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Naturwissenschaftliche Fakultät III

# Analyzing tree mortality in the Yatir forest (Israel)

A thesis submitted in partial fulfillment of the requirements for the degree of

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in Natural Resource Management

by

**Thomas Sockel**

Born on 18th October, 1984, in Löbau (Saxony, Germany)

Enrolment number: 211228165

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| 1st Reviewer: | Prof. Dr. Heinz Borg |
| 2nd Reviewer: | Dr. Angela Lausch |
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# Abstract

In 2010 a huge mortality occurred in the Yatir forest in Israel. In this thesis four possible reasons will be discussed, which could explain this mortality. These are: Cold, drought, salinity, competition. The data used here were provided by the Weizmann Institute of Science in Rehovot and by the Keren Kayemeth LeIsrael – Jewish Nationl Fund (KKL – JNF).

It was found that the lowest observed temperature in this area (-3,6°C) occurred in January 2008, two years before the mortality. This could have worked as an inciting factor for weakening the trees. The summer drought in 2008 was the longest observed drought period since establishing the forest, and the rainy season 2008/09 was one of those with the lowest precipitation. The maximum temperatures have not been observed near the time of mortality (hottest temperature: 41.2°C on 31st July 2002), so heat cannot be the reason for mortality. Almost half of the trees which died were exposed to a southern direction: 49.3% of dead trees were found on southeast to southwest exposed sites. With respect to hill slope most dead trees were found on strongly inclined slopes: 6.5 dead trees per hectare on slopes with 18-36% inclination. In contrast, 2.8 dead trees / ha were found on flat sites with 0-2% inclination. The soil salinity features of plots with mostly live trees do only differ significantly with respect to electrical conductivity from the soil salinity features of plots with mainly dead trees. It is possible that this is due to different mycorrhizal activity in the soil, but this cannot be proven.

Concerning the competition, a clear decrease of growth is visible with increasing time, and a stagnation of growth at the age of approximately 40 years. The water a tree receives per biomass seems to play a key role in tree mortality. That is corroborated by the fact that 77.7% of dead trees are older than 35 years and the mortality happened after a year with below average precipitation, but below average precipitation also occurred in earlier years without such huge damage.

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# 1 Introduction

## 1.1 Identifying the Problem

The Yatir Forest is a reforested area (Figure 1) of approximately 3000 hectares established at the northern edge of the Negev in 1964/65 by KKL – JNF (Keren Kayemeth LeIsrael – Jewish National Fund), an important Israeli environmental organization. The forest grew well until 2010 when a huge mortality occurred and at least 24,000 trees died in the area. The mortality happened after 4 out of 6 years had below-average precipitation (PREISLER *et al.*, 2012). Hence, drought is supposed to have had the most important impact on the mortality. Consequently it will also have a big part within this master thesis. I want to verify whether drought can explain the mortality or if other factors can explain the mortality better.

**Figure 1: The Yatir forest and its the distinct border with the the surrounding Negev desert**

## 1.2 Site description

The Yatir forest is located in the northern Negev desert some 30 km north-east of Be'er Sheva (31°20'N 35°04'E). In the north of the site the Hebron Mountains adjoin which constitute the termination of the Mediterranean Judean Foothill region. To the south the Negev desert extends, eastward the Judean desert and the Dead Sea valley (GRÜNZWEIG *et al.*, 2003; SREBRO, 2011).

The height of the forest landscape is 650 m and varies between 600 m in some valleys of the western part and 700 m in the east. The area slopes upwards from west to east.

The prevalent tree species in Yatir forest is *Pinus halepensis* (Aleppo pine). The forest has been established in 1964/65, but later it was successively extended so that there are different age bands.

The mean annual precipitation from the establishment of the forest until winter 2012/2013 was 279mm/a with a large fluctuation (min = 138mm/a; max = 496mm/a).

The geology of the site is in the north Mesozoic Upper Cretaceous Turonian Cenomanian volcanic rock. The lithology is loess, limestone and chalk. The soils are brown lithosols with flat loess mantles, rendzina (over soft porous limestones and chalk) and brown loamy soils of eolian origin. The climate is semi-arid (SREBRO, 2011).

# 2 Pinus halepensis

The prevalent tree species in Yatir forest is Aleppo pine (*Pinus halepensis* Mill., 1768; Figure 2). It has a high light requirement and is also often threatened by fire. The germination rate is 90%, but after fire it increases, because due to the high temperatures the cones and seeds open better, fall to the vegetation free ground and germinate. However, *Pinus halepensis* is not a pyrophyte, it only growth in areas with high fire risk.

Figure 2: Aleppo pine in Yatir forest

PANETSOS (1994-2008) notes that Aleppo pine is the most frequently and most extensively fire affected species within its dispersal area. This is because of the high amount of terpenes in the needles and the high resin content result in high flammability; so does the large stock of combustible material and dry needle litter in the stands. Approximately 5% of the Aleppo pine forests worldwide burn down each year.

The crown form varies with age and provenance. During the juvenile stage the crown is conical, later it becomes wide and storey-like. Some provenances stay conical even in their old age (PANETSOS, 1994-2008). Aleppo pine is used for timber or resin production, even though the timber does not attain best quality.

## 2.1 Ecology

The native range of Aleppo pine is around the Mediterranean Basin, especially in Spain where it covers 45% of total conifer area (CHAMBEL *et al.*, 2013). The species is typical for the Mediterranean climate. It appears in semi-arid or sub-humid to humid climate with an annual precipitation between 350-700mm precipitation and an absolute minimum temperature between -2 and 10°C (CHAMBEL *et al.*, 2013). It is a very drought tolerant species by drought avoidance mechanisms which is explained in more detail in section 3.4.1. The coldest temperature was observed in France at -18.6°C and the hottest in Tunisia at 50°C (PANETSOS, 1994-2008). The species is sensitive to late frost.

Its height reaches 10-20m, sometimes 25m (C.A.B. INTERNATIONAL, 2002; PANETSOS, 1994-2008). The trunk is often crooked, only if growth is optimal is it straight.

It grows on soils of various types, like slate, serpentine soil, gneiss etc., but mainly on calcareous soils like marl and limestone, which is also the soil in Yatir forest. In contrast to other species from the genus Pinus it also grows well on soils with a high amount of free carbonates. The best pH is at 6 to 7.5. The upper limit is 8 to 8.4, if $CaCO_3$ is responsible for the high alkalinity and not other salts. The lower limit is pH 5. The pine is intolerant to saline soils. Heavy clay soils are avoided by the species (PANETSOS, 1994-2008).

## 2.2 Roots

Aleppo pine has a taproot from seedling stage until old age. In tree nurseries 1 to 1.2 m long roots were noticed on trees 7-8 month old. In deep and well drained soils the main root and lateral roots reach depths of 3 m. In shallow substrates the lateral roots become long and strong and thus achieve a good foothold.

Some fungi build an ectomycorrhiza symbiosis with *Pinus halepensis*. This is the basis for survival in very dry areas and for getting the required nutrients in low nutrient habitats (PANETSOS, 1994-2008).

## 2.3 Stands

The Mediterranean Basin is one of the regions with the largest proportion of planted forest (FAO, 2006). In the second half of 20th century this species was used in the Mediterranean Basin to reforest huge areas (CHIRINO *et al.*, 2006)

Aleppo pine stands improve the soil properties compared to unvegetated ground. MAESTRE and CORTINA (2004) found a higher carbon fraction in the soils and higher total nitrogen in Aleppo pine stands 30 years after planting than before and CARAVACA *et al.* (2002) found higher aggregate stability six years after planting in a Aleppo pine plantation in Spain. However, the soil organic matter and total nitrogen in Aleppo pine stands is lower than in natural shrublands that would grow in Aleppo pine plantation areas (MAESTRE and CORTINA, 2004). Likewise, shrublands would have a greater aggregate stability, higher cation exchange capacity and available P and K (MAESTRE and CORTINA, 2004).

Furthermore, a plantation of Aleppo pine reduces the aquifer recharge compared to shrublands (MAESTRE and CORTINA, 2004). It also decreases the runoff and sediment yield in an area compared to an open area, but no significant difference has been found compared to areas covered by shrubs or grass (MAESTRE and CORTINA, 2004).

## 2.4 Drought adaptation

*Pinus halepensis* is characterized by typical drought avoidance (and water saver, see section 3.4.1) features (cf. LEVITT, 1972):

- Brief opening of stomata during daylight hours and ability to close stomata rapidly.
- Strong water saving cuticle on leafs. LEVITT (1972) calls this "the superior drought resistance of *Pinus halepensis* over *P. pirea"* (ibid p. 358).
- Reduction of specific surface: some plants reduce their transpiration surface by folding, rolling or shedding their leaves, for example *Eucalyptus sp.* and *Citrus sp.* (KOZLOWSKI, 1976). Aleppo pine reduces its surface by a lower needle growth rate, less amount of

needles per branch and a lower branching rate, which entails a lower leaf area index (LAI) and results in minimized water loss (LIN *et al.*, 2010).

- Light harvesting pigments in needles are reduced and the reflectance increases (LIN *et al.*, 2010).
- Excess thermal energy gets dissipated by de-epoxidation in the xanthophyll cycle. This is also called non-photochemical quenching, a process that protects higher plants from adverse effect of high light intensity and acts like a valve if sunlight causes the photosynthesis complex to produce more energy than required. With the help of non-photochemical quenching the excited chlorophyll can be de-excited by thermal dissipation. The excess energy is emitted as heat. Without this mechanisms radical oxygen species would be build in the plant and destroy the cell. Drought increases this protective mechanism in *Pinus halepensis* (MÜLLER *et al.*, 2001; LIN *et al.*, 2010).

# 3 Reasons for tree mortality

There are several reasons that can lead to tree dying which are subsumed in Figure 3 (McKERSIE and LESHEM, 1994; BRUNOLD *et al.*, 1996; KOZLOWSKI, 1997; KOZLOWSKI and PALLARDY, 2002).

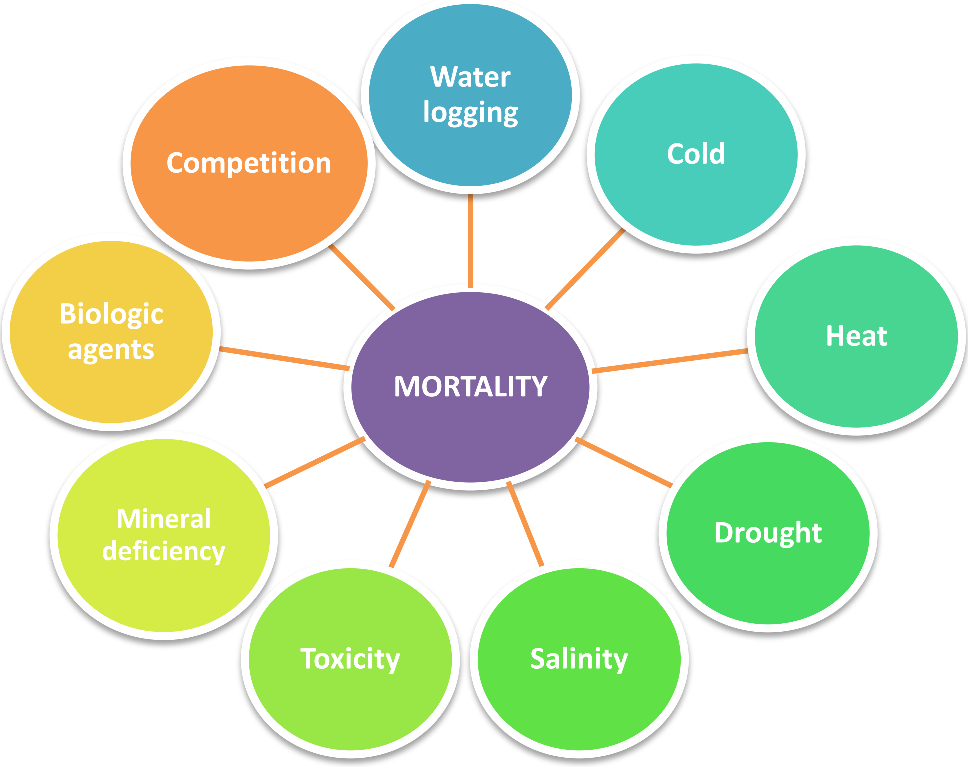

**Figure 3: Reasons for tree mortality**

The fading of tree vigor that culminates in death can be indicated by two processes which are linked to a forest's decline: a progressive growth reduction and a rapid defoliation. Defoliation is a main factor to indicate future mortality and forest health, because it integrates the effects of other factors such as water and nutrient availability (SÁNCHEZ-SALGUERO *et al.*, 2012).

Below I shall discuss why the factors shown in Figure 3 can lead to mortality.

## 3.1 Water logging

Flooded soils are problematic, because they have a poor supply of oxygen or are free of oxygen. If water infiltrates in the soil, the air get pushed out of the pores. In wet soils the oxygen uptake by diffusion is 10,000 times less than in well aerated soils. The remaining oxygen is soon consumed by microorganisms and plant roots. The initial oxidizing environment becomes successively more reducing due to microorganisms and chemical reactions. The solubility of nutrients changes with the decreasing redox potential. Most nutrients become insoluble. Concurrently toxic heavy metals become dissolved (BRUNOLD *et al.*, 1996).

These two factors, oxygen deficiency and changed chemical soil properties, can lead to a severe stress and may effect tree mortality.

Data on the response of *Pinus halepensis* to stagnant moisture are mostly only available for seedlings. KOZLOWSKI (1997) found that first changes in Aleppo pine seedlings are visible after 10 days of flooding. After 70 days significant changes are visible.

At Yatir water logging is definitely not responsible for the deaths, because the amount of rain (279mm/a) is so small that no stagnant moisture can build up. That's why water logging won't be discussed here any further.

## 3.2 Cold

There are two ways in which cool temperatures can affect plants: the first is chilling stress, the second is freezing stress. Whereas chilling stress mostly occurs in cold-sensitive plants (mostly tropical and subtropical species) at temperatures between 0-20°C (NILSEN and ORCUTT, 1996), freezing stress appears at temperatures below 0°C, where most of the chilling sensitive plants would die. *Pinus halepenis* is not chilling sensitive, so this topic doesn't matter here.

If plants are not adapted to freezing, ice formations can be build in the intracellular space, which is always lethal to the cell, because of the physical expansion which damages the plasma membrane (MCKERSIE and LESHEM, 1994; BRUNOLD *et al.*, 1996).

Aleppo pine is sensitive to late frost (PANETSOS, 1994-2008). This could be of interest in Yatir, where the growing season is in winter, so that frost may play a more important role than it would do if plant growth would cease in winter. For mature trees of Aleppo pine no information is available on how late frost exactly injures the trees. Late frost will not lead to mortality but it may be a factor which can weaken the trees and make them more vulnerable for other stresses.

## 3.3 Heat

Heat stress is mostly also related to drought, but the mechanisms of damage are different: Heat causes damage on the molecular and submolecular level by the denaturation of enzymes, alterations in membrane phase and fluidity as well as the unfolding of nucleic acids (McKersie and Leshem, 1994). Méthy *et al.* (1997) could show that the photosynthesis system of Pinus halepensis starts to suffer damage at about 48.5°C. In Yatir temperatures above 40°C were observed on 29th July 2000 (40.3°C) and 31st July 2002 (41.2°C), but not again later. Obviously it is not related to the mortality in 2010, so the thesis that heat could be related to the mortality is rejected.

## 3.4 Drought

Drought is supposed to have the most important impact to tree mortality in Yatir forest (Preisler *et al.*, 2012). That is why I want to elaborate this topic in more detail.

### 3.4.1 Physiology of drought induced tree death

#### *3.4.1.1 Carbon starvation or hydraulic failure?*

There are two main reasons that can lead to tree dying: Either the water column within a plants vessel (xylem) is exposed to such a strong tension that the liquid water vaporizes and the xylem becomes filled with air. This is called hydraulic failure or cavitation and it inhibits water transport. However, in pines refilling of cavitated elements has been observed too (McDowell *et al.*, 2008).

The other possible reason for plant dying is that the stomata stay closed during drought periods, which leads to the cessation of gas exchange and the plants can't obtain $CO_2$ to sustain their photosynthesis. In consequence the plant shall die by carbon starvation (SEVANTO *et al.*, 2014; Aroca, 2012).

Whether a tree dies by carbon starvation or hydraulic failure is determined by how it handles its water potential. Either it is able to hold the water potential in leaves and trunk stable (this is called isohydric), even with increasing drought, or it changes the water potential with surrounding moisture conditions (this is called anisohydric).

#### 3.4.1.2 *Isohydric and anisohydric behavior*

This categorization classifies plants according to how they regulate their water potential. Isohydric plants are able to reduce stomatal conductance as soil water potential decreases and atmospheric conditions dry. Thus, leaf potential remains relatively constant during midday, regardless of drought conditions. The plant maintains its leaf water potential at -2.0 until -2.5 MPa, despite severe soil drying (MCDOWELL *et al.*, 2008).

Isohydric behavior of pine prevents cavitation, even during severe droughts, so it is unlikely that they fall victim to hydraulic failure (MCDOWELL *et al.*, 2008). Here the problem during drought is carbon starvation. KLEIN *et al.* (2011) found that carbon starvation is indeed the problem that *Pinus halepensis* needs to face. The mechanism that leads to its death is starvation, because no gas exchange is possible. Aleppo Pine falls into this isohydric category

Anisohydric species by contrast have a higher stomatal conductance at a given leaf potential as isohydric plants so that the midday leaf potential declines as soil water potential declines with drought. *Juniper* for example is an anisohydric species. Through its continued transpiration it can draw the soil water potential down to -6.9 MPa, which is close to the point of hydraulic failure in *Junipers* (MCDOWELL *et al.*, 2008).

#### 3.4.1.3 *Drought avoidance and drought resistance*

Another classification characterizes plants according to their physical response to drought. If a plant does not escape from drought (Ephemerals), they avoid it by increasing stomatal and cuticular resistance or by changes in leaf area, orientation and anatomy. This equals isohydric behavior with the aim to safe water from transpiration. Drought tolerance (equals anisohydric behavior) in contrast doesn’t maintain high internal water potential if the environmental water potential is low. By maintaining an adequate cell turgor with the help of osmotic adjustment and changes in cellular and tissue elasticity (TOUCHETTE *et al.*, 2007) the osmotic potential in the plant is lowered. This results in a higher drought tolerance. Thus, plants are able to resist environmental water potentials of -200 to -300bar (equals -20 to -30MPa) in the extreme (LEVITT, 1972).

Drought *avoiders* are characterized through maintaining a high water potential when they are exposed to external water stress (LEVITT, 1972). This group can be divided into *water savers*, which avoid drought by water conservation, and *water spenders*, which avoid drought by absorbing water sufficiently rapidly to keep up with their extremely rapid water loss (LEVITT, 1972). This classification is visualized in Figure 4. *Pinus halepensis* is a water safer due to early stomatal closure and low cuticular transpiration (Levitt, 1972; Martínez-Ferri *et al.*, 2000).

In contrast to water savers, which lose just $\frac{1}{4300}$ of their weight per day, water spenders can lose more than five times of their weight per hour. Thus, water spenders lose water as much as 500,000 times as rapidly as water savers (Levitt, 1972). However, since water spenders and drought tolerating plants are not the topic of this thesis, I refer readers interested in more details on this subject to the relevant literature like Levitt (1972), Levitt (1980), Kramer (1983) or Kozlowski and Pallardy (2002) .

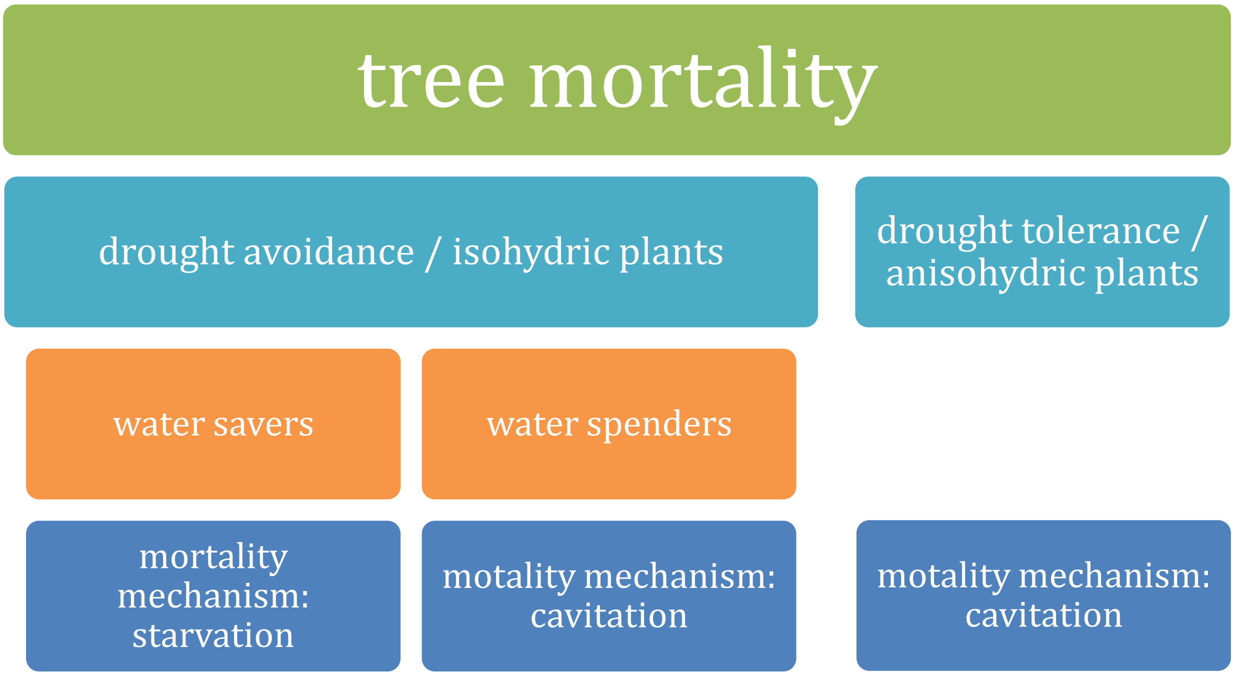

Figure 4: Classification of tree mortality

### 3.4.2 Identifying drought

Drought is the absence of water. This can have its reasons in a

- low water *supply* i.e. less precipitation,
- high water *demand* by strong irradiation and evapotranspiration or
- small *reserves* (soil water storage) that cannot buffer the local evaporative demand in the absence of precipitation.

### 3.4.3 Precipitation

Changes in precipitation are supposed to have the most important impact on tree deaths. This is also what PREISLER *et al.* (2012) point out in their mortality report. Below I want to verify this thesis and check in which way the precipitation behaviour may have changed between 1972 and 2010 and whether it is indeed the major factor that led to the observed mortality.

### 3.4.4 Evaporative demand (Irradiation and evapotranspiration)

The amount of available water is not the only possible reason that can cause drought. It is also important how much water the atmosphere demands for evaporation. This is called evaporative demand and it increases with increasing irradiation and wind, and decreases with increasing humidity.

Until approximately the 1980s and 1990s global dimming, which was caused by air pollution, lowered the global irradiation (STANHILL and COHEN, 2001). But since that time a global brightening was observed (WILD, 2012). WILD *et al.* (2008) reports a global increase in evapotranspiration by 2.4 - 6.6mm/year in the period from 1992-2000. PAPAIOANNOU *et al.* (2011) report a similar increase in Greece. With an increase of irradiation the evaporative demand increases, too, which promotes drought. In this thesis I want to check, if this change occurred and if it indeed led to mortality.

Besides a global irradiation change one can observe the effect of irradiation on a local scale due to the inclination angle of the hill slope and the aspect of the slope. If drought is the crucial factor for the mortality, then more dead trees should be seen on hill slopes exposed to the south, where irradiation is highest and, thus, evapotranspiration is higher too.

### 3.4.5 Soil water storage

The amount of water that a soil can store is described by the following characteristics:

*Saturated water content:* If a soil gets wetted and every pore is filled with water then it reaches the saturated water content (SPONAGEL, 2005).

*Field capacity*: The amount of water that an initially saturated soil can hold after two days of drainage is called as field capacity. It can be expressed in vol. %. The field capacity depends on many factors like soil texture, the type of clay present (montmorillonite has a higher specific surface [1000m$^2$/g] than Kaolinite [10m$^2$/g] (TUM - LEHRSTUHL FÜR GRUNDBAU, BODENMECHANIK, FELSMECHANIK UND TUNNELBAU, 2008)), organic matter content, soil structure, depth to groundwater etc. (HILLEL *et al.*, 1998; SCHEFFER *et al.*, 2002).

*Permanent wilting point:* When the plant takes up water from the soil, it will reach a point where it can no longer extract water. Hence it wilts. The tension at which the remaining water content in the soil is held so tightly in micropores that it cannot be extracted by the plant is called permanent wilting point (SCHEFFER *et al.*, 2002).

Only the field capacity minus the permanent wilting point is the *plant available water* (SCHEFFER *et al.*, 2002; KIRKHAM, 2004).

The depth of a soil as well as the depth to which roots are encountered is also important to determine the amount of water which is available for plants.

## 3.5 Salinity

Salinity can affect plants in two different ways: First, it changes the osmotic conditions in the soil, so that high salt concentrations in soils effect a lower availability of water to the plants. The salt content of soils can be expressed by their *electrical conductivity* (EC). It represent the major inorganic solutes $Na^+, Mg^{2+}, Ca^{2+}, K^+, Cl^-,\ SO_4^{2-}, HCO_3^-, NO_3^-, CO_3^{2-}$ in aqueous samples as a reciprocal of the electrical resistance (EC = 1 / R, (RHOADES *et al.*, 1999)). A soil is called “saline” if it exceeds the EC value of 0.4 S/m, which is equivalent to 40mmol/L NaCl or 2.3g/L NaCl (HILLEL *et al.*, 1998; VERBAND DER KALI- UND SALZINDUSTRIE E. V; SHABALA, 2012; MUNNS, 2013).

By using Van’t Hoff’s law one obtains the osmotic pressure, which in addition to matric forces in the soil holds water back from plant uptake: $\pi = cRT. \pi$ is the osmotic pressure: $\pi = cRT. \pi$ is the osmotic pressure in [Pa], c is the concentration of a salt (in mmol/l; derived from electrical conductivity), R is the universal gas constant, which is 8,314 J/mol K and T is the temperature in Kelvin which I assumed to be 298K (25°C).

Secondly, a low salt concentration and a high exchangeable sodium concentration leads to a dispersion of clay in the soil so that the soil structure is altered. That causes a lower infiltration and a lower permeability for water in soils. This is because clay particles mostly have a negative electrical charge so that they repel each other. Cations can stick to the negatively charged clay particles. Sodium is a very weak cation compared to magnesium and calcium. Additionally, sodium builds a hydrate. The big hydrate and the weak sticking power lead to the dispersion of clay particles in soils, because Na displaces the stronger cations Mg and Ca, which would bind the negatively charged clay particles together. This leads to decreasing infiltration and permeability of the soil. The ratio of sodium to calcium and magnesium is called *Sodium Adsorption Rate* (SAR), which is defined as (HILLEL *et al.*, 1998):

$$\boldsymbol{SAR} = \frac{[\boldsymbol{Na^{+}}]}{\sqrt{\boldsymbol{\frac{1}{2}}[\boldsymbol{Ca^{2+}} + \boldsymbol{Mg^{2+}}]}}$$

Whether a given SAR value in combination with a given electrical conductivity value influences the soil structure can be established with the help of tables e.g. in AGRICULTURE AND RESOURCE MANAGEMENT COUNCIL OF AUSTRALIA AND NEW ZEALAND, AND THE AUSTRALIAN AND NEW ZEALAND ENVIRONMENT AND CONSERVATION COUNCIL (2000).

Soils can possess a natural salinity, especially in areas with low precipitation where the salt will not be leached out but remains in the subsoil. Beside this primary salinity, salt can be brought to a soil either through irrigation with brackish irrigation water or by fertilizing, which is called secondary salinity. Near Yatir no source of this secondary salinity is known.

Salinization can lead to mortality, which is why I shall discuss it further.

## 3.6 Toxicity

Plants can suffer from different substances like heavy metals, herbicides, ozone or nitrous gases. Some plants even suffer from their own metabolic products. For example, conifers exhale volatile organic gases, others emit $H_2S$ (MCKERSIE and LESHEM, 1994). It is not possible to discuss each hazardous substance in detail, but one can conclude that it is most likely not the reason for tree mortality at Yatir by the following arguments: There are no symptoms of poisoning and there is no source of toxicity. For 40 years the forest grew well. If toxicity is the reason for the deaths, something must have occurred for it to appear suddenly. Such an event is unknown. Hence, toxicity cannot be a reason.

Hazardous substances could be deposited via the air, for example ozone, nitrogen oxides, hydrogen sulphide and sulphuric compounds or polycyclic aromatic hydrocarbons. However, no possible source is known and there are no symptoms of toxicity.

No data is available to look at mortality explicitly, but the named reasons suggest that toxicity is an unlikely reason for tree mortality. Therefore I shall not go into it here any deeper.

## 3.7 Mineral deficiency

The lack of nutrients can affect a plant in many ways. Almost every deficiency is indicated by necrosis or chlorosis of the needles. However, this has not been observed in Yatir. Likewise, the geology does not suggest the likeliness of mineral deficiency A lack of nutrients can affect the ability to resist stress even before necrosis or chlorosis become visible (C.A.B. INTERNATIONAL, 2002). Due to missing data it will not be discussed here anymore.

## 3.8 Biological agents

MAESTRE and CORTINA (2004) name Aleppo pine stands as a host of large numbers of insects that can become pests, especially bark beetles. More details about specific pests in such stands can be found in C.A.B. INTERNATIONAL (2002), which names a lot of biological agents. But biological agents do not only have a negative influence. A lot of studies show positive effects of mycorrhization (QUEREJETA *et al.*, 1998; CARAVACA *et al.*, 2002). These are symbiotic associations between a fungus and the tree roots. The missing of mycorrhiza, especially in dry areas, can influence tree vitality (PANETSOS, 1994-2008). MORTE *et al.* (2001) exposed *Pinus halepensis* to a four month artificial drought and found that survival of trees was higher in stand which were inoculated with ectomycorrhiza compared to uninoculated stands. Trees also recovered faster in the mycorrizhated stands and biomass increased more after rewetting than in the uninoculated stands.

Unfortunately, with respect to biological agents there are also no data available for Yatir. Hence this point cannot be discussed here any further.

## 3.9 Competition

Competition is an important factor, especially in places with limited resources, which in the case of Yatir forest is water. It makes a difference, if one tree receives the water accumulating on $10m^2$ or if it needs to share the same water with ten other trees. Since competition is growing with time it is an important factor that I will study in more detail.

# 4 Materials and methods

From the nine initially mentioned factors which may have contributed to the mortality the following four remain and shall be discussed in more detail below: Cold, drought, salinity and competition. Water logging dropped out, because the precipitation amount is low. For toxicity, mineral deficiency and biological agents there are no data available so that these factors drop out due to lack of data. The topic heat can be rejected as a reason for mortality, because the hottest observed temperatures occurred in 2000 and 2002, but not close to the mortality in 2010.

After the huge dieback in 2010 KKL - JNF managers initiated a project to investigate and understand why this extensive mortality occurred. KKL started a collaboration with the Weizmann institute of Science (WIS) to explore this phenomenon. They initiated an inventory survey, a soil survey, a genetic analysis, a spatial and geo-morphological survey and gathered ecophysiological parameters on the trees (PREISLER *et al.*, 2012). Most data I shall use later were gathered in this project.

20 plots were chosen and each plot was divided into a "live" and "dead" section, which means more than 80% of the trees within this plot are either alive or dead. To characterize these plots I shall name them below as "live" and "dead" plots.

## 4.1 Data used

Since the time was too short to collect the necessary data by myself, I could thankfully access data that were provided by KKL and the WIS. The data used are listed in Table 1.

**Table 1: Data used, its origin and the software used to process them (WIS = Weizmann institute of science, KKL = Keren Kajemeth LeIsrael – Jewish National Fund)**

| Data used | Software | Tool/method | parameter derived | origin |
|---|---|---|---|---|
| **Spatial distribution** | | | | |
| **Distribution of dead trees** | ArcGIS | Morans I + Hot Spot Analysis | hotspot, density within plots | KKL |
| **location of plots** | ArcGIS | | density of dead and live trees per plot | WIS |
| **aerial views** | ArcGIS | | density of dead and live trees per plot | WIS |
| **Cold** | | | | |
| **Temperature** | Excel | | minimum temperature | WIS |
| **Precipitation** | | | | |
| **Rainfall** | Excel | | monthly, annual and average rainfall for the observation period | |
| **Irradiation** | | | | |
| **temperature** | Python, Excel | | daily maximum and minimum temperature | WIS |
| **topology** | ArcGIS, Quantum GIS | spatial analyst → aspect, slope | hillslope exposition, degree of inclination | KKL |
| **Soil water storage** | | | | |
| **root density** | Excel | | rooting depth | WIS |
| **soil stoniness** | Excel | | begin of bedrock | WIS |
| **half hourly evapotranspiration** | Python, Excel | interpolation with a 31day moving average | daily evapotranspiration | WIS |
| **Salinity** | | | | |
| **soil laboratory data** | Excel, SPSS | Whitney-U Test, t-test | | WIS |
| EC | | | osmotic pressure due to total salt content | |
| Na | | | osmotic pressure due to sodium content | |
| Mg+Ca | | | | |
| SAR | | | | |
| **soil structure** | | | texture, field capacity, PWP, plant available water | |
| **location of plots** | ArcGIS | | | WIS |
| **density of live and dead trees within plots** | ArcGIS | | correlation coefficients of soil parameters to forest parameters | deduced |
| **Competition** | | | | |
| **KKL Inventory from 2004 and 2007** | | allometric equation | biomass per plot/single tree; biomass per age | WIS |
| DBH | Excel | | | |
| height | Excel | | | |
| stand age | Excel | | | |

Figure 5 shows the GIS layers I worked with: aerial views, topology, dead tree layer and the positions of the plots.

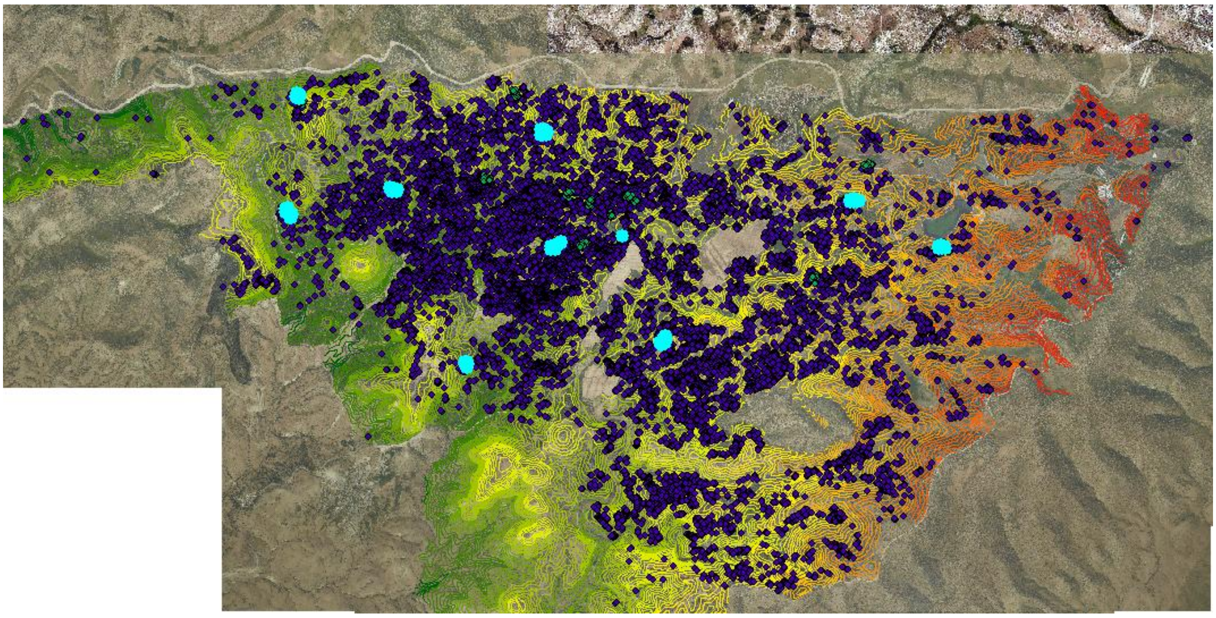

**Figure 5: Aerial view of Yatir forest. The green (450m) to yellow (650m) to red lines (850m) show the contours in ascending order. Each dark blue spot represent a dead tree. Positions of soil plots used in this thesis are marked light cyan.**

## 4.2 Spatial distribution of dead trees

It was necessary to check first how suitable the data are for this thesis, because they were not collected for this purpose. In a first step I needed to critically examine the suitability of the data for the analyses I wanted to do.

Especially these two questions arose:

1. Is the GIS-layer with the positions of dead trees accurate and does it represent the amount and position of dead trees found on site?
2. Are the positions for dead and live plots chosen at a location at which one can expect to find significant differences to explain why trees survived on some locations and died on others?

To answer the first question: The layer with dead trees was created in an earlier project in cooperation of WIS with a commercial company that build an algorithm to find tens of thousands dead trees via remote sensing in the aerial views (PREISLER *et al.*, 2012). To check how reliable the GIS-layer is, I built a rectangle around some plots and counted the dead trees that I could identify visually and compared it with the amount of dead trees in the layer (see 5.1).

The second question can be answered by using a hotspot analysis of dead trees in ArcGIS. The results should indicate that dead and live plots are not both located in a hot spot area, but that the live plots are found in hotspots and the dead plots are located in cold spots. Additionally I analyzed the soil data in SPSS for outliers and whether there was a significant difference between dead and live plots. If no significant differences will be found, the soil data do not actually qualify to explain differences (see 5.2).

By applying a hotspot analysis one determine whether dead trees are clustered or randomly distributed. If there are no clusters and the mortality is spread randomly over the area, a common reason, e.g. particularities in soil or topographical features, is unlikely.

To find a statistical significant cluster I used the tool "Morans I" in ArcGIS (ESRI ARCGIS, 2014a, 2014b, 2014d, 2014c). This is a tool which helps to find spatial autocorrelation. It returns p and z values. The p-value gives information about how likely it is that the null hypothesis is valid or not. In the case of autocorrelation the null hypothesis states a completely spatial randomness. If the p-value is high, then this hypothesis is very likely. If p is low and positive, the null hypothesis is unlikely and clustering is more likely. If p is low and negative, the features are dispersed.

The z-score equals the standard deviation which is derived from calculating the differences of feature attributes within a moving window. The size of the window can be chosen freely. A z-score of 2.5 says that the result is 2.5 standard deviations (c.f Figure 6). Hence, the greater the standard deviation, the greater is the spatial difference of feature attributes at the chosen size of the moving window. The biggest cluster can be found at the windows size with the highest z-score. The optimal size can only be found by sampling.

There are several methods two search for autocorrelation. For example, one can use inverse distance bands, which means the features are related to each other, but closer features have a higher weight than far away features. I used the fixed distance band, which works as a moving window of a fixed distance. Only features within a determined distance band can interact with each other. This is the setting that describes the small scale variation best and can give hints to soil properties or other geographical attributes that do not need to correspond with areas further afar. The distance for the window can vary and return different z-scores and p-values. At the distance where the z-score reaches its maximum the clustering is most significant.

The input layer was a grid created with a polygon "fishnet" of 100m$^2$ squares. That fishnet was joined with the dead tree layer which is a point shape-file. The result is a grid with the amount of dead trees per 10m*10m.

This grid file was used to find spatial autocorrelation with the Morans I tool. The highest z-score was obtained with a 45m fixed distance band (ESRI ARCGIS, 2014a). This band was then used to find hotspots. The results are shown in section 5.2.

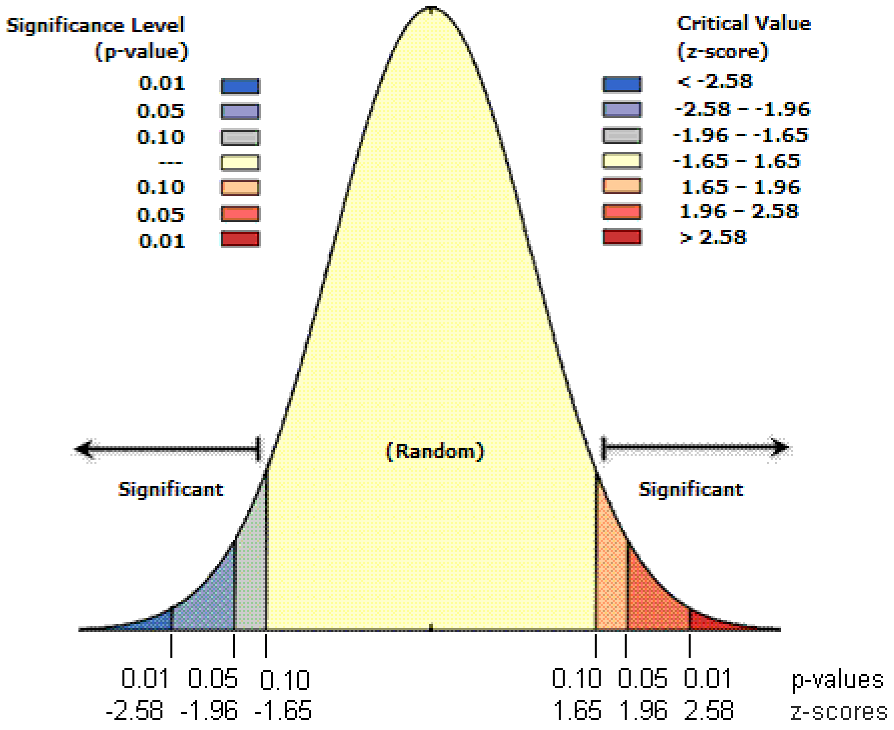

Figure 6: p-value and z-score used by Morans I (source: ESRI ARCGIS, 2014c)

## 4.3 Cold

The coldest days were indentified in the half hourly measurements from the meteorological tower in the centre of Yatir forest. The tower was built by WIS and established in 2000. In addition, the maximum and minimum daily temperatures in the past ten years before the mortality in 2010 were pinpointed.

## 4.4 Drought

### 4.4.1 Precipitation

With these four methods I tried to find changes in precipitation pattern:

- With a five-year moving average I tried to find a long term trend that indicates whether it became drier in the past years or not. This gives evidence of changes in annual precipitation.
- With a 12 month moving average I tried to find a change in intra-annual pattern. The question here was: Does the precipitation amount change on a monthly scale?
- With the cumulative sum of monthly precipitation I tried to answer the same question with the focus on cumulative effects that result by summing up two or more particularly dry month.
- With the last method I tried to find changes on a diurnal scale: On each day with rain > 2mm I subtracted 2mm from the precipitation amount. For example, ff the monthly and annual amount of precipitation stayed equal but it derived from more small rain showers, which are not able to infiltrate into the soil, this should show up as a decreasing trend, if one sums up all these rainfalls to an annual sum.

### 4.4.2 Evaporative demand (Irradation and evapotranspiration)

#### Irradiation

With the radiation measurements, which were done at Yatir forest, one could assess whether the trees encountered a higher evaporative demand around the time of the deaths. Unfortunately they were not provided to me, so I can give only an estimate by looking at the temperature which is a function of irradiation. I built the mean (monthly), maximum and minimum temperature (daily) with the help of a python script to gauge the changes in irradiation.

To assess the local impact of radiation KKL provided a digital surface of the forest to me, which I could use to analyze mortality in the light of slopes and aspect. With the GIS-layer of dead trees showing their positions I could now count the number of dead trees per slope and per aspect.

### 4.4.3 Soil water storage

During the soil survey the texture of the soil was determined. This data is suitable to estimate the field capacity. To do so the first step is to determine the texture class name. This is possible by using a textural triangle. With its help one can derive the soil class based on the fractions of the soil particle sizes. I used the German soil survey guideline “Bodenkundliche Kartieranleitung 5” to deduce saturated water content, field capacity, plant available water and wilting point per plot

(Sponagel, 2005). The rooting depth varies widely, depending on root distribution, stoniness of the soil and the depth to rocky ground.

Data on infiltration and water retention curves are not available.

Figure 7: The meteorological Tower in Yatir forest

I modelled the soil water content on a daily resolution to combine the information about precipitation and evapotranspiration to find the time spell with the greatest water deficit. For that I used the precipitation and evapotranspiration data for 10 years (2000 until 2010) which were collected with eddy covariance flux measurement (Figure 7) close to the geographic centre of the Yatir forest (Yaseef *et al.*, 2009). The data were taken every half hour and give the evapotranspirated water in g/m$^2$/s. I build the cumulative sum of evapotranspirated water per day to subtract this amount of water each day from the amount of rain which had fallen and/or was stored in the soil. To evaluate the evapotranspiration data I ran a python script to filter out dates with missing entries. Only days with complete 48 half hourly measure entries were used further to interpolate the missing days and to not distort the cumulative sum per day. Out of 3744 days (1st Oct 2000 to 31st Dez 2010) 924 lacked a complete measurement record. This is every fourth day. For the Interpolation I wrote another python script that fills the missing values using a 30day average based on the 15 days before and after the missing value.

## 4.5 Salinity

During the soil survey of WIS 22 trenches were dug in 11 of 20 research plots to investigate the differences between dead and live sites in each plot. Each plot was supposed to have a depth of 1.50m, but in some plots the rocky ground was reached at lesser depths.

From each trench, an example is given in Figure 8, several samples were taken to measure electrical conductivity, sodium, calcium and magnesium amount, and the fraction of sand, silt and clay. For further analysis the arithmetic mean of each feature was used per plot.

Figure 8: A soil trench in Yatir forest

## 4.6 Competition

KKL did a forest inventory in 2004 and 2007. Within a 200m² plot they measured the diameter at breast height (DBH) and the height and counted the number of trees per plot to get the density. In this inventory the year of planting was also noted. So I had the density, DBH and height for stands in different ages and could create a time series for the stand density and the biomass per tree. To show the temporal development of the stands I calculated for each age the biomass per tree by means of the allometric equation stated in GRÜNZWEIG *et al.* (2007):

$$\text{Biomass per tree} = 0.030553 \cdot (d^2h)^{1.031064}$$

where d is the diameter at breast height and h the height of the tree.

# 5 Results

## 5.1 Reliability of dead trees GIS-layer

The WIS gave me a GIS-layer with the positions of the dead trees. These positions were found with an algorithm that the WIS created in cooperation with a commercial company. I examined the provided layer with respect to its reliability, by comparing the numbers of trees found by the algorithm within a rectangle and those I could see with naked eye in the same rectangle on aerial photographs. One can see that the dead plot layer represents only less than half of dead trees which are visually detectable. Table 2 summarizes the differences found.

**Table 2: Comparison of dead trees found with an algorithm and by visual detection in dead (D) and live (L) plots at Yatir forest**

| Plot | Dead trees found by algorithm | | Dead trees recognized visually | |
|---|---|---|---|---|
| | D | L | D | L |
| **1** | 2.0 | 0.0 | 10.0 | 6.0 |
| **3** | 27.0 | 4.0 | 34.0 | 6.0 |
| **7** | 18.0 | 7.0 | 31.0 | 22.0 |
| **9** | 16.0 | 10.0 | 25.0 | 20.0 |
| **11** | 15.0 | 5.0 | 50.0 | 8.0 |
| **16** | 1.0 | 1.0 | 17.0 | 1.0 |
| **19** | 11.0 | 1.0 | 33.0 | 7.0 |
| **20** | 25.0 | 12.0 | 39.0 | 18.0 |
| **25** | 2.0 | 0.0 | 14.0 | 4.0 |
| **29** | 6.0 | 0.0 | 20.0 | 10.0 |
| **30** | 18.0 | 1.0 | 34.0 | 5.0 |
| **31** | 23.0 | 11.0 | 29.0 | 20.0 |
| **sum** | 164.0 | 52.0 | 336.0 | 127.0 |
| **%** | 48.8 | 40.9 | 100.0 | 100.0 |

Thus, the first question of chapter 4.2: “Is the layer with the positions of dead trees accurate and does it represent the amount and position of dead trees found in nature?” is answered. The GIS-layer with the position of dead trees I used here represent only half of the dead trees present in reality. This must be noted for all further analysis done here.

In some investigations below I therefore used the amount of dead trees I found visually, but especially in section *5.4.2.2 Irradiation* I needed the dead tree position for the whole 30km$^2$. It is not possible to do this visually within the time allocated for this thesis.

## 5.2 Spatial distribution of dead trees

The second important question regarding the data I used concerns the validity of the positions of dead and live plots, because they constitute the basis to find significant differences to explain the mortality in the dead plots and the survival in the live plots.

To answer this question I did a hot spot analysis in ArcGIS to ascertain if the dead and live plots do not lie in the same mortality hotspot. Finding spatial autocorrelation of dead trees depends strongly on the extent of the area where one wants to find clusters, because on an area of $10km^2$ one would find different clusters than on a $100m^2$ area. If I search for clusters in the whole area, the z-score will have its maximum at a fixed distance band of 2km, but this is because the forest itself does not have a rectangular shape, but the “Morans I” will always search in rectanglular patterns. So it will find the clusters that represent the shape of the forest, since in the center of the forest (which doesn’t have a rectangular shape) the dead tree accumulation is high. So it is recommendable to choose a smaller extent where the visible discernible clusters seem to be relatively even distributed.

After several trials I found a suitable extent for the “Morans I” analysis in the center of the forest with a rectangle of 1.6km x 1,2km. The z score was highest at a 45 meter distance band and had a value of 75.86. The p-value is so small that ArcGIS rounded it to 0.000000. With a second rectangle (1500m x 850m) I encompassed most of the plots which were used in further analysis.

Unfortunately one can see (Figure 9) that the positions of dead and live plots are so close to each other that they belong mostly to the same mortality cluster and hence to the same mortality hotspot. This means the dead and live plots represent rather a small scale variation within the same cluster but do not represent the difference of mortality hotspots and mortality free areas.

Since there are no other data available I shall work on with this data in that thesis. It can give still a first suggestion for the mortality reason.

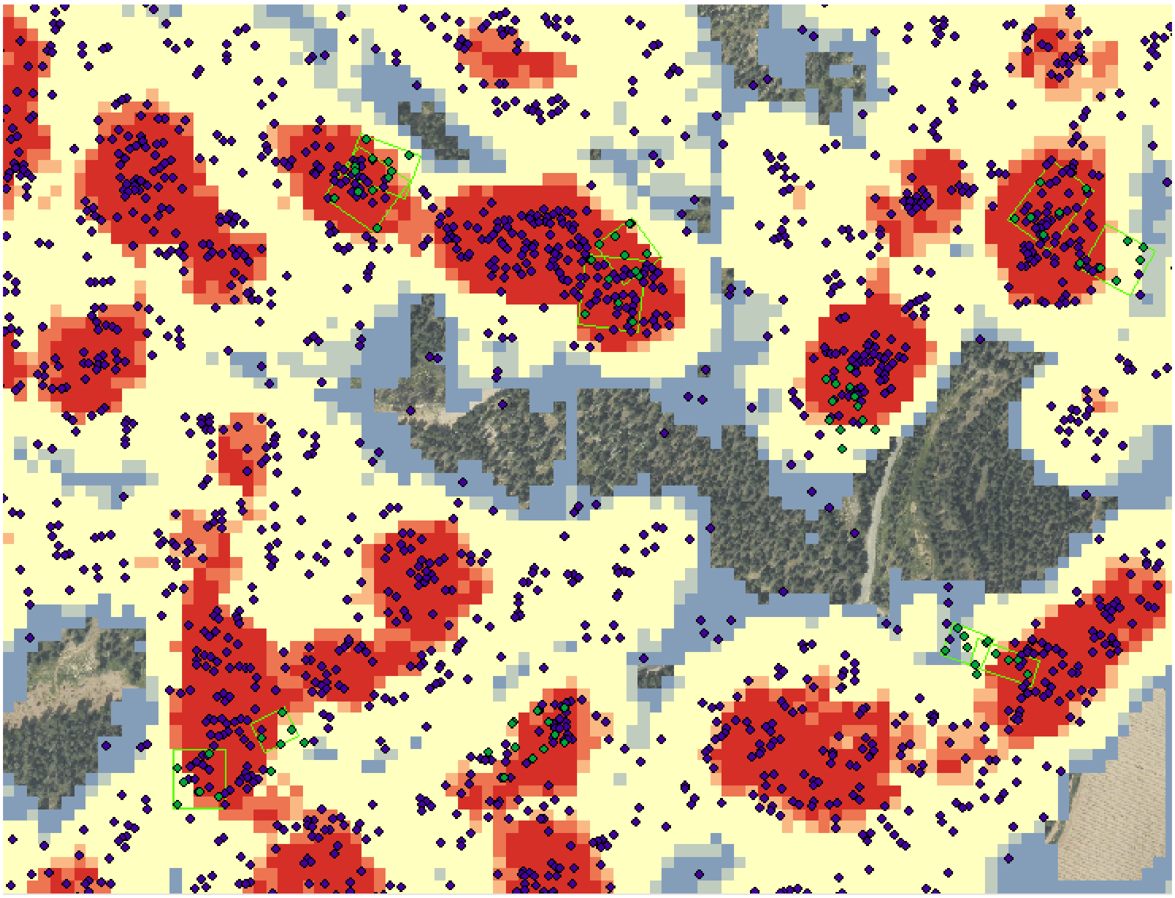

**Figure 9: This excerpt shows approximately 1km$^2$ and the results of a hotspot analysis. The green rectangle in the upper left site: plots 31L/ D, upper middle: plots 3L/D, upper right side 15D/L. The lower left site: 19D/L and lower right side 16D/L. red spots: z score > 2.58 (significant clustering), blue spots and translucent: z-score is negative (significant disperesed). The dark blue dots are the location of dead trees.**

### *Statistical analysis*

The last investigation to answer the second question of 4.2 is whether the features in dead and live plots show a significant difference or if they represent the same statistical population.

With the help of SPSS 20 I checked if the features in dead and live plots are significantly distinguished. For that I used the t-test. A necessary condition for the t-test is a Gaussian normal distribution of the features. This is tested with the Shapiro-Wilk test (Table 3). If p is greater than 0.05 the null hypothesis, which states that the features are Gaussian distributed, is accepted. Only 3 out of 14 variables fulfil this condition.

Table 3: Shapiro-Wilk test to check if the soil attributes are Gaussian distributed (p>0.05)

| **Variable** | **Shapiro-Wilk Test** | |
|---|---|---|
| | | **p** |
| **EC** | dead | 0.000 |
| | live | 0.022 |
| **Na** | dead | 0.000 |
| | live | 0.002 |
| **Ca + Mg** | dead | 0.000 |
| | live | 0.000 |
| **SAR** | dead | 0.000 |
| | live | 0.000 |
| **Sand %** | dead | 0.000 |
| | live | 0.216 |
| **Silt %** | dead | 0.001 |
| | live | 0.816 |
| **Clay %** | dead | 0.000 |
| | live | 0.072 |

In consequence one would apply a non parametric test like the Mann Whitney U Test.

Table 4: Non-parametric test that shows differences between dead and live plots

| | **EC** | **Na** | **Ca + Mg** | **SAR** | **Sand** | **Silt** | **Clay** |
|---|---|---|---|---|---|---|---|
| **Mann-Whitney U** | 327 | 395 | 375 | 466 | 521 | 495 | 491 |
| **Wilcoxon W** | 1107 | 1175 | 1155 | 1246 | 1301 | 1275 | 897 |
| **Z** | -2.784 | -1.920 | -2.174 | -1.017 | -.324 | -.650 | -.707 |
| **p (2-tailed)** | .005 | .055 | .030 | .309 | .746 | .516 | .480 |

In this case the null hypothesis states: The soil properties in dead and live plots are not different. If p is below 0.05 it means that with more than 95% likelihood the null hypothesis can be rejected. In Table 4 one can see that only the EC and the calcium and magnesium values in dead and live plots differ significantly. Na, SAR and the fractions of soil particles have the same statistical population in dead and live plots.

I performed a t-test, too, although the features are not Gaussian distributed. The Levene's test p must show a greater significance than p=0.05, if the variances are equal. Is p<0.05 the variances are different. Without filtering outliers none of the attributes have a t-test p<0.05, which is necessary to show a significant difference between dead and live plots. In other words: The measured soil characteristics in dead and live plots do not represent two significant different site properties. If I remove the outliers and conduct the t-test again the salinity features differ significant in dead and live plots (Table 5).

Table 5: t-test results after removal of outliers. Levene's test p needs to be greater than 0.05 to assume equal variances and p of t-test needs to be less than 0.05 to show significant differences between live and dead plots.

| | | Levene's Test for Equality of Variances | t-test (2-tailed) |
|---|---|---|---|
| | | p | p |
| **EC** | Equal variances not assumed | .001 | .001 |
| **Na** | Equal variances not assumed | .011 | .013 |
| **Sand** | Equal variances not assumed | .001 | .283 |
| **Ca + Mg** | Equal variances not assumed | .001 | .013 |
| **SAR** | Equal variances not assumed | .005 | .061 |
| **Silt** | Equal variances assumed | .643 | .851 |

The question of 4.2: "Are the positions for dead and live plots chosen so that one can expect to find significant differences to explain why trees survived on some locations and died on others?" can be answered with: most likely not. However, for lack of alternative data I still shall examine the data. Maybe one can see at least a hint for the mortality reason.

## 5.3 Cold

The coldest measured temperature was -3.6°C on January, 14th, 2008. In the period from 11th – 16th Jan 2008 every night had temperatures below 0°C. This frost is too light to be responsible for the mortality, but it could lead to a weakening of the trees. This will be discussed further in discussion section.

## 5.4 Drought

### 5.4.1 Precipitation

The reason suspected to be most likely responsible for the mortality is a change in precipitation. That is why I shall analyze the annual precipitation amount and its temporal change. Figure 10 shows the annual precipitation and the 5 year moving average. One can see several ups and downs, but no significant change in the annual precipitation, except that years with more than 400mm precipitation are missing since the 1991/92 rainy season.

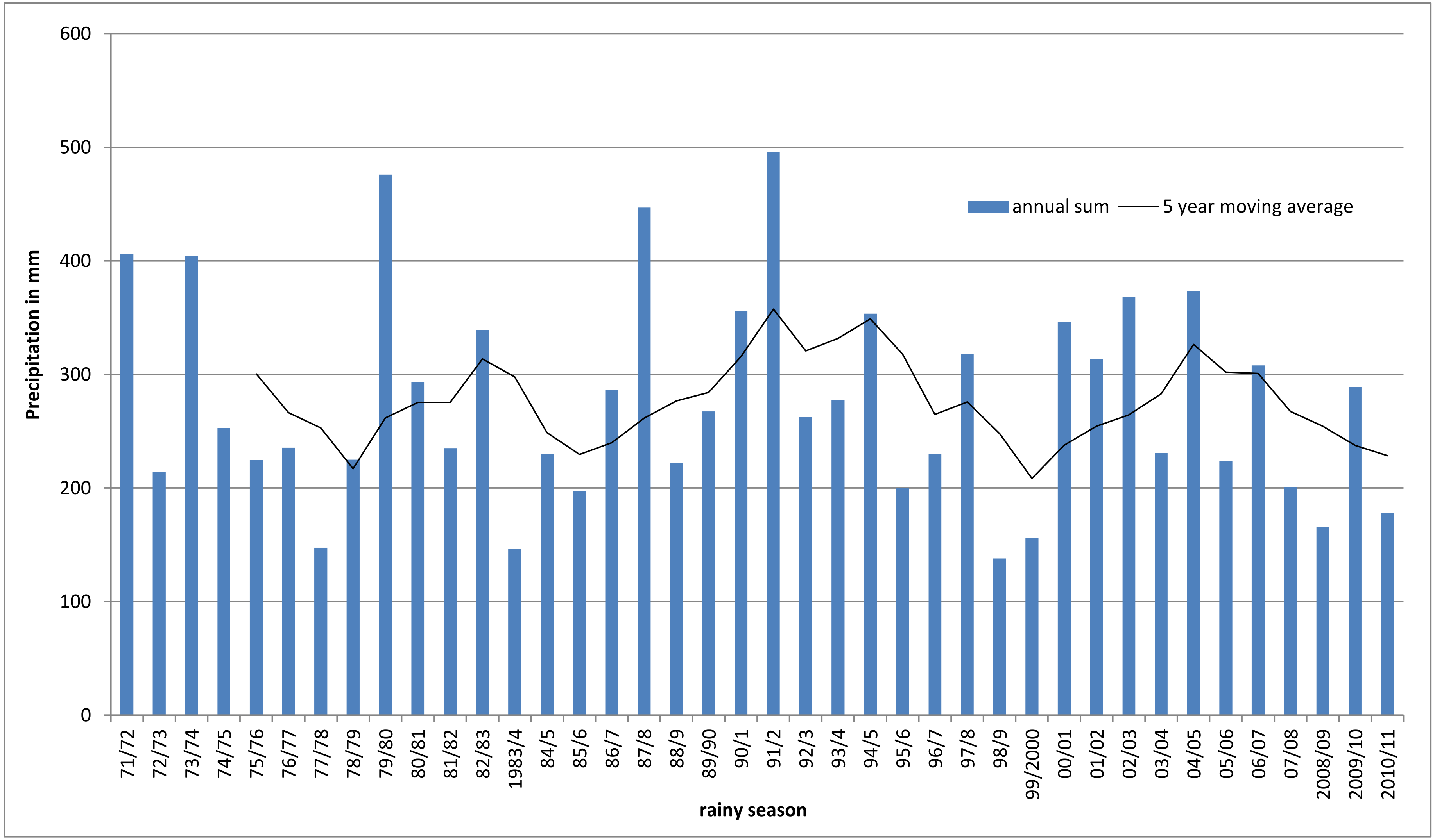

Figure 10: Annual precipitation at Yatir per rainy season and the 5 year moving average.

Figure 12 shows the annual deviation from the long term mean of 279mm. If one sums up the precipitation amount each year and fits a linear regression line to that one obtains a very good fit with $R^2=0.9988$. I calculated the deviation from this theoretical cumulative precipitation amount (Figure 12). Thus, cumulative effects are better visible, e.g. if some successive years had below average precipitation.

Figure 13 shows the monthly precipitation amount over the last 40 years and a 12-month moving average. The absolute minimum of the moving average is in the winter 2008/09 (9 mm), which I marked with a red line. During the rainy season rain fell on average on 31.5 days. The winter 1998/99 had only 16 rainfall events and so the lowest rainfall number. In contrast 1971/72 had the highest number of rainy days with 61.

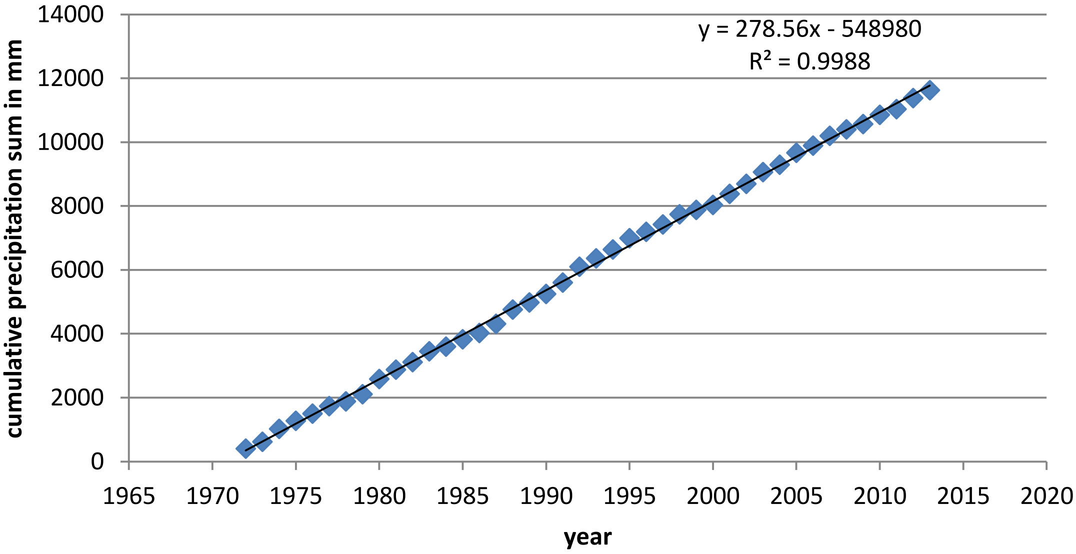

Figure 11: Cumulative precipitation Yatir forest from 1972 until 2013

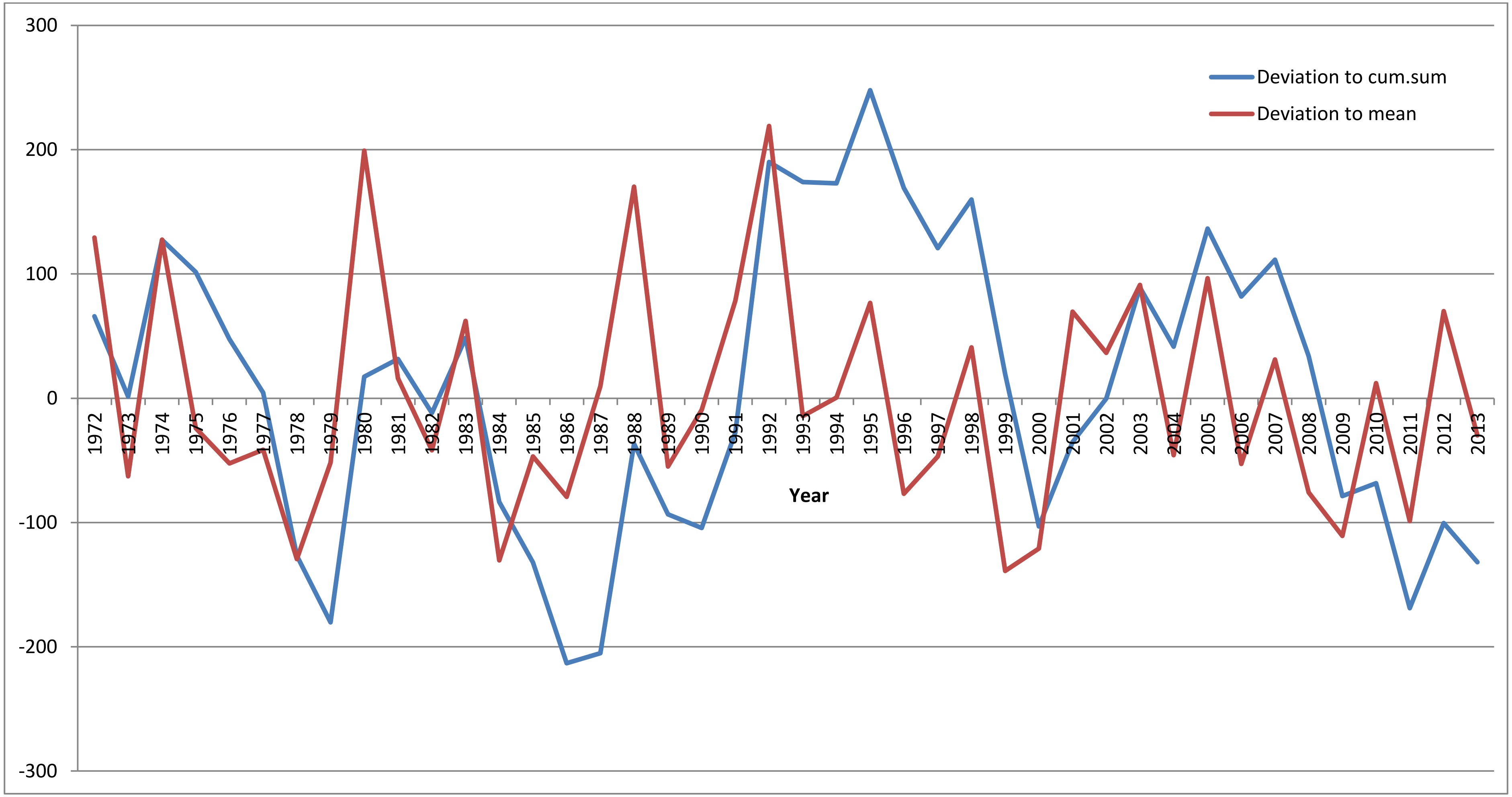

**Figure 12: Deviation of the precipitation from the long term mean and the cumulative precipitation (c.f. Figure 11)**

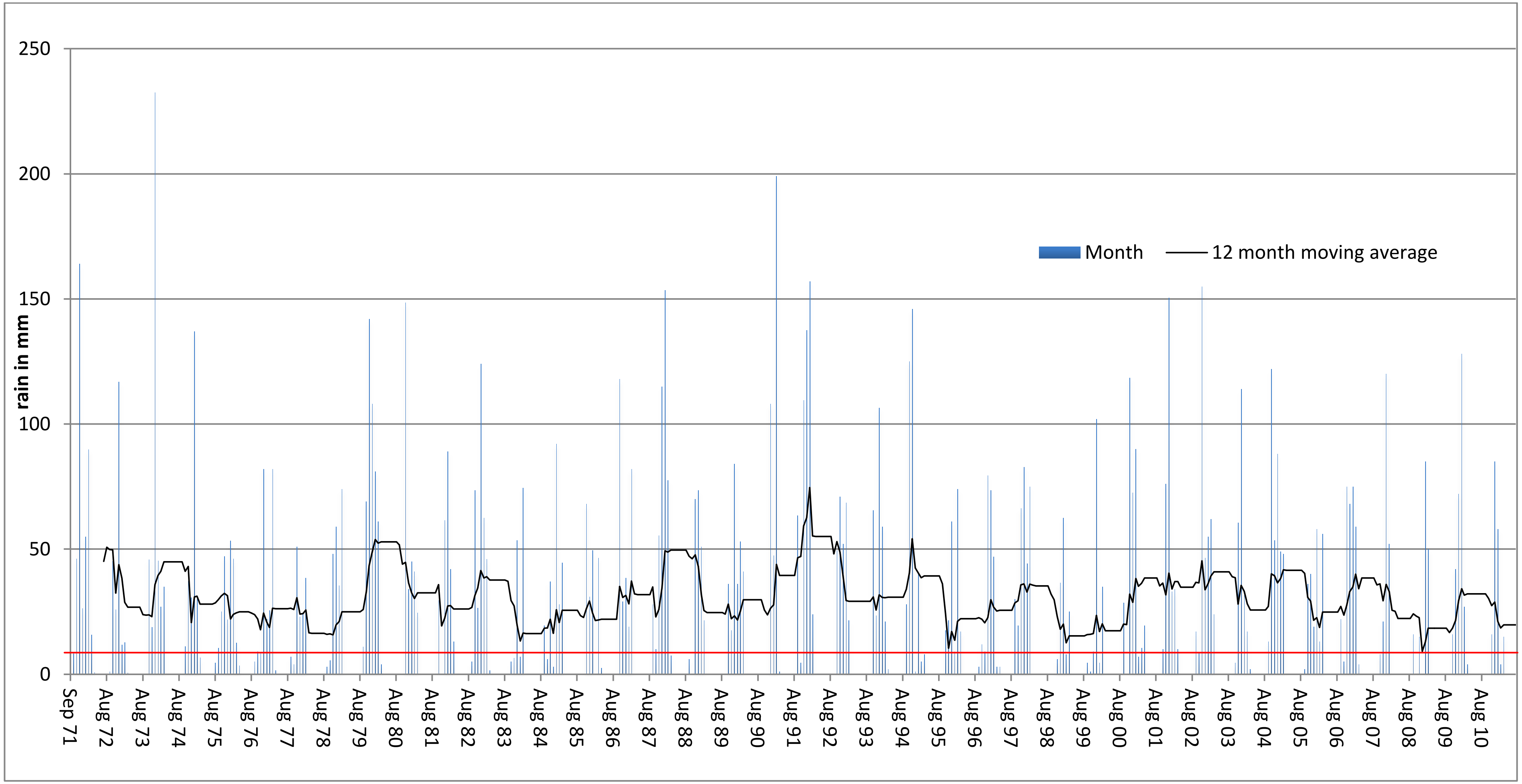

Figure 13: Monthly rainfall amount at Yatir and the 12-month moving average. The red line marks the lowest point of the moving average

Not only is the rainfall sum itself important, but also the distribution of rainfall over time. In Figure 14 I represent the cumulative precipitation during each rainy season. The red swerving line in the right lower end of Figure 14 is the rainfall distribution of 2008/09 which stands out here. It has the latest rise of cumulative precipitation sum. That means that in this year the trees needed to wait the longest time in the 40 years since the establishment of the forest to receive water after the dry summer spell.

Figure 15 shows the cumulative sum over the year, standardized by dividing each month with the related total yearly rain amount. In this fashion the intra-annual distribution is easier to compare. Figure 16 shows the same, but for better clarity only the last 10 years are depicted. In both figures the rainy season 08/09 stands out (red line). While in the most other years almost half of the annual precipitation had fallen by the middle of January, in 2008/09 just 20% of the annual rain had fallen.

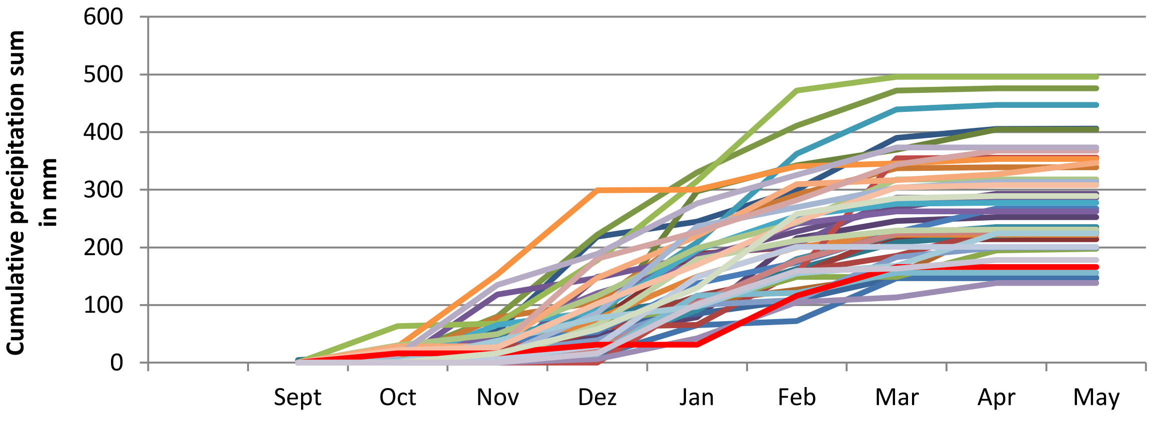

Figure 14: Cumulative monthly precipitation

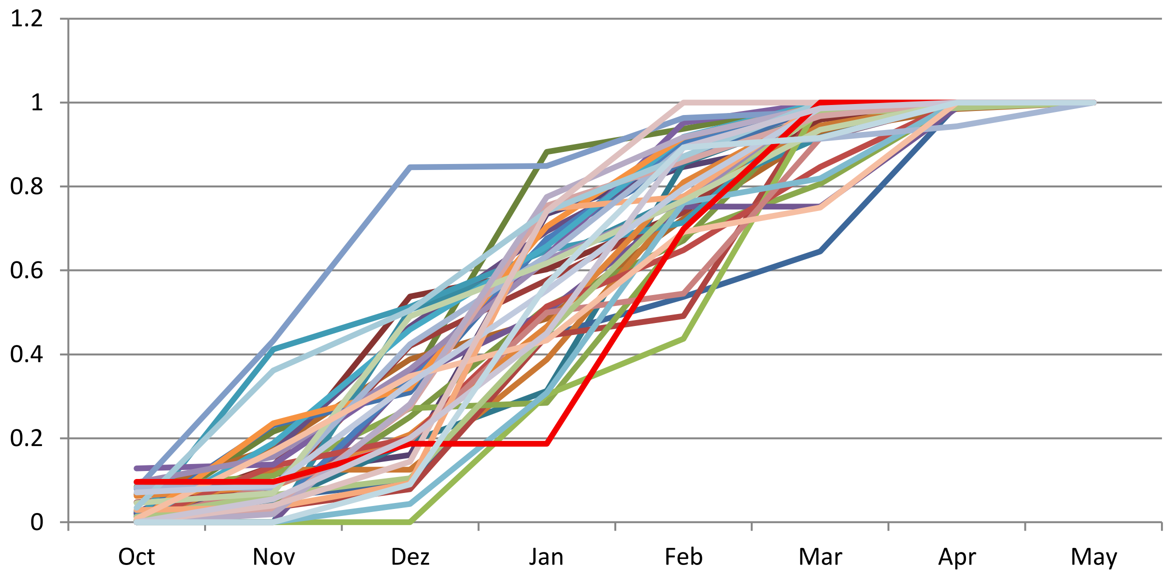

Figure 15: Standardized distribution of rainfall during each rainy season from the beginning of climate records in Yatir in 1972 until 2011

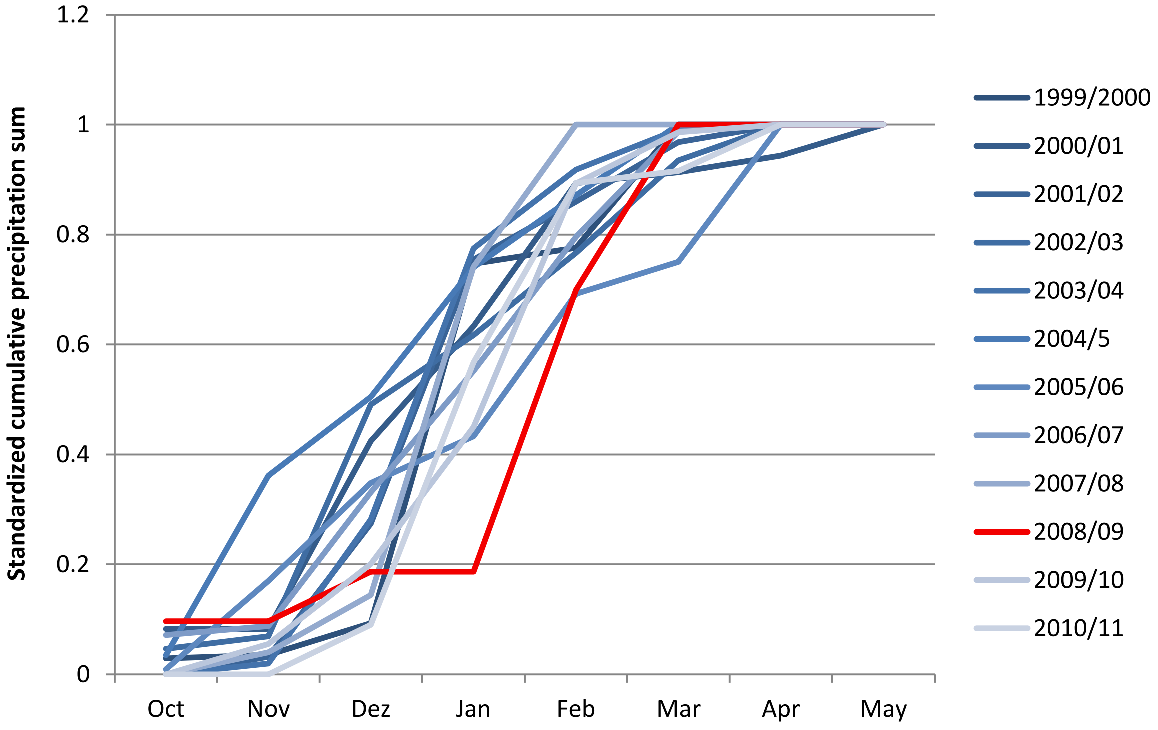

Figure 16: Standardized distribution of rainfall during each rainy season from 1999 to 2011

In Figure 17 I assumed that 2 mm of water of each rain event on a given day evaporate immediately and won’t infiltrate into the soil. From that diagram one can deduce if the rainfall intensity and frequency have changed. For example, if the same amount of rain per season was distributed over more events but with lower intensity, then the line “P sum -2” should be lower. The other scenario is that the number of precipitation events became less but that the amount of precipitation per event increased. In that case the line “P sum -2” would be higher. None of those scenarios is visible. The winter 2009/2010 does not stand out in this figure. Several years before that had less precipitation.

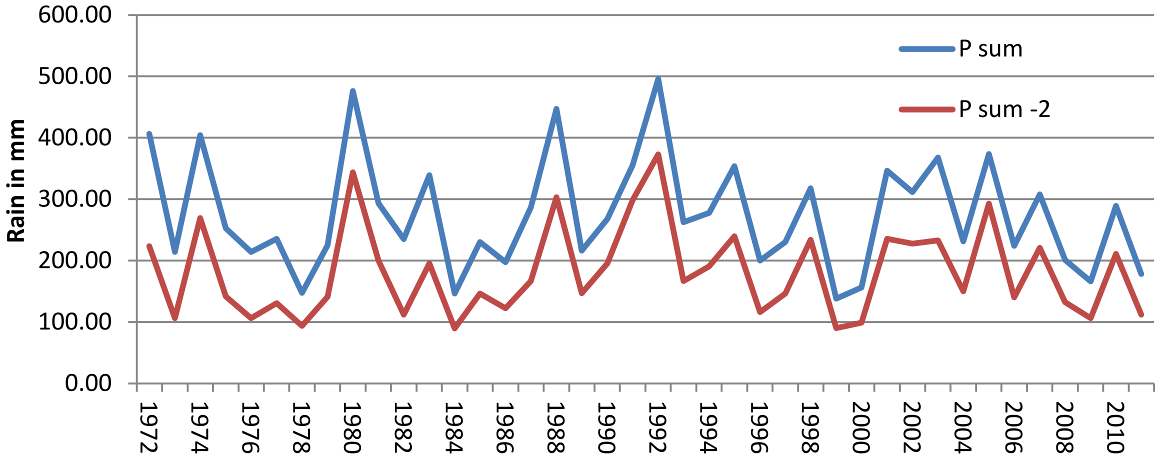

Figure 17: Annual rainfall and annual rainfall subtracted by 2mm of rain at each rain event, assumed, that these 2mm are evaporating immediately.

## 5.4.2 Evaporative demand

### *5.4.2.1 Evapotranspiration (ET)*

Figure 18 shows the measured and calculated actual ET. For the calculation I summed up all half hourly measured data which were collected with the eddy covariance technique using the meteorological tower, after I checked with a python script if all 48 data points per day were available. If they were not, i.e. at least one value was missing, I interpolated the day. For this I wrote a python script that fills the missing values using a 30day average based on the 15 days before and after the missing value.

The actual ET does not have a strong meaning for it says only something about how much of the available water went out of the system. It does not say anything about the water demand. In combination with the potential evapotranspiration it would say more about water stress and water demand.

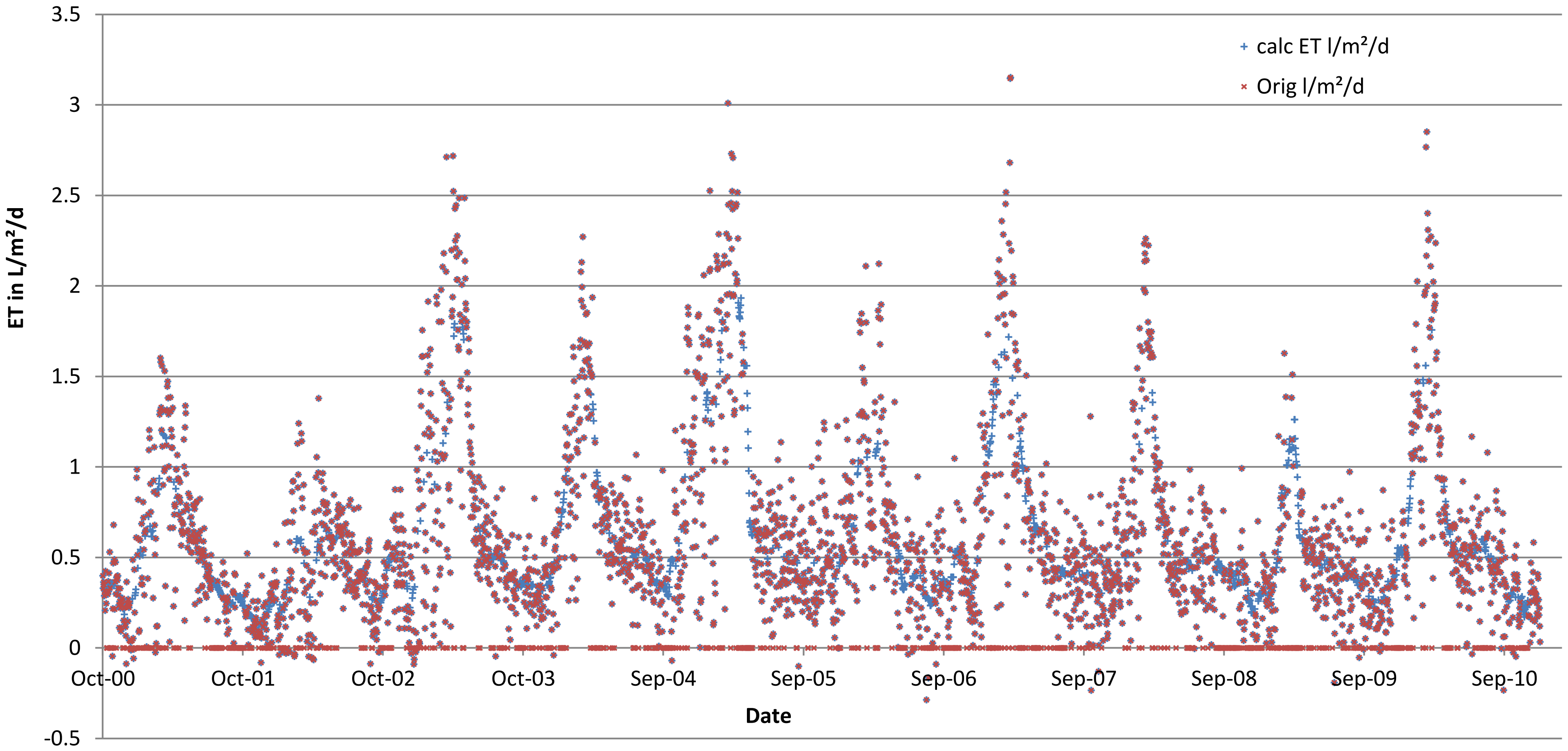

Figure 18: Calculated and measured evapotranspiration. The zero values represent missing data.

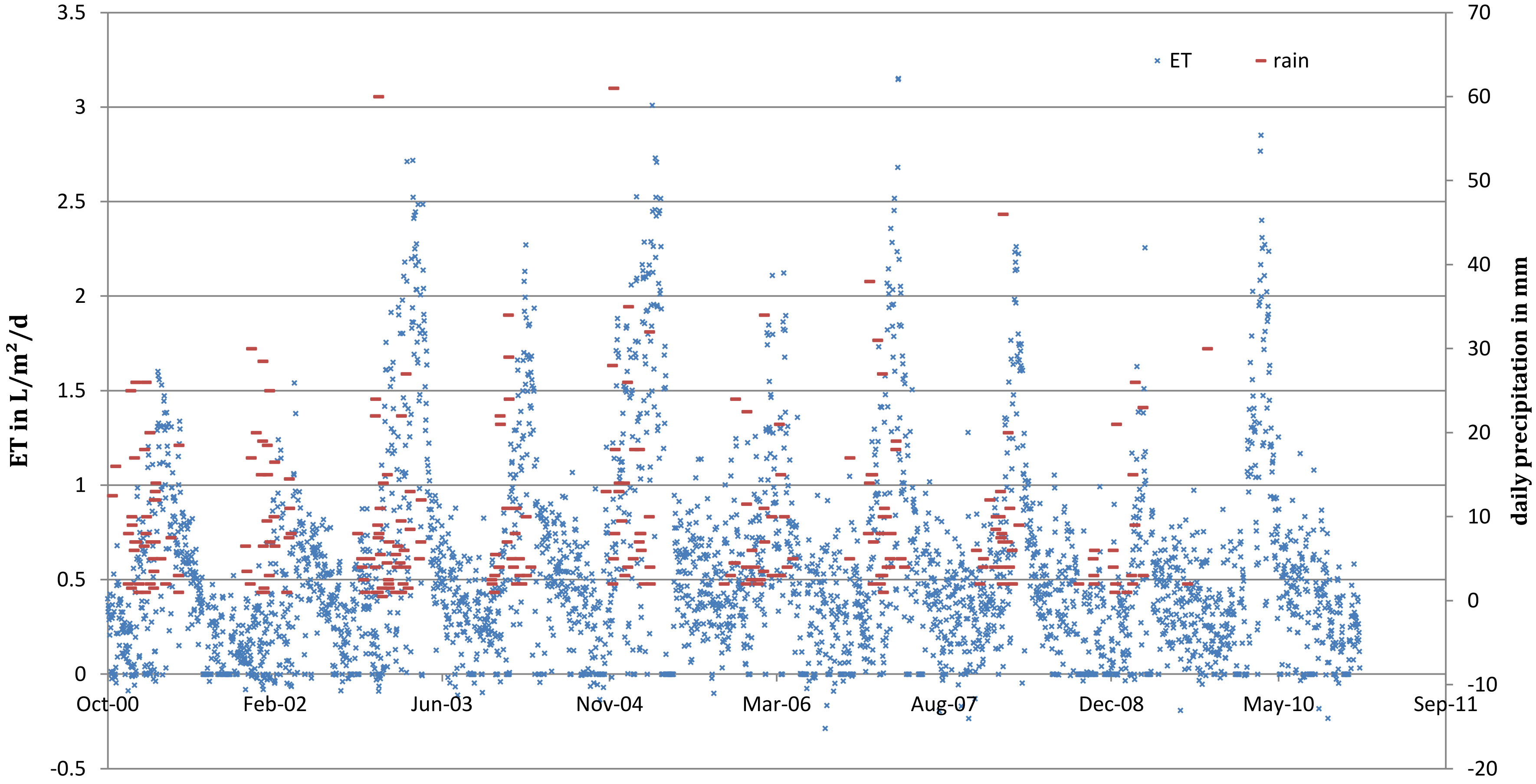

Figure 19: Measured ET and rainfall

#### *5.4.2.2 Irradiation*

Another factor that influences drought stress is irradiation, which leads to higher transpiration and thus increases water demand.

Since the temperature correlates with irradiation it can serve as an indirect measurement of irradiation. Figure 20 shows the maximum and minimum temperature for Yatir in the last 10 years before the tree deaths. There is a cooling rather than a heating. If one fits a linear regression line, the maximum and the minimum temperature show a negative slope (-0.0001 and -0.0003 respectively). This suggests that the evaporative demand did not increase. Now I want to answer the question if evaporative demand has an influence on a local scale.

The magnitude of irradiation changes with cardinal direction and slope. I found that the trees exposed to the south have the highest mortality with 18% (Table 6). The second highest is seen in southeastern direction with 16.3%, and the third most towards the southwest with 15%. In sum 49.3% of the dead trees are exposed to southern directions (southeast to southwest), i.e. almost half of the dead trees are located where they are exposed to high irradiation. In contrast to that the sum of the dead trees exposed to northern directions (from northwest to northeast) is only 29%. This is a clear indication that irradiation plays an important role in tree dying and another indication that the evaporative demand (and hence drought) plays a key role in tree mortality. Table 7 shows the same relation with different chosen angels. Evaporative demand plays an important role but only in small scale. The global irradiation doesn’t seem to have changed.

Table 6 shows to which direction the dead trees were exposed.

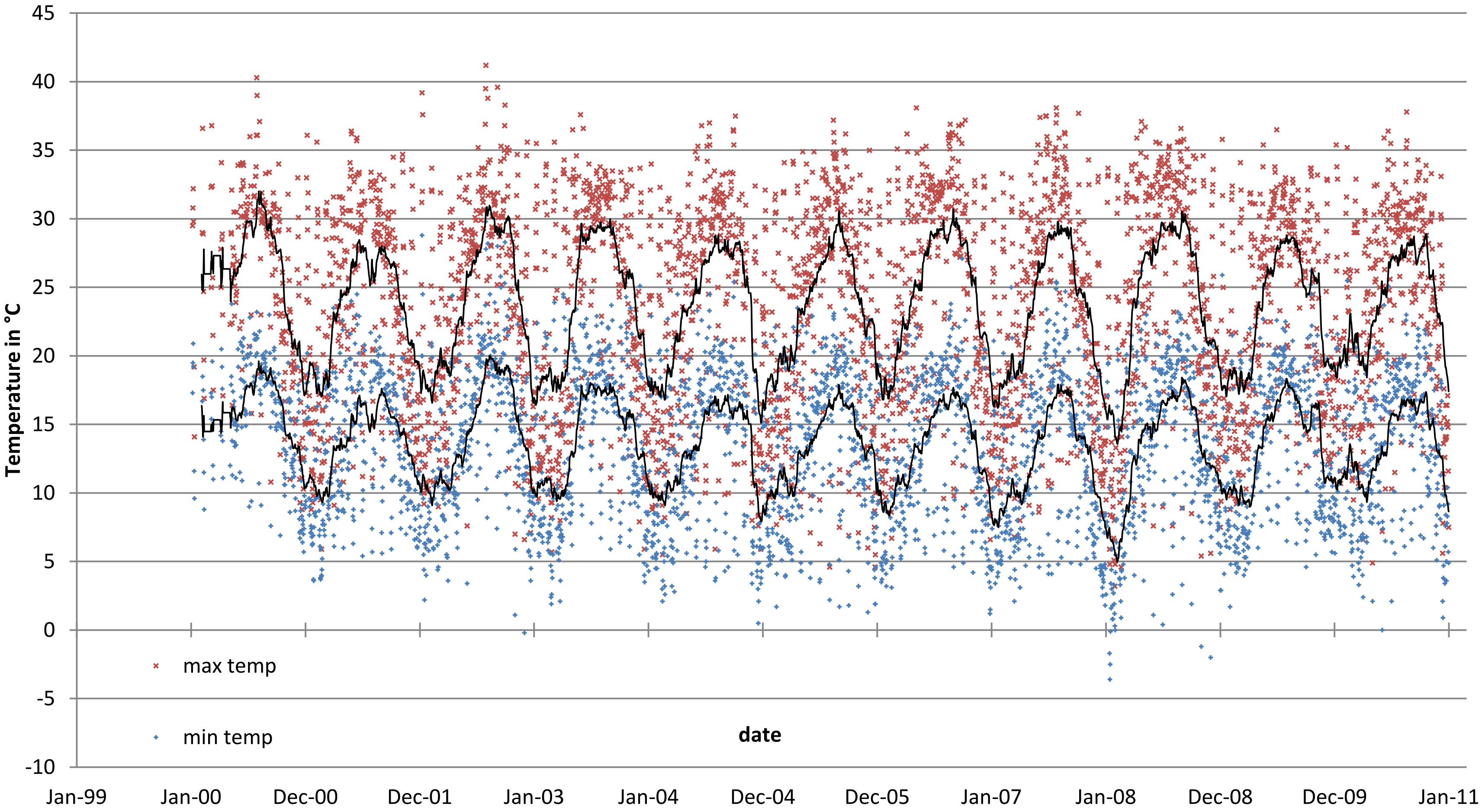

Figure 20: Maximum and minimum temperatures at Yatir

I found that the trees exposed to the south have the highest mortality with 18% (Table 6). The second highest is seen in southeastern direction with 16.3%, and the third most towards the southwest with 15%. In sum 49.3% of the dead trees are exposed to southern directions (southeast to southwest), i.e. almost half of the dead trees are located where they are exposed to high irradiation. In contrast to that the sum of the dead trees exposed to northern directions (from northwest to northeast) is only 29%. This is a clear indication that irradiation plays an important role in tree dying and another indication that the evaporative demand (and hence drought) plays a key role in tree mortality. Table 7 shows the same relation with different chosen angels. Evaporative demand plays an important role but only in small scale. The global irradiation doesn't seem to have changed.

Table 6: Dead trees per aspect (8 cardinal directions)

| Cardinal direction | Angle | Dead trees | Area in ha | Dead trees per ha | Percent dead trees per aspect |
|---|---|---|---|---|---|
| **North** | 337.5 – 22.5 | 1650 | 416.7 | 4.0 | 9.2 |
| **Northeast** | 22.5 – 67.5 | 758 | 217.1 | 3.5 | 8.1 |
| **East** | 67.5 - 112.5 | 782 | 176.1 | 4.4 | 10.3 |
| **Southeast** | 112.5 - 157.5 | 2376 | 336.8 | 7.1 | 16.3 |
| **South** | 157.5 - 202.5 | 3436 | 443.1 | 7.8 | 18.0 |
| **Southwest** | 202.5 - 247.5 | 3453 | 531.6 | 6.5 | 15.0 |
| **West** | 247.5 - 292.5 | 2650 | 536.7 | 4.9 | 11.4 |
| **Northwest** | 292.5 – 337.5 | 3203 | 636.6 | 5.0 | 11.7 |
| | | | | | |
| **sum** | | **18308** | **3294.8** | **43.2** | **100.0** |

Table 7: Dead trees per aspect (4 cardinal directions)

| Aspect | Dead trees | Area in ha | Dead trees per hectare | Percentage |
|---|---|---|---|---|
| **NW - NE = 315-45°** | 3667 | 858.8 | 4.3 | 19.6 |
| **NE - SE = 45° - 135°** | 1966 | 413.4 | 4.8 | 21.8 |
| **SE - SW = 135° - 225°** | 6775 | 896.9 | 7.6 | 34.6 |
| **SW - NW = 225° - 315°** | 5900 | 1125.8 | 5.2 | 24.0 |
| | | | | |
| **sum** | **18308** | **3294.9** | **21.8** | **100.0** |

Table 8 shows the inclination of the hills and the percent of dead trees, standardized with the area per slope. The steepest inclination shows the highest mortality. This may be a response to the runoff behaviour on a steep surface: Either the rain runs off the surface of the hill and won't infiltrate, or it will infiltrate but then move downhill as subsurface flow.

Table 8: Dead trees per degree of hill slope

| Inclination % | Inclination | dead trees | area in ha | dead trees per hectare |
|---|---|---|---|---|
| **0-2%** | Flat | 103 | 37.1 | 2.8 |
| **2-9%** | Slightly inclined | 2728 | 660.8 | 4.1 |
| **9-18%** | Moderate inclined | 8588 | 1525.3 | 5.6 |
| **18-36%** | Strong inclined | 6822 | 1042.5 | 6.5 |
| **36-58%** | Steep | 66 | 29.1 | 2.3 |

Note that the latitude of Yatir forest is 33° north. Hence, any slope inclined towards the sun at an angle of up to 33° will lead to an increase in irradiation compared to a flat surface. Any steeper inclination will decrease the irradiation again. If irradiation plays a role in tree deaths, the number of dead trees should increase up to this angle and then decrease again. This is precisely what Table 8 shows. The rather low percentage of dead trees at an inclination of 36-58% is probably due in part to the fact, too, that there were fewer trees in the first place.

Table 9 combines hill slope and exposition. While the exposition in northern direction doesn't make a difference, in the southern aspect the mortality rises to almost twice as much.

Table 9: Dead trees per exposition and hill slope

| exposed to | dead trees | area in ha | dead trees/ha |
|---|---|---|---|
| **north (337.5-22.5°) & slope > 9%** | 2739 | 621.6 | 4.4 |
| **north (337.5-22.5°) & slope > 18%** | 1157 | 264.9 | 4.4 |
| | | | |
| **south (157.5 - 202.5°) & slope > 9%** | 6917 | 1011.6 | 6.8 |
| **south (157.5 - 202.5°) & slope > 18%** | 2308 | 212.9 | 10.8 |

## 5.5 Soil water storage

The Weizmann institute took some soil samples and determined the particle size distribution. With the help of the German soil survey guideline (Bodenkundliche Kartieranleitung 5 = KA5; SPONAGEL, 2005) I derived the water holding capacity of the soils in the plots. This procedure is not very accurate, because I couldn't consider the soil density for there are no data available.

The soil texture from 14 of 21 samples shows, according to KA5, the soil type loam clay (Lt3) with a saturated water content of 43 Vol.%, but since there are also stones in the soil, the actual saturated water content is probably lower than 43%. The remaining plots have either 42% or also 43% saturated water content, but a different soil type.

16 out of 21 plots have a field capacity between 30-41 vol. % (of the remaining ones: min = 29%; max = 39%) while field capacity minus permanent wilting point in these plots is 12 – 14 vol.%. The values for the remaining plots are between a maximum of 21 vol.% and a minimum of 12 vol.%.

**Rooting depths and stoniness**

KKL and the Weizmann group analyzed the rooting depth and the stoniness in their project to identify reasons for tree mortality (PREISLER *et al.*, 2012). The main results were that the root density in plots with more dead trees is sparser than in plots with more live trees. The major part of the roots is between 0-40cm, below 60 cm there are only very few roots. The stoniness of the soils was higher in live plots than in dead plots. On average the soils in live plots are not as deep as the soils in dead plots. 100% stoniness, i.e. bedrock, is often reached after 80-100cm in live plots, but in dead plots only two reached a stoniness of 100%, while other plots had a stoniness below 50% in 1.60m depth. This result raises more questions than it answers. Maybe the soils with shallower bedrock prevent the water from seeping out of the root zone and thus make more water plant available.

Now I want to elaborate briefly the stoniness within the soils and the depth to bedrock, which is illustrated in Figure 21 and Figure 22.

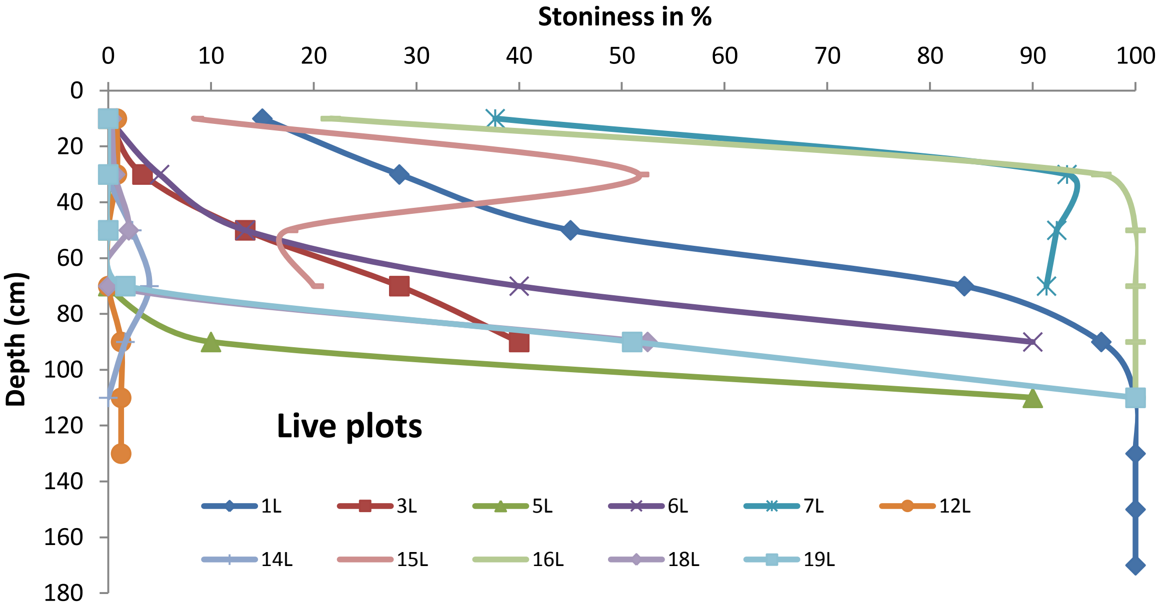

Figure 21: Course of stoniness with depth in live plots (source: WIS soil survey as described in Yakir et al. 2012)

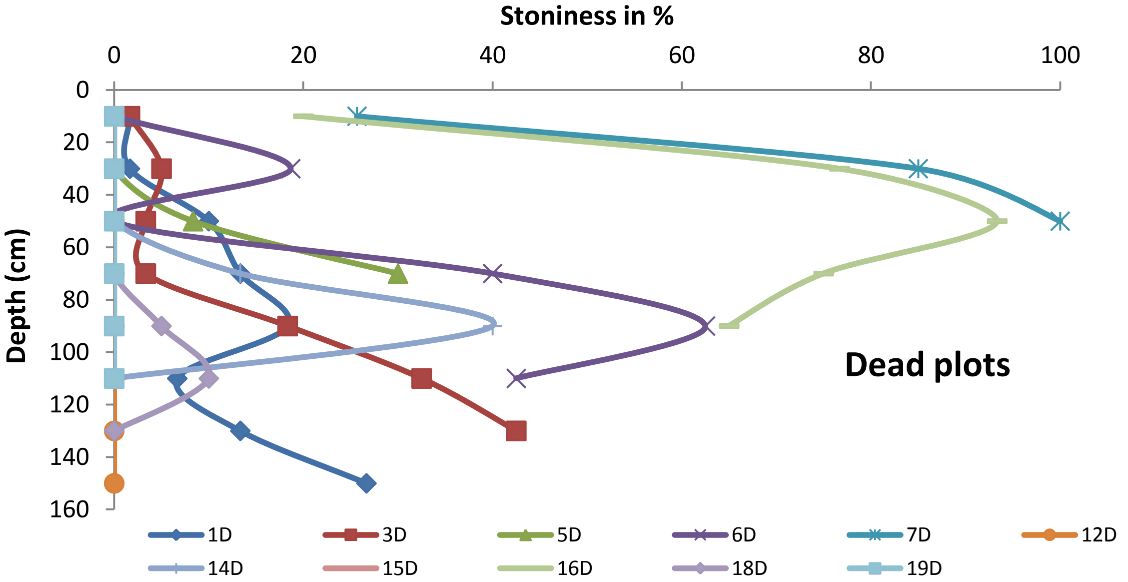

Figure 22: course of stoniness over the depth in dead plots (source: WIS soil survey PREISLER *et al.*, 2012)

In Figure 21 and Figure 22 one can see that in the live plots the bedrock is in lower depths than in the dead plots. It is possible that the shallower bedrock hinders water seepage into deeper zones and despite less rooting space the fallen precipitation could be better available for plants in a soil with less thickness.

The average rooting depth in live plots was 98cm and in dead plots 104 cm (Table 10).

Table 10: Depth of deepest roots (in cm) (source: Soil survey WIS)

| plot | live | dead |
|---|---|---|
| **1** | 100 | 160 |
| **3** | 100 | 140 |
| **5** | 120 | 80 |
| **6** | 100 | 120 |
| **7** | 80 | 40 |
| **12** | 140 | 140 |
| **14** | 120 | 100 |
| **15** | 80 | 80 |
| **16** | 40 | 40 |
| **18** | 100 | 140 |
| **19** | 100 | 100 |
| | | |
| **avg.** | 98.2 | 103.6 |

With this data I can calculate the volume of plant available water within the root zone ($paw_{rd}$):

$$paw_{rd} = (field\ capacity - permanent\ wilting\ point) \cdot rooting\ depth$$

Figure 23 shows the $paw_{rd}$ against the ratio of live trees per dead trees. The amount of live trees per dead trees seems to be the appropriate variable here. The amount of living trees and the density does not need to be necessarily related with $paw_{rd}$, it can also result from thinning or other reasons. However, the ratio of living trees per dead trees is free from these initial factors and shows the change due to the mortality only.

In the live as in the dead plots the increase of $paw_{rd}$ has a positive effect on the trees, although the effect is very week.

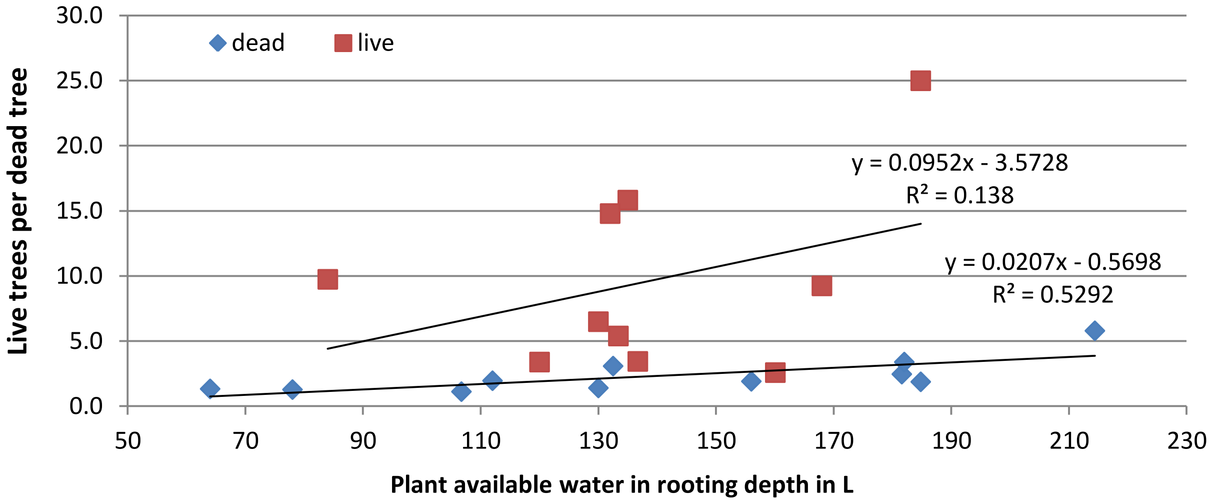

**Figure 23: Plant available water in the root zone (field capacity minus permanent wilting point times rooting depth) versus amount of live trees per dead trees.**

### 5.5.1 Calculated soil water content

In the following I tried to combine all information about precipitation, evaporation, soil depth, available field capacity and rooting depth. Unfortunately there is not enough information available to create this model with a spatial resolution. Hence, it is simplified to show the influence of evapotranspiration and precipitation on soil water content.

I calculated:

$$\theta_d = \theta_{\ d-1} - ET_d + P_d$$

Where

$\theta_d$= soil water content day d

$\theta_{\ d-1}$= soil water content on previous day

$ET_d$ = Evapotranspiration on day d

$P_d$ = precipitation amount on day d

The soil is not able to take up all water. That's why I set a maximum value of 350 liter per m$^2$, according to the saturated water content (c.f. 5.5). This corresponds to a rooting depth of 1m and a field capacity of approximately 35 Vol. % (i.e. 350 $L/m^2$ for a rooting depth of 1m). The result is shown in Figure 24.

If $\theta_d$ exceeded 350 L, the soil water content didn't increase further. The excess water will leave the system as deep percolation. 350 L were assumed as field capacity in 1m depth (ergo $paw_{rd}$ + pwp). Figure 24 shows the results. $\theta_{\ d-1}$ for the first day of calculation was set to 100 L.

With this simple model one can see a minimum soil water content at the end of 2009. Something similar occurred 5 years before, too, with the difference that since 2004 the soil hasn't been saturated anymore. This indicates that plants did not have enough water for 5 years. The dying and the drought in 2009 could be the straw that broke the camel's back. I could only investigate the last 10 years before the mortality in 2010 occurred. So I cannot say if something similar happened earlier too.

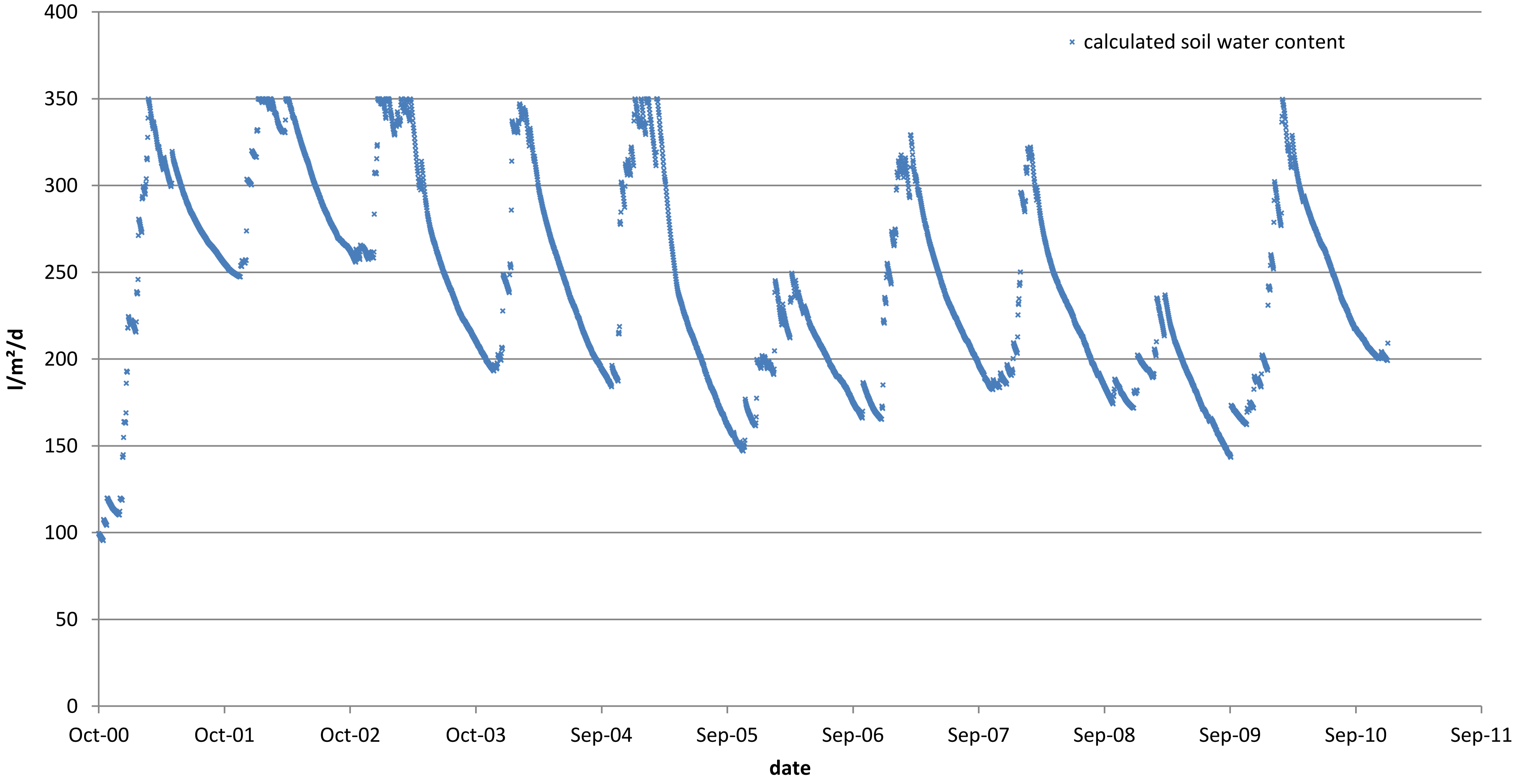

**Figure 24: Calculated soil water content. Further explanations can be found in this section.**

### 5.5.2 Salinity

Table 11 and Table 12 summarize the salinity values of the soil survey which was conducted by the Weizmann group. I calculated the osmotic pressure π to estimate the effect that salts will have on the water budget of the trees.

Table 11: Summary of salinity features in live plots

| Live plot | EC | Estimated π in hPa | Na (mmol/L) | Ca + Mg (mmol/L) | SAR |
|---|---|---|---|---|---|
| L1 | 1.52 | 376.6 | 4.49 | 5.18 | 1.97 |
| L1 | 1.74 | 431.1 | 8.29 | 4.34 | 3.98 |
| L16 | 0.60 | 148.7 | 1.74 | 2.30 | 1.15 |
| L16 | 1.15 | 284.9 | 4.84 | 3.13 | 2.74 |
| L16 | 0.95 | 235.4 | 6.55 | 1.38 | 5.59 |
| L16 | 1.10 | 272.5 | 8.76 | 1.24 | 7.87 |
| L16 | 1.36 | 337.0 | 11.02 | 1.32 | 9.61 |
| L20 | 0.58 | 143.7 | 1.54 | 2.45 | 0.98 |
| L20 | 0.72 | 178.4 | 2.43 | 2.50 | 1.54 |
| L20 | 2.67 | 661.5 | 8.06 | 10.00 | 2.55 |
| L20 | 1.33 | 329.5 | 4.00 | 4.60 | 1.87 |
| L25 | 2.47 | 612.0 | 6.76 | 10.20 | 2.12 |
| L29 | 0.85 | 210.6 | 1.85 | 3.98 | 0.93 |
| L29 | 0.65 | 161.1 | 2.07 | 2.35 | 1.35 |
| L29 | 0.91 | 225.5 | 2.96 | 2.98 | 1.72 |
| L3 | 0.83 | 205.6 | 2.07 | 2.88 | 1.22 |
| L3 | 0.78 | 193.3 | 2.31 | 2.36 | 1.50 |
| L30 | 0.36 | 89.2 | 1.08 | 1.25 | 0.97 |
| L30 | 0.96 | 237.9 | 5.20 | 1.94 | 3.74 |
| L30 | 1.40 | 346.9 | 11.02 | 1.45 | 9.15 |
| L30 | 1.85 | 458.4 | 14.79 | 1.85 | 10.87 |
| L30 | 2.05 | 507.9 | 14.79 | 3.10 | 8.40 |
| L7 | 0.67 | 166.0 | 1.54 | 2.39 | 1.00 |
| L7 | 1.35 | 334.5 | 3.38 | 4.53 | 1.59 |
| L7 | 0.86 | 213.1 | 3.84 | 2.06 | 2.68 |
| L9 | 0.49 | 121.4 | 1.08 | 1.87 | 0.79 |
| L9 Ø | 0.65 | 161.1 | 1.96 | 2.37 | 1.27 |
| L9 | 1.97 | 488.1 | 6.76 | 5.76 | 2.82 |
|  | **1.17** | **290.4** | **5.19** | **3.28** | **3.28** |
| **Std. dev.** | **0.6** | **149.5** | **4.0** | **2.3** | **3.0** |

Table 12: Summary of salinity features in dead plots

| Dead plot | EC | Estimated π in hPa | Na (mmol/L) | Ca + Mg (mmol/L) | SAR |
|---|---|---|---|---|---|
| D1 | 0.42 | 104.1 | 0.46 | 1.73 | 0.35 |
| D1 | 0.40 | 99.1 | 0.85 | 1.44 | 0.71 |
| D1 | 0.49 | 121.4 | 2.07 | 1.29 | 1.82 |
| D1 | 0.80 | 198.2 | 3.84 | 1.92 | 2.77 |
| D1 | 0.77 | 190.8 | 4.00 | 1.64 | 3.12 |
| D11 | 0.37 | 91.7 | 0.46 | 1.70 | 0.35 |
| D16 | 0.36 | 89.2 | 0.52 | 1.44 | 0.43 |
| D16 | 0.62 | 153.6 | 2.96 | 1.58 | 2.35 |
| D16 | 0.48 | 118.9 | 1.25 | 1.62 | 0.98 |
| D16 | 0.83 | 205.6 | 5.95 | 1.42 | 4.99 |
| D16 | 0.69 | 171.0 | 2.69 | 1.97 | 1.92 |
| D16 | 3.38 | 837.5 | 24.22 | 3.75 | 12.51 |
| D16 | 0.93 | 230.4 | 3.38 | 2.83 | 2.01 |
| D16 | 4.59 | 1137.3 | 33.86 | 5.97 | 13.86 |
| D16 | 5.17 | 1281.0 | 38.93 | 6.57 | 15.19 |
| D19 | 0.32 | 79.3 | 0.46 | 1.42 | 0.39 |
| D19 | 0.32 | 79.3 | 0.64 | 1.08 | 0.62 |
| D19 | 0.55 | 136.3 | 2.31 | 1.34 | 2.00 |
| D19 | 0.62 | 153.6 | 3.53 | 1.12 | 3.34 |
| D20 | 0.68 | 168.5 | 2.56 | 2.14 | 1.75 |
| D20 | 0.81 | 200.7 | 2.07 | 3.23 | 1.15 |
| D20 | 0.69 | 171.0 | 1.44 | 2.70 | 0.88 |
| D25 | 0.52 | 128.8 | 0.92 | 2.30 | 0.61 |
| D25 | 1.32 | 327.1 | 4.66 | 4.40 | 2.22 |
| D29 | 0.58 | 143.7 | 1.08 | 2.38 | 0.70 |
| D29 | 0.87 | 215.6 | 1.85 | 3.53 | 0.99 |
| D29 | 0.62 | 153.6 | 2.31 | 1.67 | 1.79 |
| D29 | 0.85 | 210.6 | 4.16 | 2.07 | 2.89 |
| D3 | 0.64 | 158.6 | 1.64 | 2.35 | 1.07 |
| D3 | 0.84 | 208.1 | 3.84 | 2.24 | 2.57 |
| D3 | 1.74 | 431.1 | 10.76 | 3.49 | 5.76 |
| D3 | 1.47 | 364.2 | 11.29 | 1.82 | 8.37 |
| D30 | 0.34 | 84.2 | 0.71 | 1.32 | 0.62 |
| D30 | 0.49 | 121.4 | 1.25 | 1.55 | 1.00 |
| D30 | 0.43 | 106.5 | 1.64 | 1.09 | 1.57 |
| D7 | 0.60 | 148.7 | 1.74 | 2.24 | 1.16 |
| D7 | 0.88 | 218.0 | 4.49 | 2.20 | 3.03 |
| D9 | 1.24 | 307.2 | 6.35 | 2.65 | 3.90 |
| Ø D9 | 1.19 | 294.8 | 5.95 | 2.56 | 3.72 |
|  | **1.00** | **247.2** | **5.21** | **2.30** | **2.96** |
| **Std. dev.** | **1.1** | **262.8** | **8.5** | **1.2** | **3.6** |

# Live plots

Table 13: Overview of live plot properties

| Plot | EC | Na (mmol/L) | Ca + Mg (mmol/L) | SAR | Sand % | Silt % | Clay % | Plant available water (vol.%) | Dead trees | Dead trees/ dunam | Density | Density/ dunam | Live trees / dead trees |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 1.6 | 6.4 | 4.8 | 3.0 | 18.1 | 42.4 | 39.5 | 13.0 | 6.0 | 4.6 | 95.0 | 73.3 | 15.8 |
| **3** | 0.8 | 2.2 | 2.6 | 1.4 | 13.1 | 45.4 | 41.5 | 12.0 | 6.0 | 3.8 | 39.0 | 24.8 | 6.5 |
| **7** | 1.0 | 2.9 | 3.0 | 1.8 | 17.1 | 43.9 | 39.0 | 12.7 | 22.0 | 14.4 | 57.0 | 37.2 | 2.6 |
| **9** | 1.0 | 3.3 | 3.3 | 1.6 | 23.5 | 43.9 | 32.7 | 13.3 | 20.0 | 11.8 | 69.0 | 40.7 | 3.5 |
| **11** | | | | | 65.3 | 32.7 | 2.0 | 21.0 | 8.0 | 4.0 | 74.0 | 37.0 | 9.3 |
| **16** | 1.0 | 6.6 | 1.9 | 5.4 | 17.3 | 43.1 | 39.6 | 12.4 | 1.0 | 1.0 | 25.0 | 25.1 | 25.0 |
| **19** | | | | | | | | | 7.0 | 8.6 | 57.0 | 69.7 | 8.1 |
| **20** | 1.3 | 4.0 | 4.9 | 1.7 | 30.1 | 42.2 | 27.8 | 15.0 | 18.0 | 11.7 | 61.0 | 39.8 | 2.8 |
| **25** | 2.5 | 6.8 | 10.2 | 2.1 | 39.3 | 47.7 | 13.0 | 21.0 | 4.0 | 6.4 | 39.0 | 62.3 | 9.8 |
| **29** | 0.8 | 2.3 | 3.1 | 1.3 | 22.9 | 42.1 | 35.0 | 12.7 | 10.0 | 7.6 | 54.0 | 41.0 | 5.4 |
| **30** | 1.3 | 9.4 | 1.9 | 6.6 | 14.1 | 46.1 | 39.8 | 12.4 | 5.0 | 2.7 | 74.0 | 39.5 | 14.8 |
| | | | | | | | | | | | | | |
| **Correlation to dead trees** | -0.1 | -0.6 | 0.1 | -0.7 | 0.0 | 0.1 | 0.0 | -0.1 | | | | | |
| **Correlation to live tree per dead tree** | 0.2 | 0.7 | -0.2 | 0.8 | -0.1 | 0.0 | 0.2 | -0.1 | | | | | |
| **Correlation to density** | 0.7 | 0.3 | 0.7 | -0.1 | 0.1 | 0.1 | -0.2 | 0.3 | | | | | |

## Dead Plots

Table 14: Overview of dead plot properties

| Plot | EC | Na (mmol/L) | Ca + Mg (mmol/L) | SAR | Sand % | Silt % | Clay % | Plant available water (vol %) | Dead trees | Dead trees/ dunam | Density | Density/ dunam | Live trees / dead trees |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 0.6 | 2.2 | 1.6 | 1.8 | 17.7 | 42.9 | 39.4 | 12.8 | 10.0 | 12.4 | 58.0 | 72.0 | 5.8 |
| **3** | 1.2 | 7.4 | 2.3 | 5.1 | 15.7 | 43.7 | 40.6 | 12.4 | 34.0 | 11.4 | 64.0 | 21.5 | 1.9 |
| **7** | 0.7 | 3.1 | 2.2 | 2.1 | 23.3 | 46.7 | 30.0 | 14.0 | 31.0 | 12.3 | 61.0 | 24.3 | 2.0 |
| **9** | 1.2 | 6.2 | 2.6 | 3.8 | 16.1 | 43.9 | 40.0 | 12.0 | 25.0 | 21.5 | 48.0 | 41.2 | 1.9 |
| **11** | 0.4 | 0.5 | 1.7 | 0.4 | 32.3 | 46.7 | 21.0 | 16.0 | 50.0 | 19.0 | 67.0 | 25.5 | 1.3 |
| **16** | 1.9 | 12.6 | 3.0 | 6.0 | 15.0 | 43.3 | 41.7 | 12.0 | 17.0 | 13.4 | 42.0 | 33.1 | 2.5 |
| **19** | 0.5 | 1.7 | 1.2 | 1.6 | 20.2 | 43.5 | 36.3 | 12.5 | 33.0 | 15.3 | 102.0 | 47.2 | 3.1 |
| **20** | 0.7 | 2.0 | 2.7 | 1.3 | 15.8 | 45.2 | 39.0 | 12.7 | 39.0 | 28.3 | 44.0 | 31.9 | 1.1 |
| **25** | 0.9 | 2.8 | 3.4 | 1.4 | 47.6 | 40.4 | 12.0 | 19.5 | 14.0 | 13.7 | 18.0 | 17.6 | 1.3 |
| **29** | 0.7 | 2.4 | 2.4 | 1.6 | 21.3 | 41.2 | 37.5 | 12.0 | 20.0 | 14.2 | 68.0 | 48.3 | 3.4 |
| **30** | 0.4 | 1.2 | 1.3 | 1.1 | 15.9 | 42.8 | 41.3 | 12.0 | 34.0 | 31.3 | 48.0 | 44.2 | 1.4 |
| **Correlation to dead trees** | -0.3 | -0.3 | -0.2 | -0.4 | -0.2 | 0.2 | 0.2 | -0.2 | | | | | |
| **Correlation to live tree per dead tree** | -0.1 | 0.0 | -0.3 | 0.0 | -0.3 | -0.3 | 0.3 | -0.3 | | | | | |
| **Correlation to density** | -0.3 | -0.2 | -0.5 | -0.2 | -0.5 | -0.3 | 0.5 | -0.5 | | | | | |

The average EC and the average SAR value in the live plots are higher than in the dead plots, but the difference in EC amounts to only 30 hPa. However, the difference within the plots seems to be greater than between the plots. In plot D16 for example we find a very low EC (0.36 dS/m) and also the highest electrical conductivity (5.17 dS/m). For plot D11 only one sample is available and for some other plots (like L1, L3, D7, D9) only two.

Table 13 and Table 14 show characteristic features of each plot. The data represent the arithmetic mean of features per plot. In the field "dead trees" I used the values I could see visually on aerial photographs, not the ones which were derived with the algorithm. Likewise, I counted the density in aerial photographs.

If one correlates the amount of dead trees and the density with salinity characteristics, one can see some correlations in the live plots, but not in the dead plots.

Figure 25 shows the sodium concentration and the amount of live trees per dead tree. It is conspicuous that in all dead plots the ratio live tree per dead tree is about 1 – 3 while it differs stronger in the live plots. The sodium soil concentration is obviously not related to the ratio live trees per dead trees. But in the live tree plots one can see a small coherence: The more sodium in the soil, the more live trees are found per dead tree. This means: the more sodium in a soil, the less dead trees can be found.

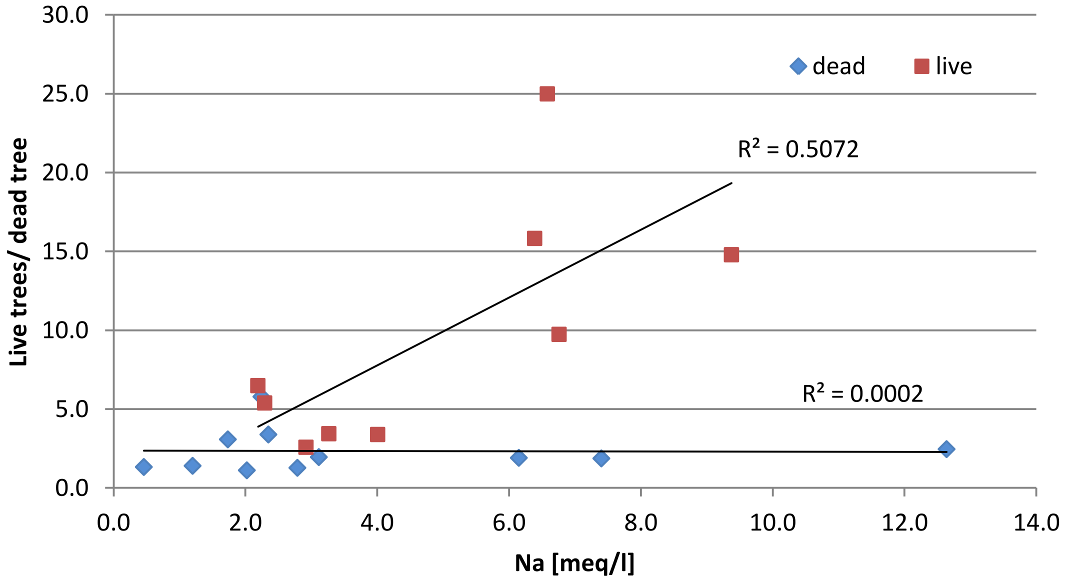

Figure 25: Sodium concentration in the soil in dead and live plots against living trees per dead tree

A possible explanation for the high correlation of live trees/dead trees to sodium (that means the more sodium in the soil the less dead trees, cf. Figure 25) could be that sodium is soluble in water. It could leach out in some plots and then accumulate in lower regions. That way the actual process which leads to a positive effect is not more salt, but more water. This could be verified with a hydraulic tracer test. The sodium itself is unlikely to have an influence on the plants here, since the maximum osmotic pressure caused by sodium is only 100 kPa (1bar), which is less than 5% of what the root is exposed to in the dry season.

Figure 26 show the mentioned positive effect for the trees with increasing sodium concentration in a different way as Figure 25 did. The correlation isn't very strong, but one can see that the amount of dead trees per dunam decreases as sodium concentration increase.

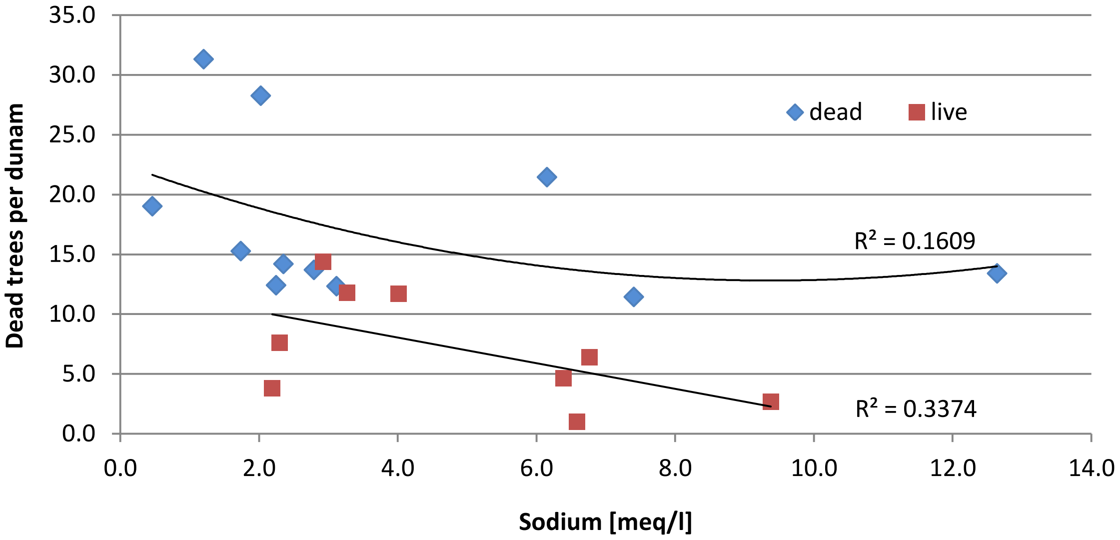

Figure 26: Sodium concentration vs. dead trees per Dunam

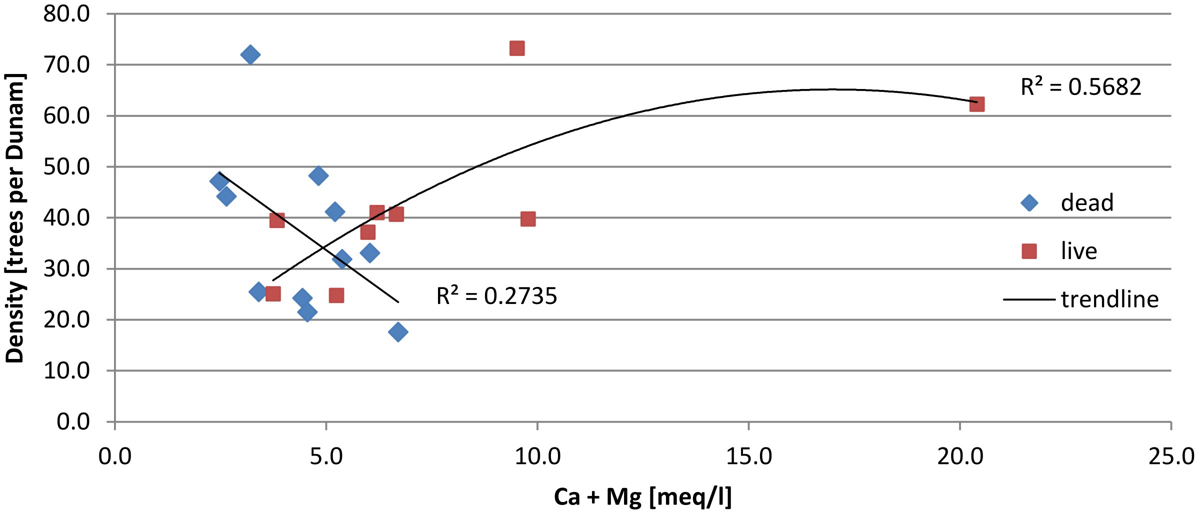

Figure 27 shows the magnesium and calcium concentration in the soils of each plot with the density that I could derive from aerial images. The question arises, if there is indeed a visible connection or if the point at 20meq/l is just an outlier that causes the high coefficient of determination.

Figure 27: Calcium and Magnesium concentration vs. density (derived from aerial photographs)

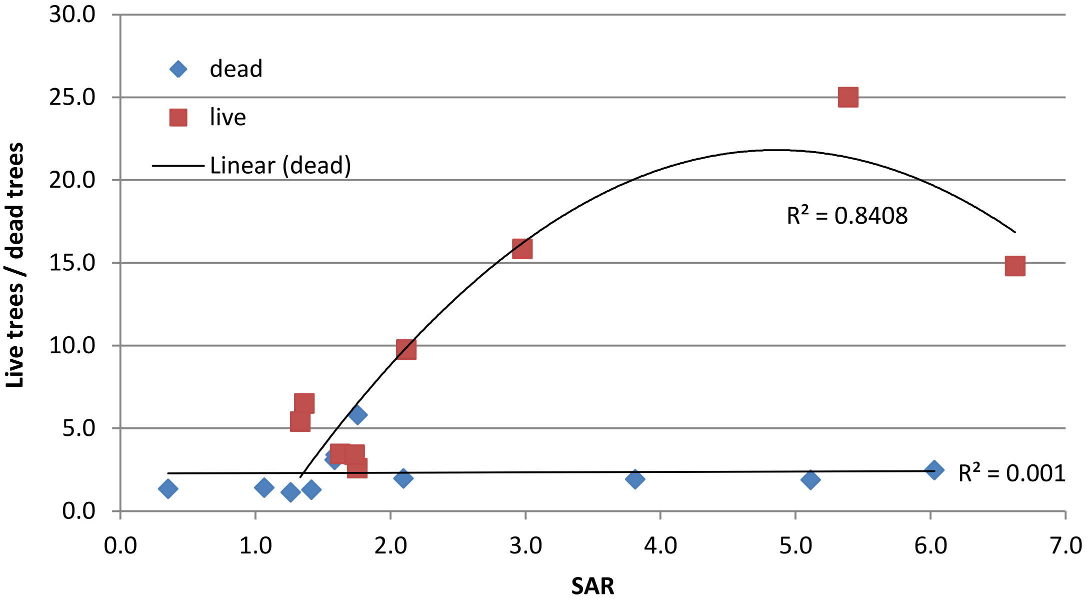

Figure 28: SAR values vs. living trees per dead trees

Figure 28 shows a strong correlation in the live Plots between SAR and the ratio live trees per dead trees. However, it is likely that there isn't a causal relationship, because there are only eight points available for that calculation. Whether the SAR value affects the soil structure depends on the electrical conductivity of the soil as well. In the "Australian and New Zealand guideline for fresh and marine water quality" a diagram is presented that explains at which EC a given SAR value can cause problems to the soil structure (AGRICULTURE AND RESOURCE MANAGEMENT COUNCIL OF AUSTRALIA AND NEW ZEALAND, AND THE AUSTRALIAN AND NEW ZEALAND ENVIRONMENT AND CONSERVATION COUNCIL, 2000). All SAR and EC combinations at Yatir are below the critical value, except two from the dead plots which are near the threshold of a stable soil structure. This is plot 16L and 30L. But since they have only 1 (16L) or 2.7 (30L) dead trees per dunam, it's unlikely that the SAR influences the soil in a negative way.

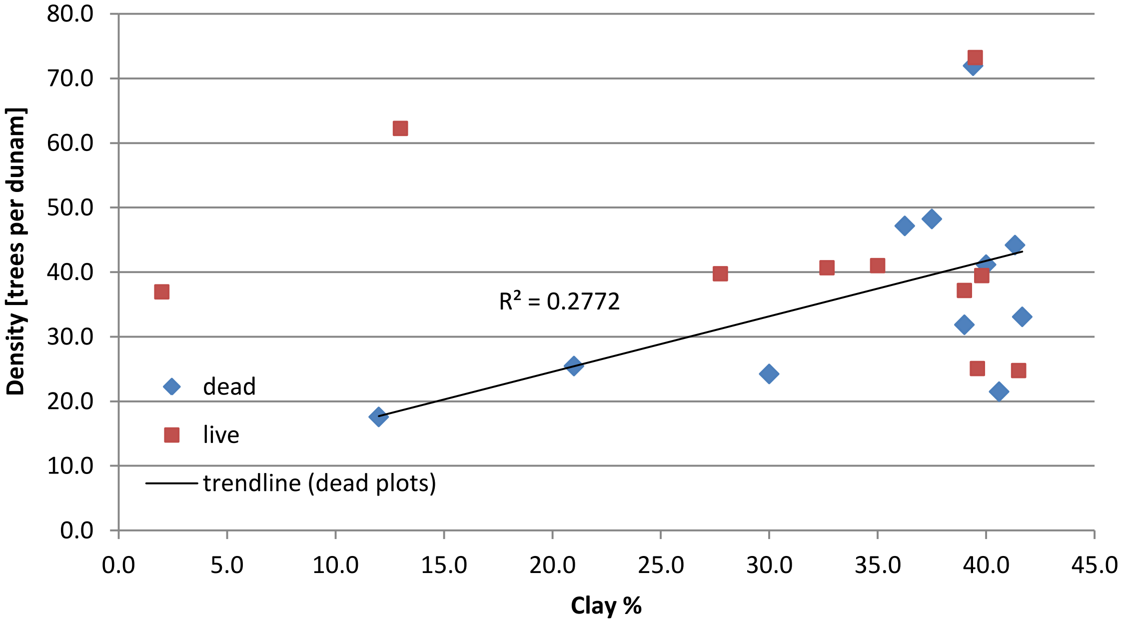

Figure 29: Amount of clay in the soil vs. tree density

Clay has two important properties: First it has a huge surface, so that substances and nutrients can absorb on its surface. If some kind of toxic substances would lead to the tree dying one should see here the first evidence for it. The second important property is that clay holds water very tightly and the plants need to exert more suction to draw water out of the clay. That means more clay in the soil leads to less plant available water. However, in Figure 29 no connection is visible.

## 5.6 Competition

Besides changes in precipitation patterns the development of total stand biomass is a very important factor. Figure 30 shows the development of single tree biomass calculated with KKL inventory data and the allometric equation (GRÜNZWEIG *et al.*, 2007) at different ages. The biomass per tree was calculated as the arithmetic mean of several single measurements from KKL inventories in 2004 and 2007 for the respective stand age. The results for both inventories are pooled in Figure 30.

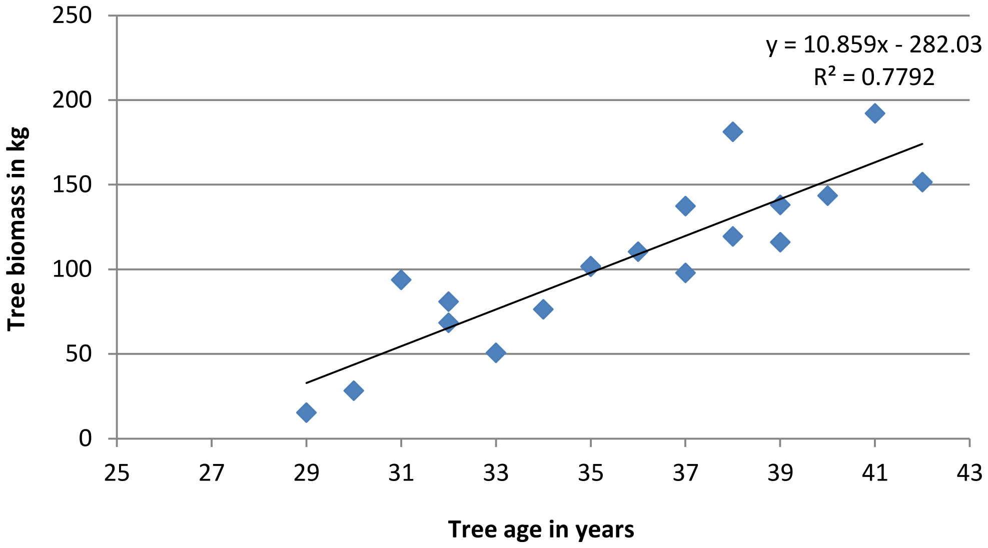

Figure 30: Biomass per tree as a function of tree age

I did the same for stand density per plot (200m$^2$). The results are illustrated in Figure 31.

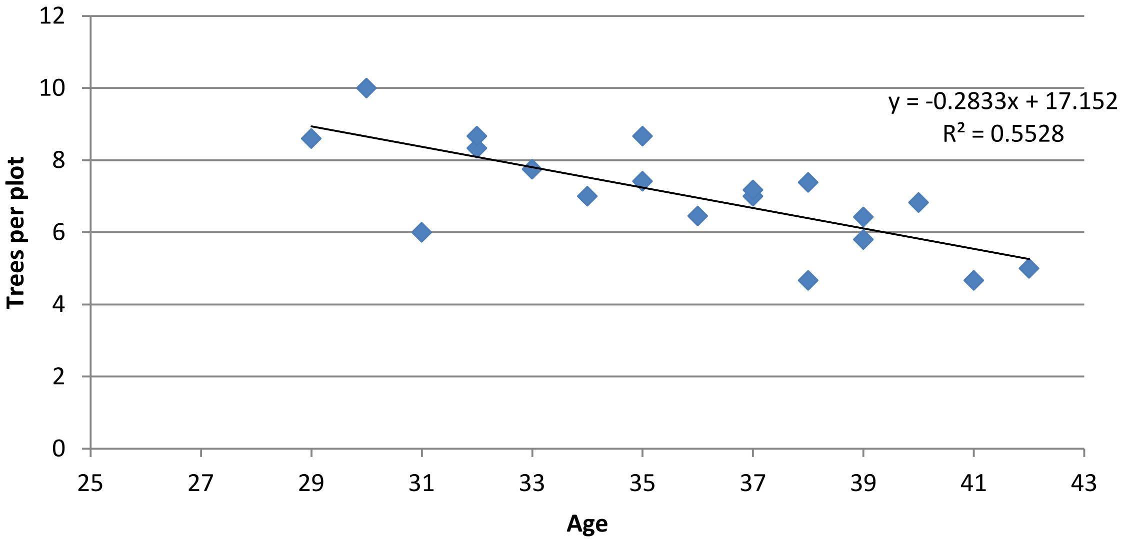

Figure 31: Density per 200m$^2$ plot (KKL inventory 2004 and 2007) as a function of stand age

If one multiplies the density per plot with the biomass per single tree one obtains the biomass per plot. This is illustrated in Figure 32. It is remarkable that the density per plot seems to stagnate at the age of 40 and seems to reach its maximum at this age, too.

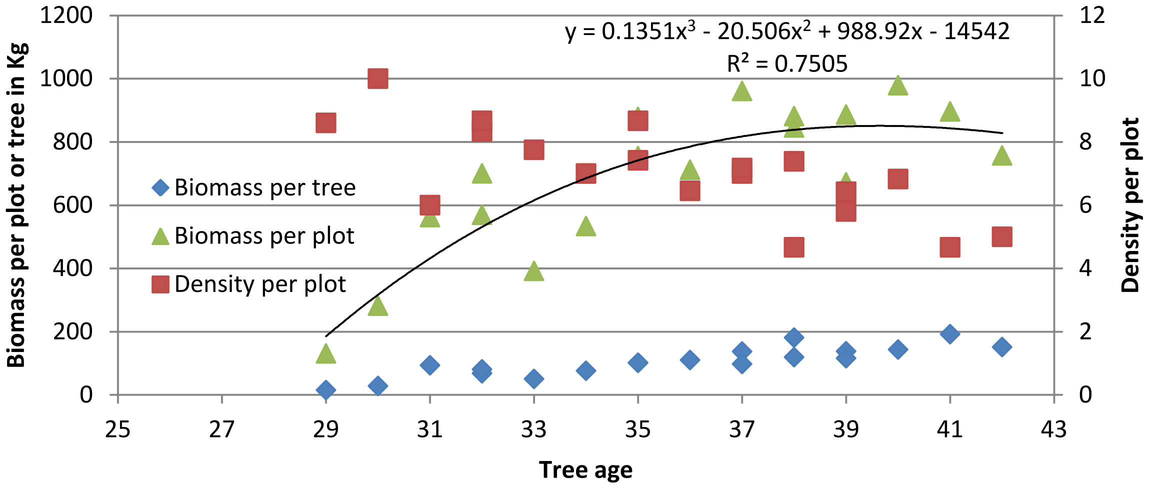

Figure 32: Density per plot, biomass per single tree and biomass per plot

In each figure from Figure 30 to Figure 32 I could fit a function. Figure 33 shows the idealized effect calculated with the fitted functions above-mentioned. The biomass in each plot seems to approach to 1 ton per plot, this means 5 t per dunam or 50 t per ha.

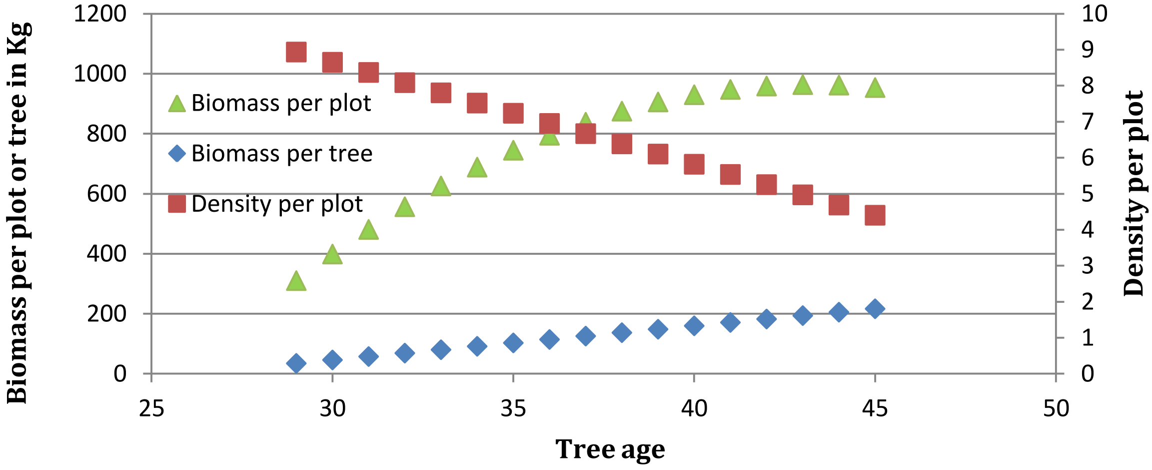

Figure 33: Calculated biomass and density as a function of stand age

Figure 34 shows a hypothetical development of a stand and its water supply. It is not the measured biomass development on a specific site, but an assumed development on the basis of the inventory data from 2004 and 2007. The youngest stand in this inventory data was 29 years old and the oldest 45 years, that's why I set the initial point here to 1994 (29 years old) and the end point to 2010 (45 years old). The precipitation per year, in contrast, is the measured one. The biomass per plot is the function I could derive from Figure 32 and idealizes the stand biomass development.

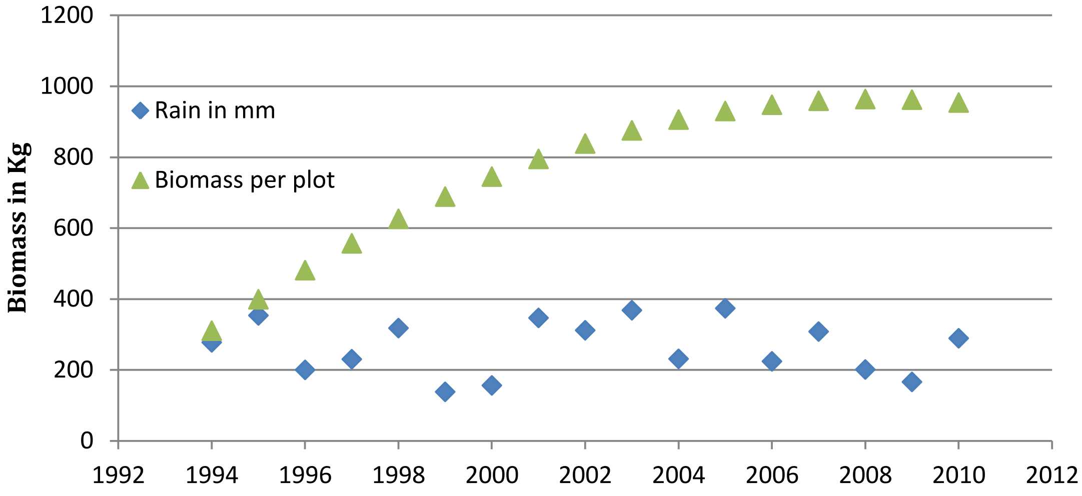

Figure 34: Biomass per plot as a function of time and annual precipitation in Yatir forest

Figure 35 shows the annual precipitation divided by the biomass per plot, which has been derived from the forest inventory in 2004 and 2007 (that means the shown biomass per plot equals not the actual biomass to the corresponding years, it is only an assumption). It is clearly visible, that the curve shows an asymptotic development with increasing age. Figure 36 shows the time course of the biomass per plot and of the water per biomass computed from the regression equations. The figure suggests that the average precipitation amount in Yatir of 279mm is just enough to sustain the biomass for a 40year old stand. The biomass does not increase after the age of 40 years.

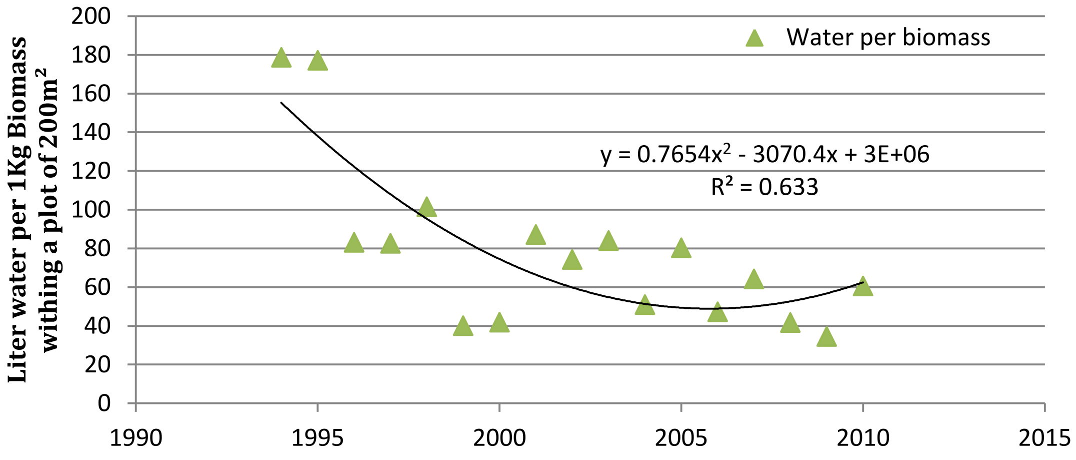

Figure 35: Theoretical water that 1Kg biomass receives within a 200m² plot. The biomass per plot grows but the average precipitation stays equal.

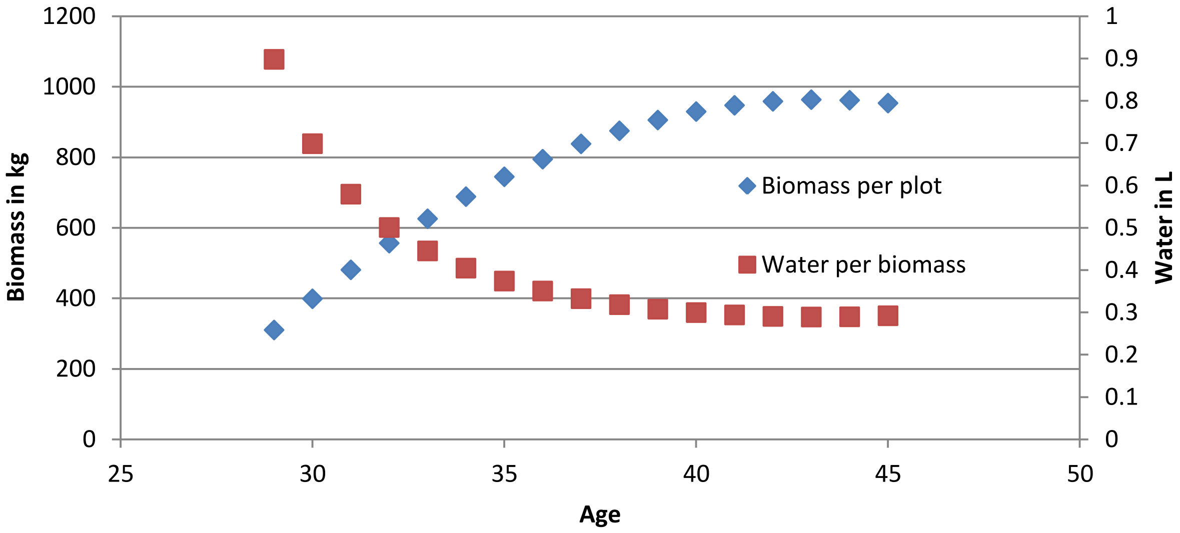

Figure 36: Biomass per plot and average precipitation divided by biomass against stand age at Yatir

The theory that the stand density and biomass have a great impact on mortality is also confirmed if one analyzes the amount of dead trees per stand age.

Table 15 shows that almost half of the area is vegetated with trees that were 2010 older than 35 year. On this area 77% of the trees died. Only 27% of the forested area is covered with trees older than 40 but dead trees in this age counted 57% of the total mortality. This is a strong indication that the stand is too dense and as a consequence of drought a natural shrinkage is induced. The basis for this investigation was the dead tree layer.

Table 15: Distribution of dead trees above various ages

| | Area in ha | Area in % | Amount of dead trees | Percentage dead trees |
|---|---|---|---|---|
| **older than 35** | 1795.9 | 54.8 | 14233 | 77.7 |
| **older than 40** | 896.8 | 27.4 | 10426 | 56.9 |
| **total** | 3276.4 | 100 | 18317 | 100 |

# 6 Discussion

## 6.1 Spatial distribution of dead trees and soil features

The hotspot analysis shows that the distance between the chosen dead and live plots is not optimal, it is too small. The live plots are mostly within the calculated hotspots, so it is obvious that one cannot find a big difference between live and dead plots. This was confirmed with the statistical analysis of soil properties that showed no significant difference between dead and live plots, except in the electrical conductivity and (depending on the test) in the Mg + Ca concentration.

Anyway, the results of soil characteristics correlated with stand parameters showed no correlation with soil particle size, but partly a high correlation with salt characteristics, at least in the live plots, whereas in the dead plots no high correlation t with any characteristic could be found.

Aleppo pine growth best on neutral or alkaline soils with a pH of 6 to 7.5 (PANETSOS, 1994-2008; C.A.B. INTERNATIONAL, 2002). Higher Ca + Mg value are most likely related to a higher soil pH value were Aleppo pine grows better. Since the Mann Whitney-U test showed only a significant difference in EC and Mg + Ca in dead and live plots. This in turn may be a result of different pH-values. Especially mycorrhiza are sensitive to soil pH (CASARIN *et al.*, 2004). Mycorrhiza is an important topic that should be investigated further.

The analysis of the soil parameter here does not suffice to explain the different mortality intensities in dead and live plots. The *Morans I* analysis showed a clustering effect on a small scale. The salinity parameters and the soil texture are dismissed as an explanation. Other explanations for small scale clustering that is related to soil properties are the rooting depth and the stoniness. Figure 21 and Figure 22 showed the course of stoniness in live and dead plots. It is conspicuous that in the live plots 6 of 11 reach a stoniness from more than 80% while only two of the dead plots did. It could be that the early beginning of rock hinders water seepage into deeper zones, which would be lost for the trees. But In this thesis I can’t give an answer to that due to missing data. With soil moisture measurements it should be possible to prove that thesis.

Nutrient analyses were not included in the soil analysis. C.A.B. INTERNATIONAL (2002) note that in some locations of Pinus halepensis deficiencies of phosphates have been observed. Mycorrhiza help to dissolve phosphates out of the soil (NENTWIG *et al.*, 2011). The soil pH plays an important role at making phosphates and other nutrients available (STAHR *et al.*, 2012). Calcium and magnesium influence the pH and hence the nutrient supply massively. Maybe herein is the importance of these salts.

To summarize the topic “soil”:

- Salt and soil texture do not suffice to explain mortality
- A possible reason for this could be, that the investigated plots are not located at the most suitable sites. (The hotspot analysis and the statistical analyses of the soil parameter in chapter 5.2 suggest this.)
- Possible explanations for the mortality related to soil not investigated here could be:
  - Mycorrhiza,
  - perching of seepage water on bedrock near ground surface,
  - nutrient availability, which could be related to soil pH

## 6.2 Cold

I found a temperature minimum in January 2008 of -3.6°C. It is difficult to say if this temperature caused some harm to the trees.

The lowest observed temperature in an Aleppo pine habitat was -18.6°C (PANETSOS, 1994-2008), but C.A.B. INTERNATIONAL (2002) names only -12°C as the minimum temperature observed. It is likely that the trees can tolerate frost very well. BRUNOLD *et al.* (1996) state that plants which in principle tolerate freezing stress face temperatures of -4 until -9 °C without any damage, even if they didn’t have a time to adapt to the cold. This and the fact that only in the nights the temperature fell below freezing makes it unlikely that frost caused the dying, but it may have led to a weakening of the trees. Furthermore PANETSOS (1994-2008) point out the sensitivity of Aleppo Pine to late frost. This frost, which occurred in the growing season, may have worked like late frost, because the plant was not dormant as it would have been with frost in winter and the growing season in summer.

BRÉDA *et al.* (2006) point out that stress does not need to lead to tree decline or mortality immediately. In most cases stress damages plant tissue. Freezing stress can bust cells. This damage needs to be repaired before normal processes can resume. The repair requires stored carbohydrates. PREISLER *et al.* (2012) measured DBH growth rate in Yatir forest. One can observe indeed a stagnation or at least a decline in growth between 2007 and 2011. The frost of 2008 and the subsequent process of repairing the damage by using stored carbohydrates could be a main factor that promotes carbon starvation, since carbon reserves are necessary to repair the arisen damage and couldn't be refilled in the rainy seasons 2007/08 and 2008/09, which had only 201 and 166mm precipitation respectively.

It needs to be noted that I only had minimum temperature data available from the year 2000 on. So I cannot tell if there was a colder year earlier and which effect it might have had.

Cold is not the reason for mortality, but it most likely led to a weakening of the trees.

## 6.3 Drought

In the annual precipitation sum no significant change was discernible. However, Figure 13 and Figure 14 signal that 2009 was the longest spell of drought. Since Pinus halepensis is a drought avoider and so threatened by carbon starvation, it is feasible that this long drought period led to death. The last "major rain" happened on 14th Feb 2008 with 20mm precipitation. The next happened one year later on 10th February 09 with 30mm. C.A.B. INTERNATIONAL (2002) mentions that a summer drought of 3 month is common for Aleppo Pine. In 2008/09 this time extended fourfold. However, one can also see that almost the same duration of drought occurred earlier, for example in the winter 1995/96. The problem is that no data of historical mortality events exist so it is not possible to compare theses events.

To evaluate the effect that the canopy has on interception I subtract 2mm of rainfall on each rainy day (Figure 17). The average number of rainy days in Yatir is 31.5 days per rainy season and the average sum of precipitation is 279mm. This means 63mm of 279mm/a (31.5 days * -2mm per day) would evaporate immediately, which equals 22% of annual rainfall. MAESTRE and CORTINA (2004) state that Aleppo pine stands reduce the water that reaches the soil surface between 15-35% whereas YASEEF *et al.* (2009) allocate only 11% interception in Yatir forest. The assumption that 2mm of precipitation per rainy day t will not infiltrate into the soil is therefore justified.

Figure 17 shows that the distribution and the amount of rain per event did not change. Hence, this factor can be discarded as a reason for mortality.

The temperature over the last ten years before the dying in 2010 does not show a warming trend (Figure 20). Hence, this implies that the irradiation did not increase and thus there was no demand for more evapotranspiration. HILLEL and ROSENZWEIG (2013) found different development of temperature in Israel, however. They point out that 2010 was the "single hottest year" (ibd p.167).

Sites that are facing to the south are more often affected from mortality (49%) than sites that face to the north (only 29%). The more a site is inclined, the more dead trees one can find there (2.8 dead trees per hectare in flat area and 6.5 dead trees in strong inclined sites).

How much water can be stored in the soil and later be absorbed by the trees is a crucial question. The problem is that I don't have detailed information about the saturated water content, the field capacity, plant available water, the wilting point and the depth to bedrock. That is why I could only estimate a mean value for the entire 32 km$^2$ area.

The data from the soil survey of WIS show a high root density in the upper 40-60cm, but some roots go deeper than 1m. Also, in some plots the stoniness reaches 100% after 40 cm, while others are almost free of stones until 1.5m. On average the last root is found at 98cm in the live plots, and at 104cm in the dead plots (c.f. 5.5), so the assumption of 1m rooting depth is justified.

From the soil structure I deduced the saturated water content and the field capacity with the help of the German pedological mapping guide (Bodenkundliche Kartieranleitung) and found in 13 out of 21 samples a saturated water content of 43% and in 16 out of 21 samples a water holding capacity between 30-41 Vol.%.

UNGAR *et al.* (2013) measured the soil water content of one site in Yatir forest with TDR-sensors up to 40 cm soil depth. In figure 1 of their paper a drainage curve visible, which stabilizes at a water content of 33 Vol.%. This would fit very well to the estimated field capacity that I derived from the soil texture.

YASEEF *et al.* (2009) calculate a maximum water holding capacity (which rather is the saturated water content) for the first 20 cm of 63mm water. That conforms to a saturated water content of 32 Vol.%. YASEEF *et al.* (2009) also names some soil characteristics: 31% Sand, 41% silt and 28% clay with a density of 1.65 g/cm$^3$. The United States Department of Agriculture developed a software to calculate the field capacity from soil texture and soil density (SAXTON and RAWLS). With the above values the field capacity comes out as 29 vol. %, the wilting point is at a water content of 17 vol.%. Hence, the plant available water is 12 vol. %. This equals the 12-14 vol.% of plant available water that I found for most plots.

This soil water calculation very simple and neglects a lot of things like the water uptake of plants and that the highest density of roots is mostly in the upper 20 cm and in depth of 1m the roots are so sparse, that they can absorb only a fraction of the water present. Furthermore, it neglects that the stoniness increases with depth, which is why the saturated water content is also not constant with depth. YASEEF *et al.* (2009) found that 63, 112 and 243 mm water are required to saturate the layers 0-20, 0-40 and 0-135 respectively. That shows indeed that the saturated water content decreases with greater depth. It neglects as well that approximately 11% of precipitation get lost by evaporation in the process of interception and do not reach the ground (YASEEF *et al.*, 2009). To consider all theses aspect a much more complex model is required, but within this master thesis there was no time. That's why only simplified calculations were made to a first orientation how evapotranspiration in interaction with precipitation may influence the drought stress that plants are exposed to in Yatir forest.

It is necessary to note that I couldn't determine the boundary conditions properly and had to set the initial water content for the calculations beginning in 2000 to 100 L/m$^2$ over a 1m rooting depth.

Tree mortality in Mediterranean areas often involves prior droughts that initiate a growth decline and a chain of interacting events (SÁNCHEZ-SALGUERO *et al.*, 2012). The multi-factor hypothesis (MANION, 1991) supports the theory that mortality is induced by "predisposing factors" that exposes plants to long term stress. Between 2005 and 2009 the assumed 350L per m$^3$ soil were not filled up. This may have worked as a predisposing factor. After this predisposing stress an "inciting-factor" like severe short term stress can lead to mortality. In the case of Yatir forest this could be the drought in 2009 when precipitation began at a very late point. Also, BRÉDA *et al.* (2006) confirm that prior droughts emphasize the effect of a subsequent drought on tree health. For example, they name the drought of 2003 in France where trees died in 2004 after they were already exposed to several stresses prior to 2003. This is because the deficiency of carbohydrates reserves may last for one or several years after a stress event (BRÉDA *et al.*, 2006).

It must be noted that I could only compare the last 10 years before the mortality so that I cannot say if the founded observed between 2005 and 2009 is a common drought interval or not.

## 6.4 Competition

MASEYK *et al.* (2011) studied tree ring chronologies in Yatir, which end in spring 2004. As expected they could find a strong correlation between growth and precipitation with $r^2 = 0.69$ and $p=0.00002$. In their paper they name 3 known thinning events: 1980, 1992 and 1997/98.

In Figure 37 one can see the standardized anomalies of the basal area increment and the related rain events in this year. In the thinning of 1980 and 1992 the rain events exceed the increment. Only in 1997/98 is the increment higher than could be explained by the precipitation. Unfortunately there is only room for speculation, because reliable data are missing. It could be that in 1997/98 the trees were just dense enough so that the thinning had an effect on competition, but it may be also just an effect by chance.

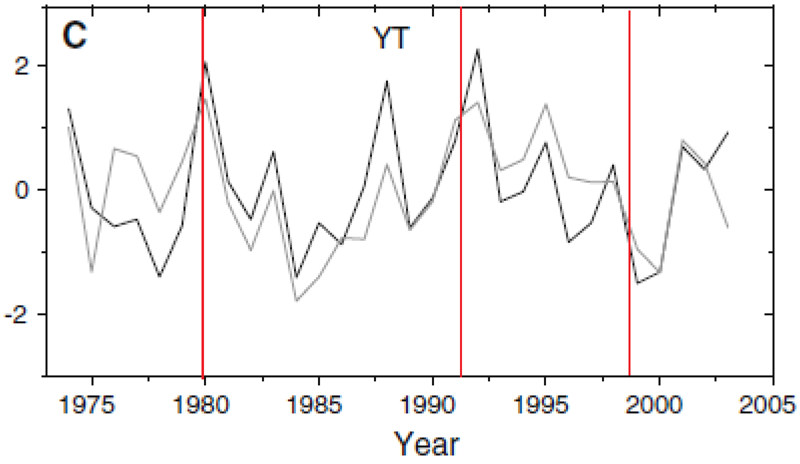

**Figure 37: Standardized basal area increment (BAI) of Yatir forest chronology. Source: MASEYK *et al.* (2011), modified. The black line shows rain events and the grey line the BAI. The red line marks the thinning events.**

Stand density and total biomass may have the most important impact on mortality, because even in a non-drought year the maximum biomass per hectare does not seem to grow any more after the age of 40 years. Most dead trees were older than 35 years (78%). In a drought year like 2009 and in an old stand a big mortality is predetermined. MAESTRE and CORTINA (2004) state that in Spain the tree cover in Aleppo pine stands older than 40 years is close to 30%. This is very sparse and seems to be the result of a natural thinning process to reduce the density to a sustainable level under the low precipitation. Also, SÁNCHEZ-SALGUERO *et al.* (2012) name density and the lack of silvicultural practice as reasons for forest decline in “rear edged forests” (populations that are at or near its range limits). Furthermore, they name some studies that show how denser stands lead to a natural self-thinning effect, because of the corresponding reduction in soil water availability per unit of basal area, They emphasize that this mechanism is particularly relevant in dense pine plantations in the Mediterranean Basin. Also, NAVARRO *et al.* (2010) showed a distinct positive effect on younger thinned stands and an significant increase of DBH in the year after thinning.

AUSSENAC (2000) showed that thinning can have an important effect on soil water availability. Likewise, MORIKAWA *et al.* (1986) could show that a removal of 25% of trees in a thinning reduces the transpiration of a *Chamaecyparis obtusa* stand by 21% and so increases the available water by reducing interception and transpiration. A strong thinning in Yatir could also have a beneficial effect.

Another thesis is presented by MCDOWELL *et al.* (2008): The dying of older trees may occur due to their height: "Trees that have reached their maximum height may be particularly vulnerable" (Ibid. p.725). This is evaluated as rather unlikely at Yatir since the tree height did not change so strong.

# 7 Conclusion

The aim of this thesis was to find a reason for tree mortality in Yatir forest in 2010. For that I looked for possible drought related changes in precipitation (water supply), irradiation and evapotranspiration (evaporative demand) and the storage capacity of soil. Furthermore I analyzed the soil for salinity, the biomass development per stand, the effect of minimum temperature.

I found no significant change in annual precipitation. There are ups and downs like it was from the beginning of weather records in 1971. If one builds a 12-month moving average of the rainfall, a minimum is recognizable in the rainy season 2008/09, which is close to the mortality in 2010. This minimum reflects the longest time between two rain events. However, in 1995/96 an almost similar minimum occurred, but no historical record is available to compare the mortality of 2010 with the eventual mortality in 1995/96.

Moreover I build the cumulative sum of monthly precipitation per rainy season. The rainy season of 2008/09 strikes here too: it has the latest rise of the cumulative rainfall curve. In January of 2009 are fallen only 20% of total rain whereas in most other years 50% of total rain fell in January.

A change in evaporative demand could have been deduced only indirectly, but no change was evident. The analysis of mortality with respect to aspect showed that most dead trees are exposed to a southern direction (49.3% from southeast to southwest) and appear on strongly inclined slopes (6.5 dead trees per ha on an inclination of 18-36%, while in flat areas of 0-2% inclination only 2.8 trees had died).

A model of soil water content suggests no full recharge to field capacity from 2005 to 2009. That means an above average stress to the trees.

In salinity no pattern is evident. In live plots the trees show a higher correlation to salinity features, but statistically live and dead plots cannot be distinguished with respect to soil properties. The higher sensitivity to salinity in live plots cannot be explained well. It is possible that different reasons killed the trees in dead plots, so that the correlations to salinity features are distorted in dead plots and represent the natural conditions in live plots.

A hot spot analyzes in ArcGIS showed that dead and live plots locations are not at a perfect position. They are too close to each other and mostly within the same hotspot. Statistical analyses of soil properties support this thesis because the appropriate non-parametric tests show that all salinity features (except electrical conductivity) belong to the same statistical population, which means that there are no differences in salinity properties between dead and live plots. Only the t-test, which is not appropriate here since the features are not Gaussian distributed, show significant differences in EC, Na and Mg +Ca, after removal of outliers.

The analysis of competition shows no increase in biomass growth above an age of 40 years. This could be derived by inventory data provided from KKL in the years 2004 and 2007, i.e. taken some years before the mortality in 2010. The aforementioned late start of precipitation in 2008/09 and the fact that the trees on this site do not grow anyway if they are older than 40 years are the most likely reason for the mortality. This is supported by the fact that more than 56% of dead trees are older than 40years and more than 77% are older than 35 years.

Additionally, in January 2008 the only frost within 10 years occurred. The literature suggests a weakening of the trees by frost.

To summarize it, the following four factors could be pointed out as reasons for mortality: a weakening of trees by the frost in January 2008, the long spell of drought of approximately one year from February 2008 to February 2009, no full recharge of soil water content from 2005 to 2009 and most importantly: the growing competition reflected in the increasing biomass per dunam, which amplifies any similar stress that may have occurred earlier.

An effective tool to combat the negative effects is thinning. NAVARRO *et al.* (2013) state that thinning decreases competition stress and heightens tree vigor so that the trees can build more total biomass. Furthermore, water is the limiting factor at Yatir and thinning increases the amount of water per single tree. MAESTRE and CORTINA (2004) state that the introduction of shrubs in Aleppo pine plantations could stimulate successional processes, increase soil water content and, through diversity, improve ecosystem resilience against disturbances, and have a positive effect on faunal communities.

It must be noted that some of the data I used were not measured but only deduced. In particular:

- Values for field capacity (deduced from soil structure)
- Stand density (deduced from aerial photographs)
- Amount of dead trees (deduced from aerial photographs)
- Biomass per stand: the values for biomass given in chapter 5.6 do not represent the actual biomass development. It shows the state of development of stands of different age at the same moment (2004 and 2007). Data on the development of the same stand over time is not available. Furthermore, the inventory data most likely represent too small an area, because too few trees were measured within one plot.

For more accurate results these data should have been measured directly. In chapter 5.1 I showed that the GIS Layer with the positions of dead trees has lots of is gaps. If the aerial photographs would be taken with infrared cameras, dead trees would be easier to identify. To count the dead trees on the ground would be sensible too, since younger trees are too small to be seen in aerial photographs, given their resolution.

Better results could be possible, if the plots would be located on a geometric grid, since the cluster analysis in section 5.2 showed that live and dead plots are mostly located within the same hotspot or on its edge. That means, too, significant differences in soil properties could possibly be found with samples from cold spot positions.

With more data about soil water tension in different places and different depths one could observe the hydraulic properties of the soil better and put it in relation to the mortality.

Several reasons for the mortality needed to be neglected within this thesis, because no data were available. This is in particular the distribution of mycorrhiza and the hydraulic soil properties on different sites of the forest, the nutrient availability as well as the specific symptoms which the trees showed at the time of death and in the preceding stage before the dying. For this thesis there was no time to collect all this data, so it needed to be limited to the reviewed topics. Nevertheless, it gives suggestions for future research.

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# Eidesstattliche Erklärung

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