (figure 1.1).

Hyperspectral analysis

Combining the current knowledge on ash-soil relationships and fire effects with modern spectral techniques offers a possibility to increase the understanding on post-fire processes on different scales.

Hyperspectral analysis may be a quick method to investigate these soil characteristics. When used as a remote sensing technique the focus is on the surface cover. The advantage of using images is that large areas can be assessed at a time. The advantage of doing in situ measurements (which is done in this research) is that there is an opportunity to measure different depths of the soil profile. When relations between the topsoil and the subsurface soil are found, this technique can be extrapolated and used in combination with imaging spectrometry to assess larger areas at a time.

Spectral analysis describes soil reflection of light and energy in different bandwidths. When a high number of bandwidths is measured over a continuous range, creating a continuous spectral signature, we speak of hyperspectral. The device used to measure reflectance values in the range between 300 and 2500 nm is called a spectroradiometer (ASDI Inc. products).

To assess impact of fire on soils spectroscopy has been used increasingly to determine fire intensity, post-fire surface cover and water repellent soils (Finley & Glenn, 2010). Point spectrometry has been used extensively in soil sciences but making the shift from point spectrometry towards spatial imaging spectrometry is still in the developing phase (Ben-Dor, et al., 2008).

Research Objective

There is much knowledge on post-fire effects in forests that include a broad range of parameters, varying from soil water repellency, microbial activity, water quality and soil moisture to runoff patterns (Certini, 2005). Using the knowledge about the parameters that are important for soil and vegetation recovery (organic matter, water repellency, slope aspect, texture, aggregate stability, soil moisture, pH and EC) this study addresses a gap in current research that needs to be filled.

The exact factors that determine the recovery of forest ecosystems, for example the effect of vegetation type on water repellency, post-fire soil chemistry and inter-layer processes are not known. In the text above there are several factors mentioned which influence the rate of recovery of a forest ecosystem. The individual contribution of properties of the soil ecological system on a micro scale is still not fully understood. Also the possible presence of threshold values within the system needs to be studied in order to understand the vulnerability and resilience of soils to wildfires.

So far there has not been much research on ash characteristics and the presence and effects of the ash through the depth of the soil profile. This study focuses not on explaining the effects of fire an ash on soil, but rather on describing the ash layer that is present on top of the soil after fires as well as relation with the subsurface layers.

The goal of this research is to

- *make a post-fire topsoil definition and classification based on the ash and soil characteristics,*
- *find a relation between the ash cover and the subsurface soil characteristics, and*
- *assess the suitability of using a hand-held spectroradiometer for measuring post-fire soil parameters.*

Thesis outline

The following chapter (chapter 2) will give a short description and history of the research area. In chapter 3 the sampling plan, field and laboratory methods are described to provide a clear image of the study's structure. Also the methods used for data analysis are mentioned in short. The results of this field and lab work are presented in chapter 4. Chapter 5 will wrap up the conclusions of these studies and give recommendations for further research opportunities.

2 Carmel Mountains

The research area will be introduced in the following paragraph with a short description of fire history, climate, geography, soils and vegetation.

Motivation and fire history

The direct motivation for this study was a major wildfire in the Carmel Mountains near Haifa in the northwest of Israel in the beginning of December 2010 (figure 2.1).



Figure 2.1. Israel and the location of the Carmel Mountains in the North.

After a very dry summer, winter started late and by the beginning of December there had not been any rainfall yet in the study area. When the fire started there were eastern winds and air humidity was very low, creating a suitable climate for the fire to grow rapidly. Extinguishing the fire was not possible and only after four days the fire was under control, after a change in wind direction and higher air humidity. (Paz et al, 2011)

The area in northern Israel has been subject to several wildfires during the last years. There were large documented wildfires during the 80's and 90's as well as in 2005, 2006 and 2010. The most recent fire in the Carmel area in the beginning of December 2010 is by far the largest in size considering the total affected area of over 2000 hectares (table 1).

Table 2.1: Occurrence of large wildfires in Mount Carmel region in the past decades, modified from Wittenberg and Malkinson, 2009.

Date			Area Burnt (ha)	Date			Area Burnt (ha)
3	November	1983	284	8	April	2005	154
19	September	1989	530	4	January	2006	132
11	October	1998	162	11	July	2006	125
12	October	1998	517	2-5	December	2010	2180
4	December	1999	158				
6	December	1999	130				

Environment

The Carmel Mountain range spreads in a southeastern direction from the coastline of Haifa in the northwest of Israel. From sea level the mountains reach a height of around 500 m within a few kilometers. The climate of the Carmel Mountains and surroundings is a Mediterranean type Cs (Köppen) characterized by dry and hot summers and rainy winters. The average annual precipitation ranges from 550 mm near the coastal plain to 750 mm at the highest elevations (Malkinson & Wittenberg, 2011). Air temperatures vary from around 8 degrees in winter to 31 degrees in summer on average (IMS, 2007) The mean annual wind direction during precipitation is southwest (figure 2.2a, (Halfon, et al., 2009)).

Soils in this part of the Carmel are Brown Rendzina and Terra Rossa and as common in Mediterranean areas they are shallow (up to around 50 cm of depth). Lithology of the Carmel is composed of Upper Cretaceous carbonate rocks. The vegetation of the Carmel is a typical Mediterranean maquis. (Malkinson, et al., 2011) The research area consists mainly of a typical Mediterranean forest of oak (*Quercus calliprinos*) and pine (*Pinus halepensis*) (Malkinson & Wittenberg, 2011). After the fire, the pine seedlings started spreading and distributed through the catchment. New oak vegetation is confined to the trunks of the burnt oak trees.

Location and maps

Paz et al (2011) validated a fire behavior model (FARSITE) with this fire event and they mapped the contours of the fire affected area on top of the fire risk map (figure 2.2b). The boundary line of the 2010 fire shows that the used model seems a reliable predictor for spreading area of the fire (Paz, et al., 2011). The area within the green square, located 3.5 kilometers south of Haifa University on an elevation of around 320 meters is used for sampling and field measurements in this study.

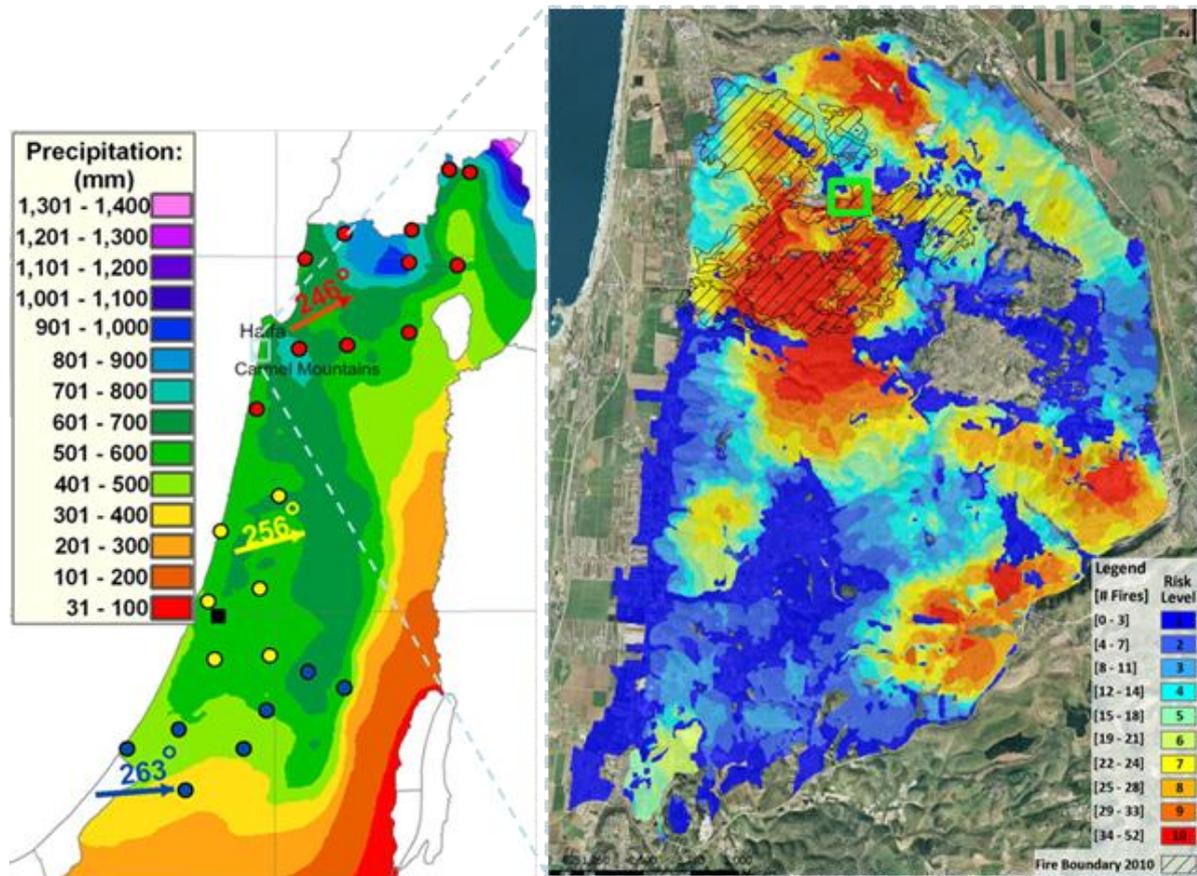


Figure 2.2a. Mean annual rainfall pattern and mean wind direction in degrees during rainfall events Israel. Adapted from Halfon et al, 2009

Figure 2.2b. The spreading area of the fire event in the Carmel Mountains of 2010 plotted in a fire risk map (Paz, et al., 2011). The location on the map indicates the study area. For a more detailed picture of the research area, see figure 2.3.

This catchment is called the Damoon drainage and covers a total area of 26 hectares. A wadi crosses the catchment that is active during winter and its bedding falls dry during summer. The wadi bank is slightly southwest sloping or level and the slopes that were used for sampling are northwest and southeast sloping. These sampling spots are situated in the downstream part of the catchment indicated with dots in figure 2.3. On the map is visible that only a small part of the vegetation survived the 2010 fire.

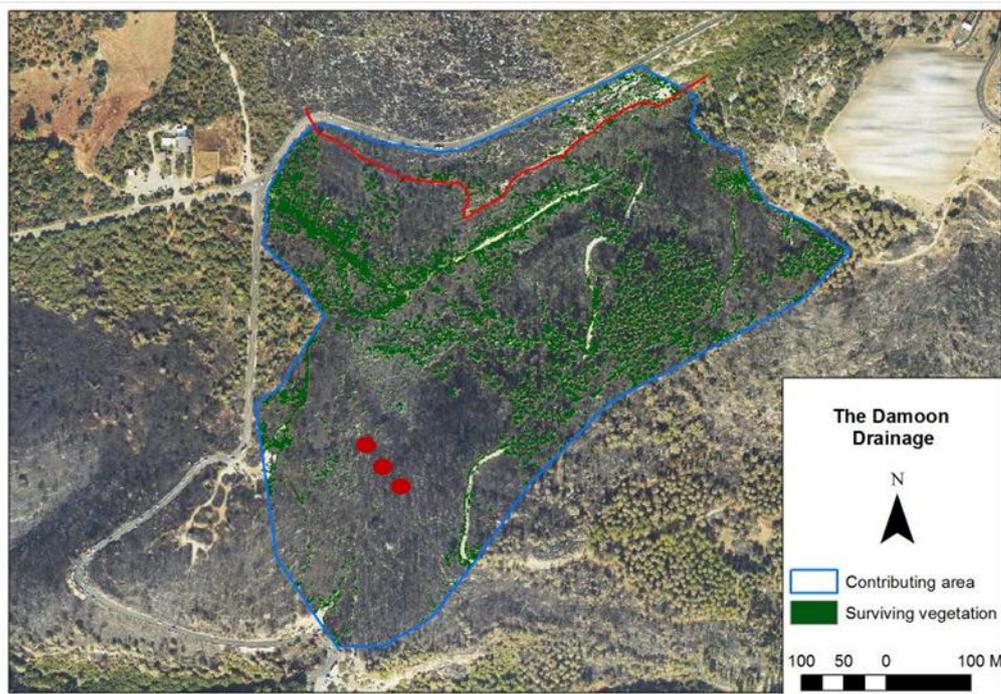


Figure 2.3. Post-fire study area indicated inside the catchment of the blue line. Sites on northwestern, southeastern sloping and bank slopes for measurements and sampling are indicated with red dots (estimation). Different lithology above the red line.

3 Methodology

In this chapter first the field methods for both soil pits description and sampling and the MDI (Mini Disk Infiltrimeter) measurements and sampling (these sample are referred to as ‘MDI samples’) are described. After that the laboratory methods will be elaborated upon.

Field sampling

Sampling locations were selected in the Damoon drainage area, an area that was heavily affected by the December 2010 fire. Soils were tested and described in the lab and the field as they were found (in situ).

The distribution of the ash types is very heterogeneous and patchy. This can partly be explained by the time that has passed since the fire event and the following rainfall events but also by the highly variable characteristics of the fire and the heterogeneity of available biofuel, slope and other environmental factors. The method for selecting sampling locations in the field could not be conducted with random sampling according to topography or other factors because of the spatial heterogeneity of the soil.

The purpose of this study is to provide a characterization of the different post fire top layers that are covering the soil surface and the effect of this layer on underlying soil. Soil samples are taken in situ and not manipulated in the lab because in previous studies it was shown that they often poorly reflect field conditions (Bodí, et al., 2011). That is why the methodology as described below is used.

For a general understanding of the characteristics of the soils a small number (6) of pits was dug to describe the soil profiles in the area. The same soil description form was used for uniformity in describing the soils (appendix A). The main characteristics of the soils were described including depth and number of layers, color, texture, presence of carbonate

(mottles) and other criteria (appendix A). Water repellency (WR) was estimated with the WDPT (see section below for explanation of WDPT) for a general idea of the presence of WR in this area. The soils are relatively shallow; they vary in depth from no soil to around 60 cm. Of each of the soil layers a sample was taken, brought to the lab in a closed plastic bag and stored in the fridge until further analysis (see lab methods later in this chapter).

After describing these broad characteristics of the ash covered burnt forest soils more specific sampling spots were chosen for further analysis. The soils consist most often of 5 distinguishable horizons based on color, texture etc., but for the description of the ash layer and its underlying layers the top three main layers are researched in this study: the top layer (ash or 'bare' soil), the middle layer (mostly hydrophobic) and the lower layer (appears mostly unaffected by the fire; close to original pre-fire soil). These three layers in the upper 15 cm of the soil are used for more detailed sampling.

There are a few parameters that were taken into consideration as guidelines for deciding upon the soil sampling sites. As explained in the introductory section of this thesis, the slope degree and angle (aspect) is an important factor to consider when observing post fire effects on forest soils. Therefore three different aspects have been chosen for soil sampling; northwest, southeast and horizontal (neutral aspect, slightly southwest facing). The samples have been taken a few meters high on the slopes and on the wadi bank where the soil surface looked undisturbed. The slope angles are on average 15% and the north facing slope is slightly steeper than the south facing slope.

The top soils were divided by sight into three classes: white ash, black ash and (baked) bare soil. Mixtures of these top soil types exist in the field but these three visually very distinct types were chosen for making it possible to describe the physical and chemical properties even with a small sampling size.

The soil profiles were generally divided into three layers in depth as described above. See table 3.1 below for the exact sampling plan.

Table 3.1. Sampling plan. For three different slope aspects and three different types of top layers, three soil layers have been sampled adding up to a sample amount of around $3 \times 3 \times 3 = 27$. For the wadi Bank the used sample codes are explained, same system is used for other slopes. For three locations only two layers could be distinguished and at one location the top layer was separated into two (white ash on wadi bank).

	Bank				Northwest			Southeast		
Black ash	Top BankB1		Middle BankB2	Lower BankB3	Top	Middle	Lower	Top	Middle/ Lower	
White ash	Top BankW1	Top BankW2	Middle BankW3	Lower BankW4	Top	Middle/ Lower		Top	Middle	Lower
Bare soil	Top BankS1		Middle BankS2	Lower BankS3	Top	Middle/ Lower		Top	Middle	Lower

Each of these samples described in the table were taken to the lab in closed bags and saved in a refrigerator.

Water repellency

For every soil layer three soil water repellency tests were done in the field using the Mini Disk Infiltrometer (MDI, figure 3.1) (Robichaud, et al., 2008).

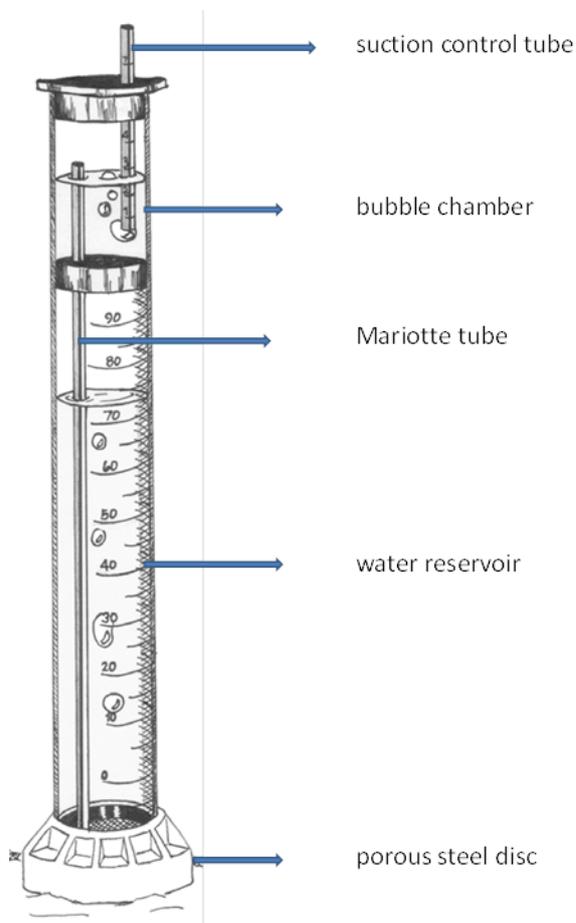


Figure 3.1. Mini Disk Infiltrometer diagram. Adapted from (Decagon Devices, 2011).

This method is described by the USDA specifically for assessing post-fire soil water repellency, using a case study of an area with similar post fire forest soil conditions as in this study¹. Unlike the WDPT (water drop penetration time) this method gives a quantitative value of milliliters per minute and also correlates highly to the WDPT method (Robichaud, et al., 2008), especially in water repellent soils. This method is more valid when the water repellency is spatially highly variable since the WDPT will give a very limited point measurement while measuring with the MDI method will include a bigger surface as the water is infiltrating deeper into the soil. This possibly gives a more realistic image of what happens in reality when (rain, stream) water enters the fire affected area. Although the WDPT is a fast and relatively easy method, it is more susceptible to subjectivity when it comes to valuing the water drops. Using the Mini Disk is slightly more time consuming but at

¹ "...fire-induced soil water repellency has most often been detected at 1 to 3 cm below the surface. In burned areas, surface measurements (immediately below the ash layer where soil and ash mix) often indicate non-water repellent soil, making sub-surface testing necessary to determine the existence and extent of a fire-induced water repellent soil layer. The data from James Creek is typical of forested areas burned at high severity—no detectable soil water repellency at the surface with a strongly water repellent soil layer at 1 to 2 cm below the surface..." (Robichaud, et al., 2008)

the same time allows to work more objectively by quantifying the water repellency in volume of water per time.

To make good contact between the soil layer and the mini disk's porous disk, construction sand was used to create a smoother and more level surface. This sand also takes up water and it was measured that the small layer of sand in average takes up 3 mL of water from the MDI. The final infiltration in mL/min is corrected with 3 mL prior to conversion into classes of water repellency described in the USDA method (table 3.2).

Table 3.2. Water repellency classes according to the USDA method of Robichaud et al 2008.

Infiltration (mL min ⁻¹)	Water repellency
0 -< 3	strong
3 -< 8	weak
=/> 8	no

Lab methods²

Soil pit samples

The samples taken in the end of April, 2011 for describing the six soil pits (26 samples in total) were analyzed in the geography lab of Haifa University on soil moisture, pH and EC. Prior to this they were air dried and oven dried at 105 degrees to measure the difference between these treatments. The samples that were dried at 105 degrees were weighed prior to and after drying (3 repetitions per sample) to determine the soil moisture of the sample. For measuring pH and EC the following protocol was used. The soil samples were treated according to the following method: 50 mL of demineralized water is added to 50 grams of soil to make a suspension of 1:1 soil-water ratio (Ryan, et al., 2008). This suspension is stirred and left standing during an hour according to the protocol. The pH and EC values are then read and recorded.

'Mini Disk' samples

The samples that were taken (table 3.1) simultaneously with the water repellency test with the mini disk infiltrometer (hereafter called 'mini disk' samples) were treated in a similar way to the samples taken from the soil pits. The 29 samples were analyzed in the lab of the Ruppin Soil Erosion Research Station, 60 kilometers south of Haifa.

Part of the amount of soil was air dried and part of it was oven dried. The *color* of the air dried samples was determined for both dry and wet samples using the Munsell color system. The oven dried samples were weighed for *soil moisture* measurement before and after oven drying at 105 degrees Celsius. To determine the *texture* of the soil a small amount of this <2 mm sieved sample was left overnight in a shaker with a 5 % sodium hexametaphosphate solution as a dispersing agent. The following day when all the aggregates were dissolved in the solution the samples were used for particle size analysis with the Malvern 'Mastersizer 2000'. The classes were sorted according to the FAO standard for soil particle size classes. The oven dried samples were also used for calculating *soil organic matter* using the dry combustion method described by Ben-Dor and Banin for Israeli soils (Ben-Dor & Banin,

² Unless stated otherwise, all measurements have been executed in threefold.

1989). The samples were ignited in crucibles for 8 hours at 400°C and then weighed for obtaining the mass of soil organic matter.

The air dried samples were used for several other analyses described in this section. First the samples were sieved with a 2mm sieve. *EC and pH* were measured using the method as described in the previous section.

For determining *aggregate stability* a wet sieving apparatus was used (Eijkelkamp, 2008). The protocol for using this method differs strongly for various studies choosing the most suitable method was not very straightforward. Since after a few tests the samples seemed to be highly stable, in this research no pre-wetting method was used. Often pre-wetting is used to prevent slaking of the aggregates, but since the aggregates were so stable this treatment was not considered necessary. Not doing so also provides a more uniform treatment, with less chance of influencing the samples differently before the analysis. It will not be possible to compare the exact data with other studies that do use pre-wetting methods but the aim of using the aggregate stability test in this research is to try to define a relative difference in stability between the samples. The protocol used was as follows: the soil sample was first sieved so that only the fraction between 1 and 2 mm was used. A few grams of soil (approximately 4) were placed in the sieve of the wet sieving apparatus and the cans of water were filled with distilled water. After 3 minutes of immersing the sieves in the cans, the cans of water are replaced by cans with sodium hexametaphosphate solution. The process is then repeated for as long as it takes to dissolve all aggregates.

The ratio between stable aggregates (particle weight in sodium hexametaphosphate solution) and unstable aggregates (particle weight in water) gives a ratio or percentage that is defined as aggregate stability. For each sample 2 repetitions were done since in previous studies the method has proved very accurate, and due to time constraints.

All samples were then (sieved < 2mm) put in small containers and measured for *hyperspectral signature*. The FieldSpec® 3 Portable Spectroradiometer is a hand held device that gives a spectral signature of the measured location for wavelengths varying from 350 to 2500 nm (example figure 3.2). A hyperspectral sensor measures the reflectance of the measured spot without atmospheric noise as the measurement is taken close to the sample. Another advantage of this field sensor compared to remote sensing is that it is a site specific, small scale and high resolution measurement that provides the spectral signature of one point of interest as well as in depth information from one geographical point. (ASDI Inc. products, n.d.)

Results are analyzed with ViewSpecPro and ParLes (see results section).

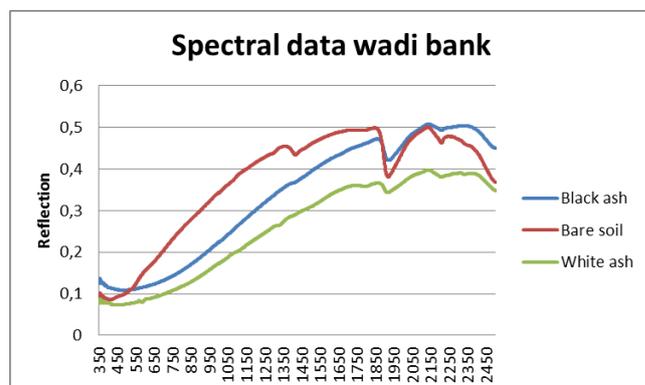


Figure 3.2. An example of a set of spectral signatures for wavelengths 350-2500 nm on the x-axis and reflection values on the y-axis.

To wrap up, the samples have been analyzed on water repellency, color, soil moisture, texture, soil organic matter, pH, EC, aggregate stability and hyperspectral signature.

4 Results: ash unraveled

This chapter will give a description of physical and chemical aspects of the soil layers that are distinguished in the field campaign of this study. The major part of this study is highly descriptive and qualitative as the limited amount of soil samples allows for only basic statistical analysis. This study combines traditional sampling and analytical methods with spectral analysis methods and as there is no reference to a similar study in a fire affected area it is explorative of nature.

First the soil pits results will be presented followed by the MDI measurements and laboratory results of the soil samples. After that the spectral results are discussed as well as their analysis with PLSR.

Soil Pits

The soil pits are described using standard soil description forms. An example of a form is available in the appendix (appendix A) for more detailed information. Part of these soil samples (4 of the soil pits) were sent to an external lab for further analysis. The results from the external lab as well as the geography lab of Haifa University are presented in appendix B and in short discussed in the following paragraph.

The lab results of the soil pits provide the basis for determining the further sampling plan although they do not show significant relations between the soil parameters.

In figures 4.1a and b the soil organic matter content is plotted against depth, showing a strong relationship (after removal of one extreme measured value) as expected, because of the higher amount of organic material (vegetation) available in the topsoil.

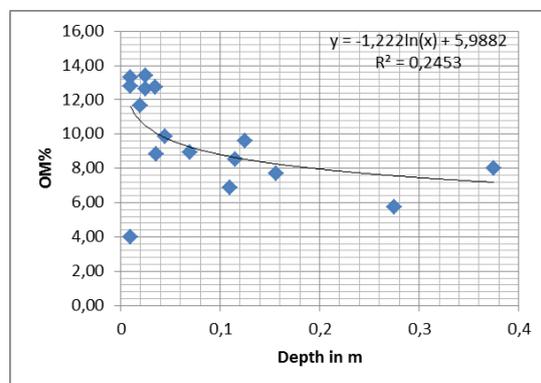


Figure 4.1a. Organic matter content as a function of depth.

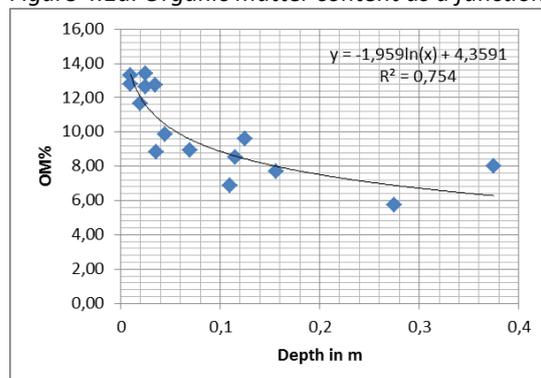


Figure 4.1b. Organic matter content as a function of depth with one extreme value removed. The logarithmic correlation between organic matter content is relatively high ($R^2=0.75$).

Soil moisture content shows a decline with depth (figure 4.2). During the time of sampling there were still rainfall events, which caused the upper layer to contain the highest percentage of moisture. The water does not infiltrate deep into the soil as the deeper layers contain the lowest amounts of moisture. This may be the effect of a water repellent layer.

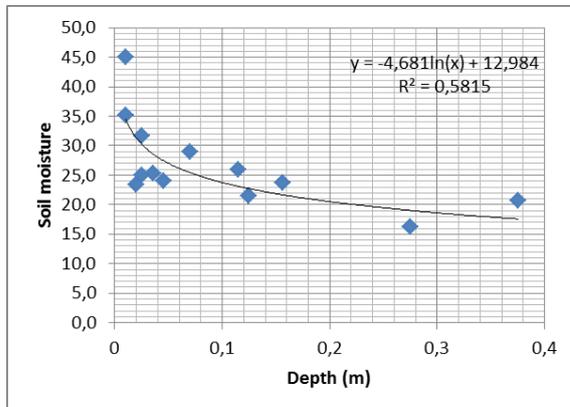


Figure 4.2. Soil moisture as a function of depth. In the end of April, the soil is wettest on the top and is dryer deeper in the soil. The logarithmic relation shows an R^2 of 0.58.

The characteristics of the soils vary strongly between small distances and especially in depth within the catchment. The depth of the soil varies from no topsoil and very shallow soils to soils with a depth of 60 cm. The depth of the top layer of ash or soil varies strongly and also the water repellency varies from no WR to strong WR. Top soil and ash layers are distinguishable by color and aggregates and presence of roots. The top layer is greyish and contains many (ash-) aggregates and the color turns reddish deeper into the soil (figure 4.0) where less ash-particles are found and more carbonate mottles. Burnt roots are found in the top layers, below the top layer there are small unburnt roots of plants and even deeper there are no small roots except for an occasional burnt root of a tree.



Figure 4.0. Soil color varies from light grey on top to reddish brown deeper in the soil profile.

Ash layers and water repellent layers vary in thickness and in depth and therefore depth itself cannot be used as a criterion for sampling. Instead the chosen sampling method for the second part of the study (MDI samples) is to sample the top soil, the water repellent layer (if any) and the layer below that (as a more or less unaffected soil) disregarding the depth. Aggregates and soil color are important factors that determine sampling depths and small drops of distilled water are used to locate the WR layer.

Obtained using these sampling criteria in the next chapter will be presented the results of the second part of the field campaign.

MDI (Mini Disk Infiltrometer) results

In this section the results for the measurements with the mini disk infiltrometer in the field will be presented as well as the laboratory results of the correlating samples. The measurements are taken according to the following sampling plan (as described in the methodology section) and the results are presented accordingly.

Table 4.1. Copy of table 3.1

	Bank			Northwest			Southeast			
Black ash ^B	Top ¹		Middle ²	Lower ³	Top ¹	Middle ²	Lower ³	Top ¹	Middle/ Lower ²	
White ash ^W	Top ¹	Top ²	Middle ³	Lower ⁴	Top ¹	Middle/ Lower ²		Top ¹	Middle ²	Lower ³
Bare soil ^S	Top ¹		Middle ²	Lower ³	Top ¹	Middle/ Lower ²		Top ¹	Middle ²	Lower ³

Water repellency

The results of the water repellency tests with the MDI show a clear separation between different soil layers.

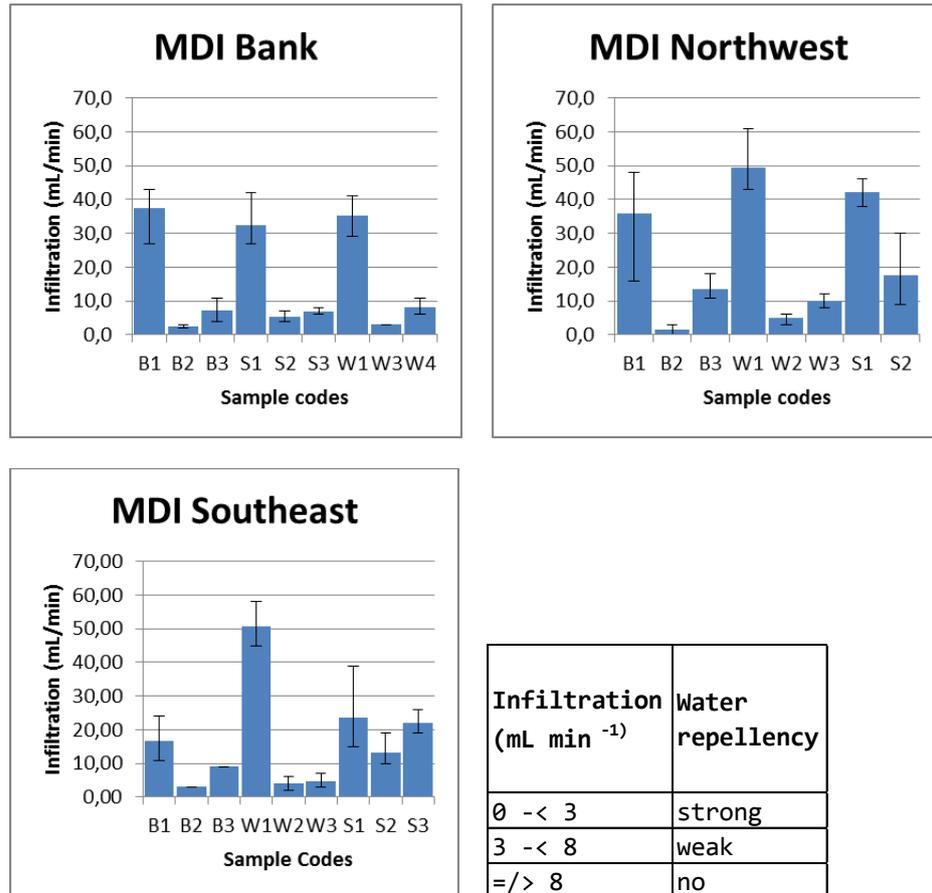


Figure 4.3a, b and c. Infiltration values with measurement deviation bars for measurement of one minute with a Mini Disk Infiltrimeter on wadi bank, northwestern slope and southeastern slope respectively. B, W and S stands for black ash, white ash and soil top layer. 1, 2 and 3 stands for top, middle and lower layer of the soil. Legend shows water repellency classes according to USDA method of Robichaud et al 2008.

As figures 4.3.a-c show, water repellency is occurring below the top layer. The top layer is the most wettable, with no water repellency; there is a drop in infiltration in the middle layer that has strong water repellency (with the exception of two samples). The deepest layers (that are least affected by the fire and closest to original pre-fire conditions) are not or weakly water repellent.

Lab results soil parameters

There are a few different ways to analyze the data. The soil characteristics that have been measured can be compared amongst each other in the different clusters of top/middle/lower soil layer, black ash/white ash/bare soil and bank/northwest/southeast slope direction. The results are shown in table 4.3.

Table 4.3. Average values of some soil parameters for depth, top soil type and slope aspect.

	Aggregate Stability	Organic Matter	pH	EC	sand	silt	clay	moisture
	%	%		uS/cm	%	%	%	%
Total average	96,4	11,8	7,8	616	38	52	9	9,8
Total deviation	3,0	3,9	0,2	312	11	9	4	5,8
<i>Depth</i>								
Top average	96,0	13,1	7,8	654	37	54	9	4,3
Middle average	98,1	12,6	7,7	721	45	48	7	11,0
Lower average	94,5	9,0	8,1	413	31	57	12	16,9
<i>Top soil type</i>								
White average	95,7	10,2	7,8	817	32	58	11	9,2
Soil average	95,6	11,6	7,9	444	41	49	9	10,1
Black average	98,1	14,0	7,8	559	43	50	7	10,2
<i>Slope aspect</i>								
Bank average	95,5	12,9	7,8	581	36	52	12	11,5
South average	97,3	10,4	7,8	543	44	49	7	6,4
North average	96,8	11,8	7,8	767	36	56	8	10,9

Soil sampling sites were chosen based on the topsoil, as explained in the methods. The color of the samples is used for determining sample locations and depths and is not presented in the tables. For a more extensive table of results, see appendix C.

The moisture pattern for these samples is an inversion of the moisture pattern for the soil pits. Moisture is 4% on average for the top soil and increases to an average of 17% for the lower layer. In figure 4.4 these points are plotted (the location of the points are an estimation) on the moisture-depth graph of figure 4.2.

The lower layer fits in the pattern of the rainy season and the upper two layers are much dryer when there is no rainfall. The continuity of the moisture content in the lower layer can be explained with the water repellent layer as well. As the water repellent layer keeps water from infiltrating deeper into the soil, it also may prevent water from evaporating from the lower layer.

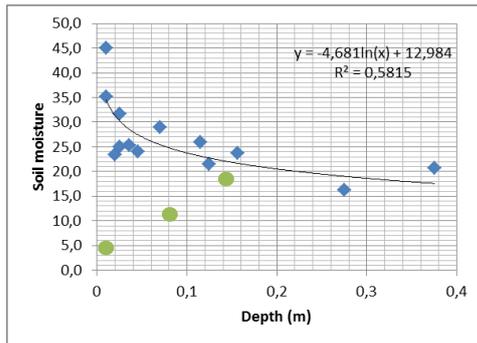


Figure 4.4 Soil moisture content in soil pits as a function of depth (figure4.2), now includes the average soil moisture content of the 'MDI samples' in green.

The previous table shows that by analyzing the different soil layers the results that deviate from the averages will be lost. There is a clear difference between the different soil types that is not visible when all layers are combined in one table.

The tables in the following section (tables 4.4a,b,c) show values for only the top layers, middle layers and lower layers disregarding the slope aspect and this way the distinction within the post-fire soil and ash types becomes visible.

For each of the following tables results will be discussed in a few lines.

Table 4.4a. Soil parameters of topsoil; black, white and bare soil.

Top soil	Aggregate Stability	Organic Matter	pH	EC	sand	silt	clay	moisture	infiltration
				<i>uS/cm</i>	%	%	%	%	<i>mL/min</i>
<i>Black ash topsoil</i>	98,4%	16,4%	7,6	555	45	48	7	4,6	37,0
<i>Bare soil top soil</i>	96,6%	13,9%	7,7	595	45	47	8	4,8	29,8
<i>White ash topsoil</i>	96,0%	10,0%	7,9	672	26	65	9	3,1	42,1

Black ash has the highest aggregate stability as well as soil organic matter content. White ash contains a relatively high percentage of silt and had a high infiltration rate. The white ash top layer consists of very fine, flaky material and is highly wettable. The white ash topsoil contains the lowest percentage of moisture. All top layers are wettable and no water repellency is measured. The values of the bare soil samples are somewhere in the middle of the other values, however these differences are not significant.

Table 4.4b. Soil parameters of middle layer; black, white and bare soil.

Middle layer	Aggregate Stability	Organic Matter	pH	EC	sand	silt	clay	moisture	infiltration
				<i>uS/cm</i>	%	%	%	%	<i>mL/min</i>
<i>Black ash middle layer</i>	98,9%	13,5%	7,8	647	49	44	6	9,7	0
<i>Bare soil middle layer</i>	97,4%	11,9%	7,9	485	47	46	8	10,9	9,1
<i>White ash middle layer</i>	98,0%	12,3%	7,6	953	39	53	8	12,2	1,0

In the middle layer there are a few remarkable results. The infiltration rates in the middle layers show that where the layers below the black and white ash are (highly) water repellent, while the soil below the 'bare soil' shows no water repellency (higher infiltration rates). Perhaps the agent causing water repellency is present in the ash layers and therefore is lacking in the bare soil samples.

The texture analysis of these soil layers shows a high fraction of silt in the soil below the white ash. This could be a sign of percolation of the ash into the lower soil layers.

Aggregate stability and organic matter show smaller differences, although the black ash middle layers still have the highest values.

Table 4.4c. Soil parameters of lower layer; black, white and bare soil.

Lower layer	Aggregate Stability	Organic Matter	pH	EC	sand	silt	clay	moisture	infiltration
				<i>uS/cm</i>	%	%	%	%	<i>mL/min</i>
<i>Black ash lower layer</i>	96,5%	11,0%	8,1	432	31	60	9	19,2	7,0
<i>Bare soil lower layer</i>	92,7%	9,0%	8,2	252	33	55	12	14,6	9,0
<i>White ash lower layer</i>	95,1%	6,9%	7,9	636	27	57	16	19,0	4,7

The lower layers seem similar and have less difference amongst each other except for a few minor observations.

The deeper soil layer underneath the black ash has a relatively high organic matter content considering that the organic matter content overall is lower with higher depths in the soil profile. The soil below the bare soil has the lowest value of aggregate stability and EC as well as the highest pH value which may be a result of the absence of a water repellent layer and more percolation.

In figure 4.5 the samples are plotted for soil moisture content as well as infiltration (water repellency). For these two soil parameters, we see that the samples are divided into three clusters: the topsoil, middle and lower soil layer. The topsoil is dry and has highest wettability; the middle layer is wetter and has high water repellency. The lowest layer contains most moisture and has weak to no water repellency.

Overall, there are a few main observations: Infiltration is clearly different for top, middle and lower layers; soil moisture increases with depth; (figure 4.5) white ash consists of a large silt fraction and bare soil subsurface layers have deviating values for the measured soil parameters compared to the black and white ash topsoils.

These results are obtained using 'traditional' time-consuming lab methods. In the next chapter we will evaluate whether hyperspectral analysis is a suitable method for analyzing these soil characteristics as well.

data from three spectral regions there is a spectral discontinuity in the data around 1000nm and 1830nm. To correct this discontinuity a splice correction is performed with ViewSpecPro before further analysis (example in figure 4.7).

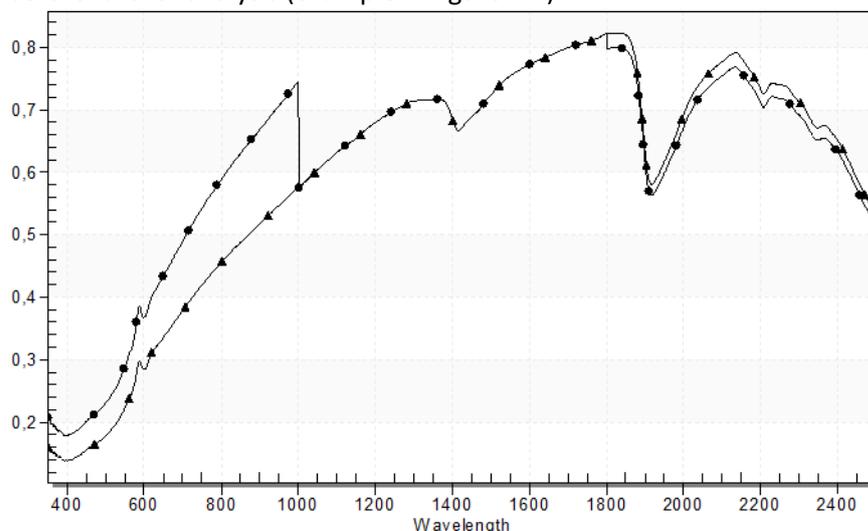


Figure 4.7. Spectral signature before (dots) and after (triangles) splice correction. Note the smoothing of the spectral discontinuities around 1000 and 1830nm.

For further preprocessing and analysis the data is analyzed using ParLes for partial least squares regression (PLSR) (Viscarra, 2007).

ParLes Results

ParLes is software designed for chemometric analysis of soil spectroscopic data (Viscarra, 2007). For this small sampling size it is not possible to conduct an extensive analysis on chemical composition of ash, but ParLes is suitable for conducting PLSR on each of the soil parameters with the hyperspectral data. In short, PLSR is an extended principal component analysis using multiple axes to describe the sampling point cloud for one parameter.

Input

For analysis of texture, only the amount of sand particles is used since the amount of clay particles is relatively constant and this enables using texture as an input. Also (log) organic matter, soil moisture, pH, EC, aggregate stability, color (Munsell value) and water repellency (infiltration) are imported into PLSR as y-variables.

All spectral data is exported from ViewSpecPro into an ASCII file and the spectral region between 300 and 400 is removed to reduce noise effects. The spectral data is then imported into ParLes (x-variables), transformed into $\log_{10}(1/R)$ units and mean centred (figure 4.8).

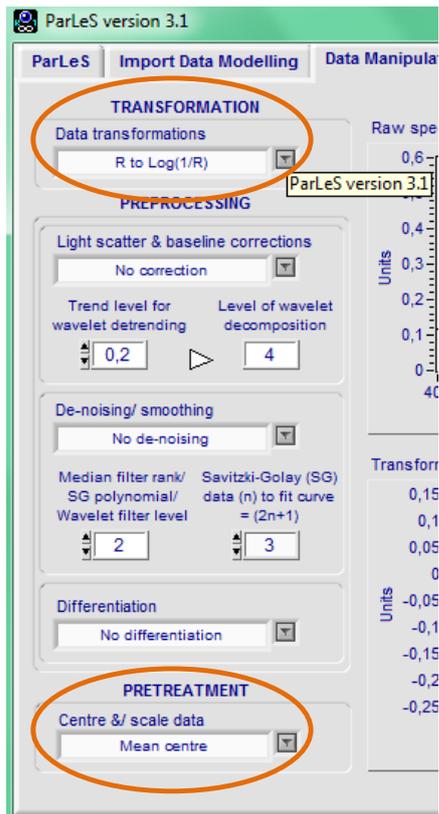


Figure 4.8. ParLes interface for data manipulations.

Output

ParLes gives information about the root mean square error (RMSE) and over fitting of the model (AIC). With the option to change the amount of factors ('x'-values) for modeling the observed and predicted values are plotted in a graph (figure 4.9). The program plots the values of the samples on new axes to describe the data in a model and the amount of new axes used for this model is represented with the 'x'-value. When more and more axes will be used, the data will have a better fit in the model but this will only describe these samples and not be applicable for new samples. To prevent over fitting, of the Akaike Information Criterion (AIC), the first number of factors representing the lowest AIC is used. Note that this method does not give any information about the relationship between variables but the emphasis is on predicting responses (Tobias, 2007).

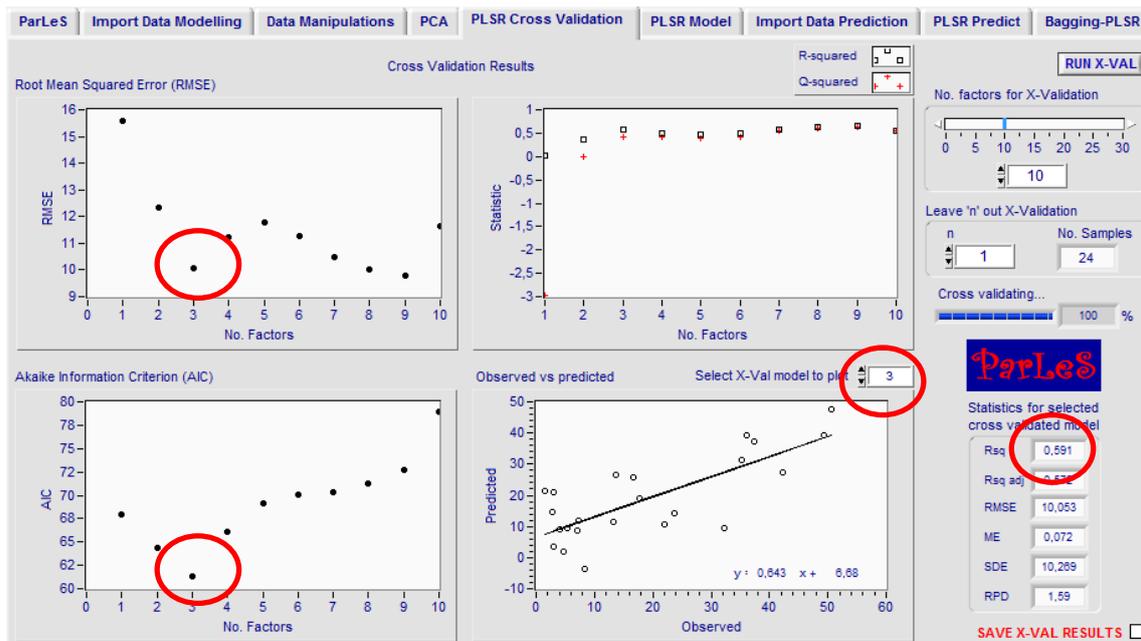


Figure 4.9. ParLes PLSR interface. Circled: first lowest RMSE and AIC, X-Value (3) and R^2 (0.59).

For each of the separate soil parameters we can see whether the hyperspectral signatures are able to create a model to predict correct values. The results of this PLSR show no significantly high values of R^2 when observed and predicted values are compared. The two parameters that give the highest values are organic matter and infiltration (water repellency). For the \log_{10} of organic matter and infiltration an R^2 value of 0.4 and 0.6 respectively is found (figure 4.10a and b).

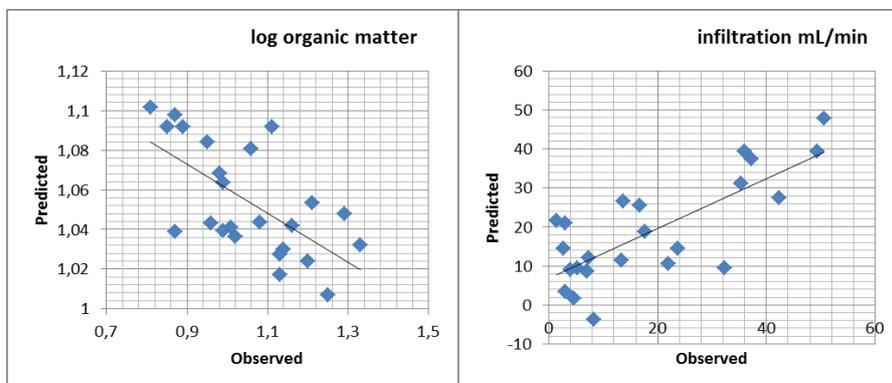


Figure 4.10a,b. a: Predicted organic matter values (log of SOM%) as a function of observed values in ParLes $R^2=0.4$. b: Predicted infiltration values (mL/min) $R^2=0.6$

In short, the hyperspectral analyses shows that there is a difference in reflectance values for different top soil layers as the white ash has lowest reflectance values. In addition, the southeastern slope gives the highest reflection values. PLSR models are (within this dataset) most suitable to predict organic matter content of soils and infiltration (soil water repellency) with R^2 values of 0.4 and 0.6.

5 Conclusions and recommendations

The main findings of the presented data in the last chapter will be discussed in the following paragraph, where feedback will be given on the goals of this research that were stated in the introduction. After that there will be some recommendations for further research.

The goal of this research is to

- *make a post-fire topsoil definition and classification based on the ash and soil characteristics,*
- *find a relation between the ash cover and the subsurface soil characteristics, and*
- *assess the suitability of using a hand-held spectroradiometer for measuring post-fire soil parameters.*

The soil parameters that have been analyzed include organic matter, water repellency, slope aspect, texture, aggregate stability, soil moisture, pH and EC.

Topsoils and underlying soil layers

The analyses show that white ash contains the lowest amount of organic matter as well as the highest amount of silt fraction. White ash is composed of a fine, flaky substance and also the subsurface layer contains more silt which indicates that the fire affected top soil may affect the lower layers through percolation of the ash with (rain)water through the profile. an increase in the silt fraction has been reported in previous studies as an effect of extreme soil heating (Stoof, et al., 2010).

Water repellency has only been reported in subsurface layers, spread throughout the catchment. WR can be positive for post-fire recovery of the soils and vegetation as it keeps the lower layers of the soil from losing its moisture by evaporation. In wintertime (wet season) soil moisture decreases with depth while in summer this pattern is inverted, which indicates that the water repellent layer possibly influences soil moisture content. This moisture pattern however is not necessarily resulting from a water repellent layer but can be naturally occurring for non-water repellent soil simply through seasonal drying and wetting.

Below both white and black ash a water repellent layer is found, whereas below the bare soil there is less evidence for water repellency. This could be an indication of a difference in fire intensities that affects underlying soil. It is known that soil water repellency is spatially heterogeneous and temporally highly variable (Malkinson & Wittenberg, 2011). Where an ash layer is lacking, and also a water repellent layer, soil hydrology will be different: there is more percolation of water and with that nutrients and soil(/ash) particles. Whether the ash layer is the cause for these processes (Bodi, et al., 2012) or whether the substrate is already different prior to a fire event is a question that remains unanswered in this study and might be a topic for further research.

As mentioned before percolation can cause top soil to affect subsurface layers, but percolation may be prevented by the water repellent layer. The nutrients and chemicals of the top layer can percolate deeper into the soil when a WR layer is absent. When a WR layer prevents water from percolating, their transport is limited. The locations of bare soil samples have fewer occurrences of a WR layer, lower aggregate stability, lower EC and slightly lower moisture content than the lower layers below other topsoils. The sampling size of this study however, is not sufficient to draw statistically significant conclusions. A larger sampling size is needed to confirm the relationship between different (ash) top soils and a water repellent

layer as water repellency is seen as one of the most important factors influencing post-fire erosion (Varela, et al., 2010).

Spectral analysis

South facing slopes have remarkably higher spectral reflectance than the other slopes. A possible explanation for this result is that the soil samples still contained moisture after air drying. The southern slopes have lower initial soil moisture content since they receive more solar radiation and thus higher evaporation. In general, reflection increases with decreasing moisture content (Lobell & Asner, 2002).

The reflectance values of white ash are significantly lower than of the other soil types. This is remarkable since these values are expected to be higher because white reflects more; at least in the visible spectrum (Smith, et al., 2005). According to Smith et al (2005) the reflectance of black ash soils is lower than white ash and reference soils and increased with increasing particle size. The relationship between reflectance and ash color is not found in this study, but the white ash samples do contain high amounts of silt. The high silt levels or chemical composition of white ash samples may be of greater effect than the effect of color and moisture content, but further research is necessary to define the composition of different ash types. A clear chemical and physical classification of white, black ash and bare post-wildfire soils has not yet been found.

Spectroradiometry for post-wildfire soil assessment

The PLSR performed in ParLes gives promising results for the prediction of water repellency and soil organic matter content. A significant relationship is not found in this study, but the direction of focus for further research is clear.

Hyperspectral analysis can be a fast way of assessing a fire affected area. To use this method there is a need for a larger sampling plan specifically on ash and top soils in order to do chemometric analysis on the spectral data and to create a better fitting model for predicting soil characteristics. This method could save a lot of time and money as opposed to using only traditional field methods (McBratney, et al., 2006).

Using (traditional) field observations in combination with (modern) hyperspectral methods gives the opportunity to create a method to map large fire affected areas quickly. Field-based methods provide point data and data from smaller areas with a high accuracy and in situ measurements but it is necessary to understand whether it can be extrapolated to areas (McBratney, et al., 2006) (Ben-Dor, et al., 2008). This is not within the reach of this research and could be a topic for further research on the subject.

Expanding this micro scale study to a broader picture there is a need for developing a tool to both decrease negative impacts of wildfires on forest ecology and to save money on unnecessary measures by apt (post)fire management. To set up a method there is a need for a quick and cheap field based assessment on resilience of the ecosystem to decide upon the most suitable management practice. This method could be used within a decision support system for both firefighting and post-fire management, creating a possibility to avoid unnecessary repression or management practices.

Bibliography

Arianoutsou, M., Koukoulas, S. & Kazanis, D., 2011. Evaluating Post-Fire Forest Resilience Using GIS and Multi-Criteria Analysis: An Example from Cape Sounion National Park, Greece. *Environmental Management*, Issue 47, pp. 384-397.

ASDI Inc. products, n.d. *FieldSpec3 Portable Spectroradiometer*. [Online] Available at: <http://www.asdi.com/products/fieldspec-3-portable-spectroradiometer> -[Accessed 27 March 2012].

Ben-Dor, E. & Banin, A., 1989. Determination of organic matter content in arid-zone soils using a simple "loss-on-ignition" method. *Communications in Soil Science and Plant Analysis*, Issue 20, pp. 1675-1695.

Ben-Dor, E., Taylor, R.G., Hill, J., Demattè, J.A.M., Whiting, M.L., Chabrilat, S. and Sommer, S., 2008. Imaging Spectrometry for Soil Applications. *Advances in Agronomy*, Volume 97, pp. 321-381.

Bodi, M., Doerr, S., Cerdà, A. & Mataix-Solera, J., 2012. Hydrological effects of a layer of vegetation ash on underlying wettable and water repellent soil. *Geoderma*, Volume In press, pp. 1-10.

Bodí, M., Mataix-Solera, J., Doerr, S. & Cerdà, A., 2011. The wettability of ash from burned vegetation and its relationship to Mediterranean plant species type, burn severity and total organic carbon content. *Geoderma*, Issue 160, pp. 599-607.

Casady, G., van Leeuwen, W. & Marsh, S., 2010. Evaluating Post-wildfire Vegetation Regeneration as a Response to Multiple Environmental Determinants. *Environ Model Assess*, Issue 15, pp. 295-307.

Certini, G., 2005. Effects of fire on properties of forest soils: a review. *Geologica*, Issue 143, pp. 1-10.

Decagon Devices, 2011. *Mini Disk Infiltrometer User's Manual Version 9*. [Online] Available at: <http://www.decagon.com/assets/Manuals/Manual-Infiltrometer.pdf> [Accessed 6 June 2012].

Doerr, S. & Cerdà, A., 2005. Fire effects on soil system functioning: new insights and future challenges. *International Journal of Wildland Fire*, Issue 14, pp. 339-342.

Eijkelkamp, 2008. *Operating instructions 8.13 wet sieving apparatus*, Giesbeek: Eijkelkamp agrisearch equipment.

Finley, C. & Glenn, N., 2010. Fire and vegetation type effects on soil hydrophobicity and infiltration in the sagebrush-steppe: II. Hyperspectral analysis. *Journal of Arid Environments*, 74(6), pp. 660-666.

Halfon, N., Levin, Z. & Alpert, P., 2009. Temporal rainfall fluctuations in Israel and their possible link to urban and air pollution effects. *Environmental Research Letters*, Issue 4, p. 12.

Hockaday, W., Grannas, A., Kim, S. & Hatcher, P., 2006. Direct molecular evidence for the degradation and mobility of black carbon in soils from ultrahigh-resolution mass spectral analysis of dissolved organic matter from a fire-impacted forest soil. *Organic Geochemistry*, Issue 37, pp. 501-510.

IMS, 2007. *Israel Meteorological Service: Climate Information*. [Online] Available at: <http://www.ims.gov.il/IMSEng/CLIMATE> [Accessed 4 June 2012].

Lobell, D. & Asner, G., 2002. Moisture Effects on Soil Reflectance. *Soil Science Society of America Journal*, Issue 66, pp. 722-727.

Malkinson, D. & Wittenberg, L., 2011. Post fire induced soil water repellency – Modelling short and long-term processes. *Geomorphology*, Issue 125, pp. 186-192.

Malkinson, D., Wittenberg, L., Beerli, O. & Barzilai, R., 2011. Effects of Repeated Fires on the Structure, Composition, and Dynamics of Mediterranean Maguis: Short- and Long-Term Perspective. *Ecosystems*, Issue 14, pp. 478-488.

McBratney, A., Minasny, B. & Viscarra Rossel, R., 2006. Spectral soil analysis and inference systems: A powerful combination for solving the soil data crisis. *Geoderma*, Issue 136, pp. 272-278.

Mitri, G. & Gitas, I., 2008. Mapping the severity of fire using object-based classification of IKONOS imagery. *International*, Issue 17, pp. 431-442.

Moody, J., Kinner, D. & Úbeda, X., 2009. Linking hydraulic properties of fire-affected soils to infiltration and water repellency. *Journal of Hydrology*, Issue 379, pp. 291-303.

Neary, D., Klopatek, C., DeBano, L. & Ffolliott, P., 1999. Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology and Management*, Issue 122, pp. 51-71.

Pardini, G., Gispert, M. & Dunjó, G., 2004. Relative influence of wildfire on soil properties and erosion processes in different Mediterranean environments in NE Spain. *Science of the Total Environment*, Issue 328, pp. 237-246.

Parsons, A., Robichaud, P.R., Lewis, S.A., Napper, C and Clark, J.T., 2010. *Field Guide for Mapping Post-Fire Soil Burn Severity*, Fort Collins: U.S. Department of Agriculture.

Paz, S., Carmel, Y., Jahshan, F. & Shoshany, M., 2011. Post-fire analysis of pre-fire mapping of fire-risk: A recent case study from Mt. Carmel (Israel). *Forest Ecology and Management*, Issue 262, pp. 1184-1188.

Pérez-Caballo, F., Ibarra, P., Echeverría, M. & De La Riva, J., 2010. Post-fire land degradation of *Pinus Sylvestris* L. woodlands after 14 years. *Land Degradation and Development*, Issue 21, pp. 145-160.

Pérez-Cabello, F., De La Riva Fernández, J., Montorio Llovería, R. & García-Martín, A., 2006. Mapping erosion-sensitive areas after wildfires using fieldwork, remote sensing, and geographic information systems techniques on a regional scale. *Journal of Geophysical Research*, Issue 111, p. G04S10.

Reyes Ruiz-Gallardo, J., Castaño, S. & Calera, A., 2004. Application of remote sensing and GIS to locate priority intervention areas after wildland fires in Mediterranean systems: a case study from south-eastern Spain. *International Journal of Wildland Fire*, Issue 97, pp. 92-115.

Robichaud, P., Lewis, S. & Ashmun, L., 2008. *New Procedure for Sampling Infiltration to Assess Post-fire Soil Water Repellency*, Fort Collins, CO: U.S. Department of Agriculture, Forest Service.

Ryan, J., Estefan, G. & Rashid, A., 2008. *Lab Manual*. [Online] Available at: http://www.icarda.org/Publications/Lab_Manual/read.htm [Accessed 5 May 2011].

Shakesby, R., 2011. Post-wildfire soil erosion in the Mediterranean: Review and future research directions. *Earth-Sciences Reviews*, Issue 105, pp. 71-100.

Smith, A., Wooster, M.J., Drake, N.A., Dipotso, F.M., Falkowski, M.J. and Hudak, A.T., 2005. Testing the potential of multi-spectral remote sensing for retrospectively estimating fire severity in African Savannahs. *Remote Sensing of Environment*, Issue 97, pp. 92-115.

Stoof, C., Wesseling, J. & Ritsema, C., 2010. Effects of fire and ash on soil water retention. *Geoderma*, Issue 159, pp. 276-285.

Tobias, R., 2007. *An Introduction to Partial Least Squares Regression*, Cary: SAS Institute Inc..

Úbeda, X., Pereira, P., Outeiro, L. & Martin, D., 2009. Effects of fire temperature on the physical and chemical characteristics of the ash from two plots of cork oak (*Quercus Suber*). *Land degradation & development*, Issue 20, pp. 589-608.

Van Leeuwen, W.J.D., Casady, G.M., Neary, D.G., Bautista, S., Alloza, J.A., Carmel, Y., Wittenberg, L., Malkinson, D. and Orr, B.J., 2010. Monitoring post-wildfire vegetation response with remotely sensed time-series data in Spain, USA and Israel. *International Journal of Wildland Fire*, Issue 19, pp. 75-93.

Varela, M., Benito, E. & Keizer, J., 2010. Wildfire effects on soil erodibility of woodlands in NW Spain. *Land Degradation and Development*, Issue 21, pp. 75-82.

Viscarra, R., 2007. *ParLeS: Software for chemometric analysis of spectroscopic data*, s.l.: Chemometrics and Intelligent Laboratory Systems.

Wittenberg, L. & Malkinson, D., 2009. Spatio-temporal perspectives of forest fires regimes in a maturing Mediterranean mixed pine landscape. *Eur J Forest Res*, Issue 128, pp. 297-304.

Wittenberg, L., Malkinson, D., Beerli, O., Halutzky, A., Tessler, N., 2007. Spatial and temporal patterns of vegetation recovery following sequences of forest fires in a Mediterranean landscape, Mt. Carmel Israel. *Catena*, Issue 71, pp. 76-83.

Appendices

Appendix A. Example of a soil description form.

OBSERVATION #	DATE	OBSERVER	SLOPE ANGLE	EROSION FEATURES		VEGETATION		
S3	01/05	LEA AND HEIKE	<5 DEGREES	SMALL ROLL OF FEW CM WIDTH		ALMOST NOTHING, SURROUNDED BY CIRCLE OF GRASS!		
PROXIMITY TO TREE/ROCK		ASH TYPE (BY COLOUR)	BANK/SLOPE	PENETRATION RESISTANCE		MICROTOPOGRAPHY		
~2 M		BLACK	BANK	-		VERY GENTLY SLOPING		
DEPTH	TEXTURE	STRUCTURE	ROCK FRAGMENTS % > 1MM	COLOUR (MOIST SOIL)		CaCO ₃	ORGANIC MATTER/ ROOTS/ BIOTURBATION	ADDITIONAL REMARKS
	SAND/SILT/CLAY							
0.02	Ash	Lab	0%		Black	3 (++)	Charcoal	Hydrophilic layer
0.03	Silt/sand with little clay	-	Increasing downwards		2.5Y4/3	2 (+)		Layer below charcoal is hydrophobic>5 min WDPT.
0.06	Silt/sand with little clay	-			2.5Y3/2	2 (+)		Transition, hydrophobic>5 min WDPT.
0.12	lab	-			10YR3/2	3 (++)		Hydrophilic
0.30	lab	-			7.5YR3/3	3 (++)		Hydrophilic
Bedrock								
Moist conditions after rainfall event, but still hydrophobic! Calcium concretions more present towards the bedrock.								

Appendix B. Laboratory and field results for 4 soil pits on wadi bank, including NPK analysis.

Sample	Depth in m	Moisture %	pH	EC (uS/cm)	Hydrophobicity	K meq/l	P (olson) mg/kg	N nitrat mg/kg	OM %	CaCO3%	texture class FAO	Saturation %
S3A	0-0,02	44,9	7,8	434,0	no	0,64	64,1	58,1	13,31	28,9	loam	-
S3B	0,02-0,03	25,0			yes	0,56	25,2	166,6	12,62	31,4	clay loam	115
S3C	0,03-0,06	24,0	7,8	470,0	yes	0,39	20,3	113,6	9,87	35,5	sand loam	71,6
S3D	0,06-0,12	25,3			no	0,35	17,5	51,4	8,83	37,7	clay loam	36,2
S3E	0,12-0,30	23,7	7,8	538,0	no	0,32	20,7	44,2	7,70	36,4	clay loam	112,2
S4A	0-0,02	35,2	8,0	568,0	no	0,55	41,2	71,2	12,80	54,5	loam	-
S4B	0,02-0,03	31,6	7,8	612,0	yes	0,60	40,0	80,7	13,43	42,1	loam	146,5
S4C	0,03-0,20	25,9	7,8	394,0	yes	0,33	15,1	27,1	8,52	54,5	loam	-
S4D	0,20-0,55	20,7	7,8	404,0	no	0,27	15,9	14,1	8,01	57,9	clay loam	-
S5A	0-0,04	23,4	8,0	136,5	no	0,43	34,8	9,9	11,68	41,3	loam	98,5
S5B	0,04-0,10	29,0	7,9	156,4	no	0,43	40,8	2,6	8,92	35,5	loam	-
S5C	0,10-0,15	21,4	7,8	157,9	no	0,23	13,9	5,2	9,60	37,2	clay loam	-
S5D	0,15-0,40	16,3	7,8	300,0	no	0,19	32,0	4,8	5,73	42,1	clay loam	67,5
S6A	0-0,02	-	7,6	436,0	yes	0,05	105,9	27,6	4,04	35,5	loam	123,3
S6B	0,02-0,05	-	7,6	567,0	no	0,56	33,2	8,2	12,72	43,0	loam	88,3
S6C	0,05-0,17	-	7,6	520,0	no	0,44	27,6	14,3	6,89	53,7	loam	56,4

Appendix C. Total table for results of soil parameters for 'MDI samples'.

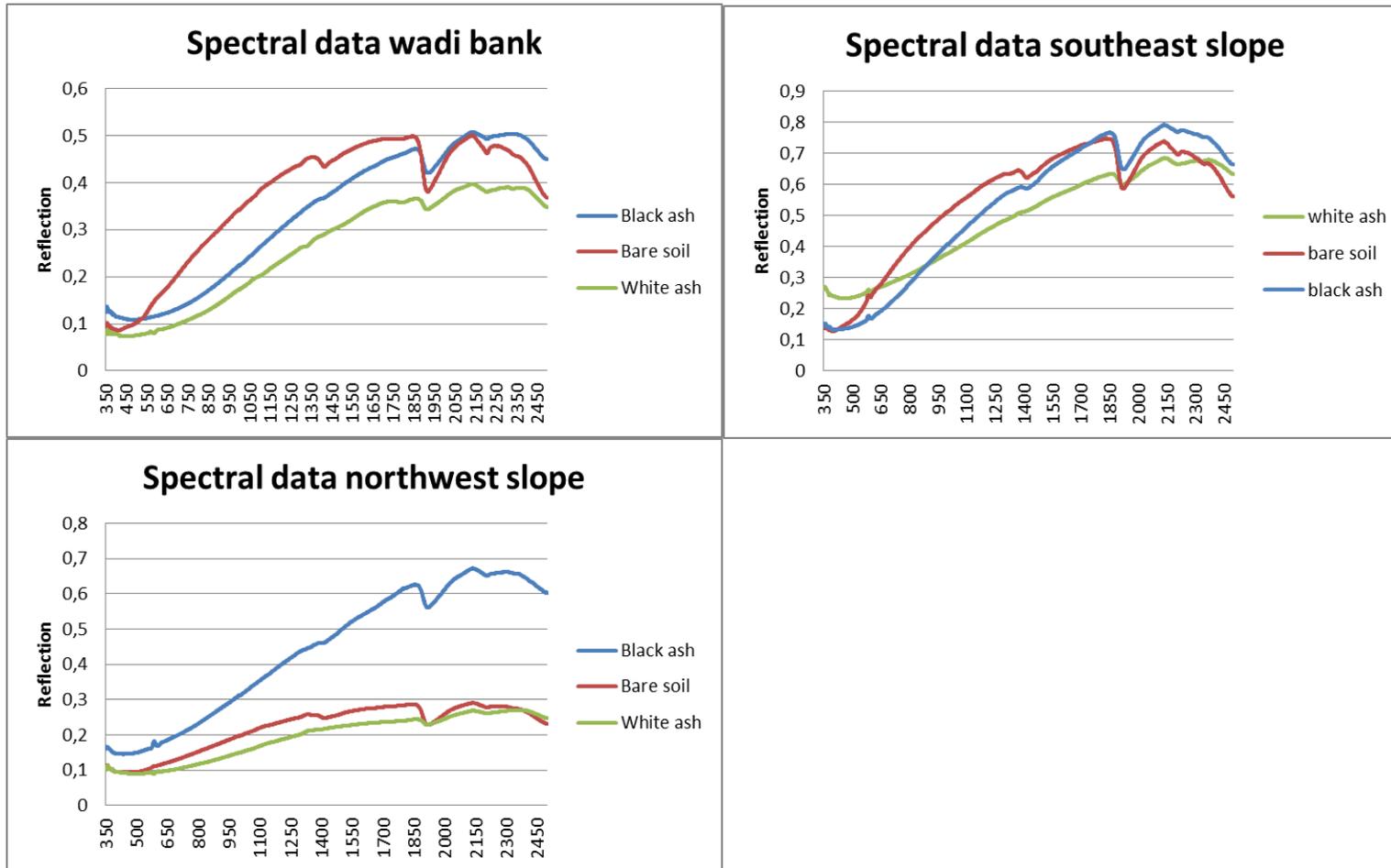
	Aggregate Stability	Organic Matter	pH	EC	infiltration (- 3 mL)	water repellency	moisture	sand	silt	clay	texture class FAO	Munsell dry	Munsell wet
<i>Wadi Bank</i>	%	%		<i>uS/cm</i>	<i>mL/min</i>		%	%	%	%			
<i>BankB1</i>	98,4	19,3	7,7	303	34,3	no	5,4	41	51	8	silt loam sandy	2.5Y3/1	10YR2/1
<i>BankB2</i>	98,9	17,9	7,7	580	0	strong	11,0	61	34	4	loam	10YR5/3	2.5Y3/2
BankB3	98,1	12,1	8	458	4,3	weak	18,5	33	58	9	silt loam	7.5YR3/3	2.5Y3/3
<i>BankS1</i>	98,8	16,1	7,8	366	29,3	no	4,8	43	49	8	loam	10YR4/2	10YR3/2
<i>BankS2</i>	99,1	14,6	7,6	772	2,3	strong	8,9	51	42	8	loam	10YR4/4	2.5Y3/3
BankS3.1	94,6	10,3	8,2	300	4	weak	16,3	27	60	13	silt loam	10YR3/3	10YR3/4
BankS3.2	91,2	9,2	8,2	190	4	weak	19,5	24	61	15	silt loam	7.5YR3/3	10YR3/4
<i>BankW1</i>	93,0	9,6	7,9	487	32,3	no	4,1	27	57	16	silt loam	10YR4/1	10YR2/1
<i>BankW2</i>	87,2	10,6	7,8	1076	x	x	5,6	22	56	22	silt loam	10YR3/2	10YR2/1
<i>BankW3</i>	98,5	15,7	7,5	1081	0	strong	13,6	40	48	12	loam	10YR3/2	10YR2/1
BankW4	92,1	6,5	7,9	774	5,3	weak	19,0	27	57	16	silt loam	10YR3/3	10YR3/4
<i>Northwest</i>													
<i>NorthB1</i>	98,1	8,9	7,6	990	33	no	3,9	38	54	8	silt loam	2.5Y3/1	10YR2/1
<i>NorthB2</i>	98,6	9,7	7,6	1020	0	strong	9,1	34	57	10	silt loam	10YR4/2	10YR2/2
NorthB3	95,0	9,8	8,1	405	10,7	no	19,9	29	62	9	silt loam	10YR3/2	10YR3/2
<i>NorthS1</i>	96,3	13,9	7,7	1143	39,3	no	5,7	48	44	9	loam sandy	10YR3/2	10YR2/2
<i>NorthS2</i>	97,6	13,5	8	373	14,7	no	18,5	43	50	7	loam	10YR3/3	10YR3/3
<i>NorthW1</i>	97,1	13,3	8	455	46,3	no	3,8	25	70	5	silt loam	2.5Y4/1	GLE1 2.5N
<i>NorthW2</i>	94,6	13,1	7,7	983	2	strong	15,7	34	60	6	silt loam	10YR4/2	10YR3/2
NorthW3	x	x	x	x	7	weak	x	x	x	x	x	x	x

Appendix C, continued

	Aggregate Stability	Organic Matter	pH	EC	infiltration (- 3 mL)	water repellency	moisture	sand	silt	clay	texture class FAO	Munsell dry	Munsell wet
<i>Southeast</i>	%	%		uS/cm	mL/min		%	%	%	%			
<i>SouthB1</i>	98,7	21,2	7,6	373	13,67	no	4,4	55	40	5	<i>sandy loam</i>	10YR3/2	10YR2/1
SouthB2	99,2	12,8	8	342	0	strong	9,1	53	42	5	sandy loam	10YR4/3	2.5YR3/3
SouthB3	x	x	x	x	6	weak	x	x	x	x	x	x	x
<i>SouthS1</i>	94,8	11,6	7,7	275	20,67	no	3,8	43	49	8	loam	10YR4/3	2.5Y3/3
SouthS2	95,6	7,7	8	311	10,33	no	5,3	46	45	8	loam	10YR4/4	10YR3/3
SouthS3	92,3	7,4	8,2	266	19	no	8,0	47	44	9	loam	10YR4/4	10YR3/4
<i>SouthW1</i>	97,8	7,1	7,8	1074	47,67	no	1,5	26	69	5	<i>silt loam</i>	10YR5/1	2.5Y3/1
SouthW2.a	99,6	x	7,6	887	1	strong	6,3	38	54	9	silt loam sandy	10YR4/2	10YR3/3
SouthW2.b	99,2	8,2	7,6	860	x	x	13,0	45	50	5	loam	10YR5/4	10YR4/3
SouthW3	98,2	7,4	7,9	497	1,67	strong	x	x	x	x	x	10YR4/3	10YR3/3

Legend to Appendix C	
Topsoil	<i>italic</i>
Middle soil layer	regular
Lower soil layer	bold
Black ash	grey
Bare soil	<i>orange</i>
White ash	no fill

Appendix D.1 Hyperspectral signatures of topsoil wadi bank and the two slopes after splice correction.



Appendix D.2. Average hyperspectral signatures of top layers black, white and bare soil (after splice correction)

