Land Dynamics Group

Thesis report

Properties of dark anthropogenic soil layers and influence of charcoal on crop growth in the Negev desert

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Properties of dark anthropogenic soil and influence of charcoal on crop growth in the Negev Desert (Israel)

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Summary

Research into the sustained fertility of Terra Pretas in the humid tropics has led to the discovery of enriched levels of charcoal. At Horvat Haluqim, an Iron Age dessert village in the Central Negev Highlands (Israel), dark anthropogenic soil layers containing pieces of charcoal have also been found. The objective of this study was twofold. The first objective was to assess the differences in chemical and physical soil properties between the anthropogenic and the non-anthropogenic soil horizons at Horvat Haluqim and to assess whether they could be attributed to charcoal fertilization. The observed differences were compared to the effects of charcoal that have been reported for soils in the humid tropics. The second objective was to identify possible beneficial effects, in terms of chemical and physical soil fertility, of the addition of charcoal on crop production in the Negev soil and to compare this to the reported effects of addition to the soils in the humid tropics.

The anthropogenic soil horizons have significantly lower mean bulk density (1.21g cm^{-3}) compared to non-anthropogenic soil horizons (1.39 g cm^{-3}). The anthropogenic horizons also have more often a weak structure compared to the non-anthropogenic horizons. These differences are not related to the charcoal content of the soil horizons, because the charcoal content of the soil is very low, ranging from 0.06 to 0.19% and is comparable between the anthropogenic and non-anthropogenic horizons, even though there is a distinct difference in colour. Furthermore, the soil horizon with the highest charcoal content does not have the lowest bulk density or the weakest structure.

No differences were found in pH, EC and cumulative infiltration between the anthropogenic and non-anthropogenic soil horizons from Horvat Haluqim.

Charcoal addition to the soil in the pot experiment slightly increased soil pH and EC, but water retention decreased.

Charcoal additions to soils in the humid tropics usually lead to an increase in pH that is much larger than the increase that was observed in this study.

A pot experiment with wheat was conducted with the anthropogenic and non-anthropogenic soil from Horvat Haluqim with or without the addition of charcoal and ash. The addition of charcoal led to significant lower crop growth and biomass production compared to the control. This was most likely caused by N deficiency, since charcoal has a high C/N ratio, which can lead to N immobilization. In contrast to what was found in this study, charcoal addition to highly weathered soils of the humid tropics often leads to increased crop growth and biomass production due to reduced Al availability and the addition of nutrients.

The dark colour of the anthropogenic soil horizons at Horvat Haluqim is not due to the presence of charcoal and in that sense they are not comparable to the Terra Pretas in the humid tropics. The creation of ‘Terra Pretas’ in arid regions with loess soils through addition of charcoal, as has been done in the humid tropics, shows no great potential, since it decreases water retention and can lead to N deficiency.

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1 Introduction

Archaeologists have discovered large areas of very fertile dark soils in the Amazon Basin (Terra Preta do Indio). These ancient anthropogenic soils are very fertile in comparison to the normally infertile soils in the humid tropics that are highly weathered and leached (Lehmann *et al.*, 2003). Research into the sustained fertility of the anthropogenic soils has led to the discovery of enriched levels of charcoal. Terra Pretas can contain 8-70 times more charcoal than the surrounding soils. Glaser *et al.* (2001) found a charcoal content of 25 Mg ha^{-1}.

Several studies have shown changes in soil chemical and physical properties as a result of the addition of charcoal. Charcoal addition can lead to increased soil pH (Tyron, 1948), increased nutrient retention and delayed leaching of certain nutrients (Lehmann *et al.*, 2003) due to increased CEC (Liang *et al.*, 2006). Furthermore, charcoal itself may also be a source of nutrients, but N availability may decrease with charcoal additions due to high C/N ratios resulting in immobilization (Lehmann *et al.*, 2003). Charcoal addition to a sandy soil can increase the available moisture, while this can decrease in a clay soil (Tyron, 1948).
Several studies have also shown a positive effect of charcoal on crop production, with or without an additional source of nutrients (Topoliantz *et al.*, 2002; Lehmann *et al.*, 2003; Topoliantz *et al.*, 2005; Steiner *et al.*, 2007).

The Terra Pretas in the Amazon are not the only anthropogenic soils that contain charcoal. At Horvat Haluqim, an Iron Age desert village in the Central Negev Highlands (Israel), anthropogenic soil layers containing charcoal have also been found (Bruins and Van der Plicht, 2007). Horvat Haliqum has an arid climate and receives less than 100 mm average annual rainfall. In order to enable agriculture in this desert region, local people who lived here in the past engaged in run-off farming. This is an agricultural practice in which cross-channel terraces are established by building a series of check dams along the length of a wadi. Run-off water from the surrounding catchment can accumulate against the dams and subsequently infiltrate into the soil of the terrace fields (Bruins, 1986). The presence of tiny pieces of charcoal and bone particles indicate that local inhabitants used home refuse to fertilize the soil in order to increase fertility, which is normally low in a desert environment (Bruins and Van der Plicht, 2007).

Until now research into the effects of charcoal on soil properties has mostly focused on the highly weathered and leached soils in the humid tropics. However, very little is known about the effects of charcoal in arid regions with different soil types. If the presence of charcoal in these anthropogenic soil layers in the Negev loess soil has beneficial effects on crop production, this would create opportunities for farmers to improve crop production in marginal regions with similar soil and climate in a relatively easy and affordable manner.

The objective of this study is twofold. The first objective is to assess the differences in chemical and physical soil properties between the dark anthropogenic and the non-anthropogenic soil horizons at Horvat Haluqim and to assess whether they can be attributed to charcoal fertilization. The observed differences will be compared to the effects of charcoal that have been reported for soils in the humid tropics. The second objective is to identify possible beneficial effects, in terms of chemical and physical soil fertility, of the addition of charcoal on crop production in the Negev soil and to compare this to the reported effects from soils in the humid tropics.

Research questions

Do dark anthropogenic soil horizons at Horvat Haluqim have different chemical and physical soil properties compared to non-anthropogenic soil horizons and are they related to the charcoal content?

- What are the chemical and physical properties of the anthropogenic and non-anthropogenic horizons at Horvat Haluqim?

How does charcoal and ash addition to the Negev loess soil influence crop growth and soil properties and how does this compare to the effects of charcoal in the humid tropics?

- How does the addition of charcoal and ash influence crop growth under different moisture regimes?
- How does the addition of charcoal and ash influence soil properties?
- What are the reported effects of charcoal addition to crop growth in the humid tropics?

Hypothesis

It is expected that the effect of charcoal on chemical and physical properties of the loess soil in the Negev are similar to those observed in the humid tropics. However, the effects will be less pronounced, because the soil properties of the loess soil in the Negev are less extreme than that of the highly weathered and leached soils in the humid tropics, especially in the case of chemical properties. Charcoal addition will probably influence crop growth positively, since it can be a source of nutrients. The effect of charcoal on moisture availability will probably also be positively influenced.

2 Theory

2.1 Properties of charcoal

Charcoal is produced by thermal decomposition of organic material under oxygen limited conditions and relatively low temperatures. It is also produced in small quantities when biomass is burned in a fire in areas with limited oxygen supply (Lehmann and Joseph, 2009).

The properties of charcoal are highly variable and depend on the type of organic material and the pyrolysis system by which it is made. This includes heating rate, highest temperature, pressure, reaction residence time, type of reaction vessel, pre-treatment, the flow of ancillary input and post-treatment (Downie *et al.*, 2009). The defining property of charcoal is high C content, which mainly consists of aromatic compounds that are characterized by rings of six C atoms linked together without oxygen or hydrogen atoms. If these rings were stacked perfectly and aligned in sheets, it would be graphite. However, under the temperatures used to make charcoal, graphite does not form to a significant extent. In stead, much more irregular arrangements of C atoms will form, containing O and H and, in some cases minerals depending upon feedstock (Lehmann and Joseph, 2009). The degree of alteration of the original biomass structure (micro structural rearrangement, attrition during processing and formation of cracks) depends on the processing conditions.

During pyrolysis mass is lost mostly in the form of volatile organics (Downie *et al.*, 2009).

2.1.1 Nutrient content

During thermal degradation K, Cl and N are vaporized at low temperature, while Ca, Mg, P, S and Si are released at much higher temperature. Other element such as Fe and Mn are largely retained during charcoal formation (Amonette and Joseph, 2009).

Minerals found in charcoals include sylvite (KCl), quartz (SiO_2), amorphous silica, calcite ($CaCO_3$), and other minor phases such as Ca phosphates, anhydrite ($CaSO_4$), various nitrates and oxides and hydroxides of Ca, Mg, Al, Ti, Mn, Zn or Fe (Amonette and Joseph, 2009).

Information on the nutrient content and properties of charcoal is very limited and few agronomic studies have included the nutrient content of the used charcoal. Mineral N is usually very low and available P is highly variable. In contrast, available K is usually high (Chan and Xu, 2009).

Nutrient content of various charcoals are listed in Table 1. Nutrient content of the listed charcoals is variable, but low. The one property that all charcoals have in common is the high C/N ratio, ranging from 56 to 571.

Charcoal inevitably contains ash with free bases such as K, Ca and Mg. These are easily soluble and available as nutrients for plant growth (Glaser *et al.*, 2002). The ash content of charcoal is also highly variable. Pastor-Villegas *et al.* (2007) found that ash content in wood charcoal ranged from 2.06 to 20% in charcoal produced from different feedstock and under different process conditions. However, ash content of 0.23% was found by Rondon *et al.* (2007).

Table 1 Nutrient content of different charcoals

Source	C g kg^{-1}	N g kg^{-1}	C/N	P g kg^{-1}	Mg g kg^{-1}	Ca g kg^{-1}	K g kg^{-1}	Reference
Amazonian wood	708	10.9	56	6.8	0.32	1.3	0.89	(Lehmann *et al.*, 2003)
Pine chip pellets-379	742	1.3	571	0.87	-	0.36	0.44	(Gaskin *et al.*, 2007)
Pine chip pellets-401	760	1.4	543	0.89	-	0.38	0.66	(Gaskin *et al.*, 2007)
Pine chip pellets-426	752	1.7	442	0.12	-	0.53	1.29	(Gaskin *et al.*, 2007)
Hard wood chips - 382	695	2.8	248	0.07	-	0.39	0.39	(Gaskin *et al.*, 2007)
Hard wood chips – 400	703	3.0	234	0.09	-	0.53	0.69	(Gaskin *et al.*, 2007)
Hard wood chips - 426	735	3.6	204	0.12	-	0.58	1.13	(Gaskin *et al.*, 2007)
Pecan shell	834.2	3.41	245	0.26	0.70	3.64	4.15	(Novak *et al.*, 2009)
Eucalyptus deglupta Blume	823.7	5.73	144	0.58	1.31	-	-	(Rondon *et al.*, 2007)
Wood (not specified)	905	5.64	160	0.27	-	-	5.05	(Topoliantz *et al.*, 2002)
Mixture of grass, cotton trash and plant prunings	360	1.8	200	-	0.01	0.01	0.82	(Chan *et al.*, 2007)

2.1.2 pH

The pH of charcoal can also be highly variable (Table 2). Charcoals can be produced at any pH between 4 and 12 (Lehmann, 2007). However, charcoals used as soil amendments in research are usually alkaline (Chan and Xu, 2009).

2.1.3 CEC

Charcoal has oxidized functional groups that originate from oxidation of charcoal itself or from adsorption of partially oxidized charcoal or other materials. This surface oxidation is the cause for high CEC. Additionally, a high specific surface area may also contribute to the high CEC of charcoal (Liang *et al.*, 2006). The CEC of charcoal is also variable (Table 2).

Table 2 pH and CEC of different charcoals

Source	pH	CEC (cmol kg^{-1})	Reference
Pine chip pellets-379	-	19.5	(Gaskin *et al.*, 2007)
Pine chip pellets-401	-	27.0	(Gaskin *et al.*, 2007)
Pine chip pellets-426	-	18.6	(Gaskin *et al.*, 2007)
Hard wood chips - 382	-	22.6	(Gaskin *et al.*, 2007)
Hard wood chips – 400	-	23.0	(Gaskin *et al.*, 2007)
Hard wood chips - 426	-	14.1	(Gaskin *et al.*, 2007)
Douglas-fir wood	4.15	20.66	(Gundale and DeLuca, 2007)
Douglas-fir bark	4.18	19.42	(Gundale and DeLuca, 2007)
Ponderosa pine bark	4.81	34.48	(Gundale and DeLuca, 2007)
pecan shell	7.6	-	(Novak *et al.*, 2009)
Eucalyptus deglupta Blume	7.00	4.69	(Rondon *et al.*, 2007)
Wood charcoal	9.60	-	(Topoliantz *et al.*, 2005)
Teak and rosewood	7.5	-	(Asai *et al.*, 2009)
Mixture of grass, cotton trash and plant prunings	9.4	24	(Chan *et al.*, 2007)

2.1.4 Bulk density

There are a limited number of research papers that directly present physical data of charcoal (Downie *et al.*, 2009). However, some values for bulk density could be found. Different studies have found bulk density ranging from 0.24 g cm^{-3} to 0.46 g cm^{-3} (Pastor-Villegas *et al.*, 2007) and from 0.03 to 0.30 g cm^{-3} (Gundale and DeLuca, 2007)

2.2 Properties of wood ash

Wood ash is composed of the inorganic constitutes that remain after burning (Ulery *et al.*, 1993). During combustion of wood, organic compounds are mineralized and the basic cations are transformed to their oxides, which are slowly hydrated and subsequently carbonated under atmospheric conditions (Demeyer *et al.*, 2001). The properties of wood ash depend on the type of plant, the soil type and climate in which the plant has grown, conditions of combustion, collection and storage (Someshwar, 1996). As a consequence available data on the properties of wood ash are very variable and generalizations are difficult to make (Demeyer *et al.*, 2001). However, some general properties and influences on soils can be found in literature.

2.2.1 Nutrient content

Wood ash is a direct source of nutrients. Its application to soil causes increases in the contents of most major nutrients, inorganic Ca, K, Mg and P. However, relative to K and Ca, P in wood ash is much less soluble and less available for plant uptake (Ohno, 1992; Ulery *et al.*, 1993; Vance, 1996; Demeyer *et al.*, 2001). It also contains large amounts of micro nutrients, such as Fe, Mn, Zn and Cu (Erich, 1991; Demeyer *et al.*, 2001). Wood ash contains virtually no C and N, since this is oxidized during combustion and transformed into gaseous forms (Unger and Fernandez, 1990; Demeyer *et al.*, 2001).

2.2.2 Neutralizing capacity

The alkalinity or neutralizing capacity of wood ash is high (Ulery *et al.*, 1993; Muse and Mitchell, 1995; Demeyer *et al.*, 2001). Its pH ranges from 9 to 13 (Etiégni and Campbell, 1991). The very high pH and neutralizing capacity of freshly produced ash is caused by the presence of oxides, hydroxides and carbonates of Ca, Mg, Na and K (Ulery *et al.*, 1993; Muse and Mitchell, 1995; Vance, 1996). However, calcite ($CaCO_3$) is the major component of wood ash (Etiégni and Campbell, 1991; Ulery *et al.*, 1993).

The above mentioned elements are for the most part readily soluble and undergo hydrolysis and develop alkalinity (Tyron, 1948). Various studies have shown that application of wood ash to the soil increases soil pH and therefore, it is often used as liming agent (Erich, 1991; Ulery *et al.*, 1993; Muse and Mitchell, 1995; Demeyer *et al.*, 2001). It reacts quickly with the soil, which results in a strong pH increase, but only for short period of time since the most soluble hydroxides and carbonates are easily leached (Ulery *et al.*, 1993; Muse and Mitchell, 1995). The pH increase results in an initial decrease in the availability of micro nutrients and P as a result of reduction in solubility. As soil pH decreases again over time, micro nutrients will become more mobile and plant-available (Erich, 1991; Vance, 1996; Demeyer *et al.*, 2001).

2.2.3 Electrical conductivity

Wood ash has also been shown to increase the EC of soils linearly with increasing wood ash amendment. This is probably due to the solubility of wood ash supplied elements (Clapham and Zibilske, 1992).

2.3 Soils in the Amazon

2.3.1 Non-anthropogenic soils

Generally, upland Amazonian soils are highly weathered and poor in nutrients due to prolonged leaching and because the weathering front of the geological substrate is too deep to provide nutrients for plants (Smith, 1980; Lehmann *et al.*, 2003). High rainfall and low nutrient exchange capacity make these soils highly susceptible to leaching (Hölscher *et al.*, 1997; Renck and Lehmann, 2004). Low cation exchange capacity is due to the dominance of Fe and Al oxides and kaolinite, as well as low pH and low soil organic matter content (Lehmann *et al.*, 2003). Loss of N through leaching is one of the major limitations for crop production in the humid tropics (Steiner *et al.*, 2008), since N mineralization and nitrification both proceed very rapidly under humid tropical conditions and because nitrate is very mobile in most soils (Renck and Lehmann, 2004).

2.3.2 Anthropogenic soils

The highly weathered and nutrient poor soils in the humid tropics are thought to be too infertile to sustain agriculture (Glaser *et al.*, 2001). However, in the Amazon fertile soils have been found, the so called Terra Pretas. These soils are highly valued by farmers for their sustained fertility and production potential (Lehmann *et al.*, 2003). These soils not only contain higher concentrations of nutrients such as N, P, K and Ca, but also greater amounts of stable soil organic matter (Glaser *et al.*, 2001).

Terra Pretas have a C rich black top layer which is usually less than 50 cm thick, but is sometimes as thick as 100 cm (Sombroek, 1966). Frequent findings of charcoal and highly aromatic humic substances suggest that residues of incomplete combustion of organic material are a key factor in the persistence of soil organic matter. Due to its polycyclic aromatic structure, black charcoal is chemically and microbially stable and persists in the environment over centuries (Glaser *et al.*, 2001). Sombroek (1966) found a carbon content of 4-5% in the top 20 cm of the black layer and 1-2% below in fine textured Terra Pretas. Coarse textured Terra Pretas had 1-2% carbon in the upper 20 cm and 0.5% in the lower part of the dark layer. Despite their very humic appearance, the present organic matter content of the black layer is only moderately high and roughly two times the average of non-enriched soils of comparable texture. The colour is probably the result of complex formation of organic matter and Ca^{2+}, which forms a coating on the soil particles (Sombroek, 1966).

These Anthrosols have persisted over many centuries despite the humid tropical conditions and rapid mineralization rates (Lehmann *et al.*, 2003). The presence of charcoal and the nutrient contents of Terra Preta soils as discussed above are responsible for the high crop production potential and higher sustainable soil fertility of Terra Preta soils compared to the surrounding Ferralsols (Glaser, 2007).

The Terra Pretas acquired their fertility from dung, household garbage and refuse (bones) of hunting and fishing (Sombroek, 1966) and ash (Smith, 1980).

2.4 Influences of charcoal on chemical soil properties in the humid tropics

2.4.1 Soil acidity

Soils in the tropics generally have a low soil pH (Lehmann *et al.*, 2003) and plant growth can be negatively affected by Al availability (Rondon *et al.*, 2007).
The pH of normal Amazonian soils (Oxisols and Ultisols) usually have a pH below 5, while the average pH of Terra Pretas was determined to be 5.4 (Smith, 1980). Lehmann *et al.* (2003) also found a significantly lower pH in the Amazonian Ferralsol (5.14) compared to the Terra Preta (5.71) and also a significantly lower Al availability in the Terra Preta.

Different effects of the addition of freshly produced charcoal to the soil on soil pH have been found. Rondon *et al.* (2007) found increased pH in a clay loam Oxisol from 5.04 to 5.41 after 90 g kg^{-1} charcoal addition. Novak *et al.* (2009) found an increase in pH from 4.8 to 6.4 after a 69 day incubation period with 2% of charcoal addition to a loamy sand soil. Topoliantz *et al.* (2005) also observed increased pH from 4.40 to 4.88 after charcoal application in combination with manioc peel. In an earlier study, the application of only charcoal also increased pH significantly (Topoliantz *et al.*, 2002).
Lehmann *et al.* (2003) found a pH increase from 5.14 to 5.89 after the addition of 20% charcoal dust (1 mm) to an Amazonian Ferralsol. Steiner *et al.*, (2007), on the other hand found that the addition 11 Mg ha^{-1} of powdered charcoal (<2 mm) did not change soil pH. The addition of charcoal pieces (>10 mm) did increase the soil pH from 4.50 to 4.79, although not significantly. In contrast, Tyron (1948) found that fine charcoal pieces (<1 mm) were more effective in raising soil pH than coarse pieces (2-5 mm) in non-tropical soils.

Tyron (1948) studied the influence of different types of charcoal on different textured non-tropical soils. The pH of a sand, loam and clay soil all significantly increased. The pH of the sand soil was most affected, while the pH of the clay soil was least affected due to the higher buffering capacity. Hardwood charcoal was more effective in increasing the pH than conifer charcoal due to the higher ash content of the hardwood charcoal (6.38%) compared to the conifer charcoal (1.48%), which is responsible for the increase in pH.
Charcoal inevitably contains a small amount of ash with free bases such as K, Ca and Mg that are added to the soil solution, increasing the pH (Tyron, 1948; Glaser *et al.*, 2002).

Increased pH due to charcoal addition in acid soils decreases Al availability (Rondon, 2007; Lehmann *et al,* 2003). However, Steiner *et al.*, (2007) observed a slight increase in Al availability after charcoal application, while the pH did not change. However, this was not a significant increase. Charcoal application in combination with mineral fertilizer decreased Al availability to zero, while the pH only slightly increased. The application of only mineral fertilizer led to a significant increase in pH and to a large decrease in Al availability, although, not as large as with combined mineral fertilizer and charcoal addition.

Lehmann *et al.,* (2003) found decreased Al availability with charcoal addition and this decreased even further when also mineral fertilizer was applied.

2.4.2 Fertility

A few extensive agronomic field trials have been performed in highly weathered tropical soils in the Amazon to study the effect of charcoal addition.

A long-term experiment was done by Steiner *et al.*, (2007) on a Ferralsol. Soil plots were amended with low nutrient charcoal, mineral fertilizer or a combination of both. Plants were grown in four consecutive seasons with a cropping cycle that started with one season of rice (*Oryza sativa* L.), followed by three seasons of sorghum (*Sorghum bicolor*, L. Moech).
Soils that received mineral fertilizer in combination with charcoal had a higher amount of available nutrients compared to soils that received only mineral fertilizer. However, this difference was not statistically significant. Even though nutrient export from the soil that received both mineral fertilizer and charcoal was higher, nutrient contents of the soil did not decrease in comparison to the soil that only received mineral fertilizer. Even after four harvests the nutrient content was still higher.
There was a synergetic effect on crop growth when both mineral fertilizer and charcoal were applied to the soil, as crop growth was positively influenced in four consecutive harvests.
In the first harvest the application of only charcoal had only a minor effect on grain yield. However, stover production increased by 29% and grain yield production by 73% when the soil received both charcoal and mineral fertilizer in comparison to plots that received only mineral fertilizer. In the second harvest the stover production increased by 820% and the grain production by 167% compared to the plots that received only mineral fertilizer. In the third and fourth harvest the grain production increased 1.5 and 2.0 times and the stover production increased by a factor 1.3 and 1.4 when charcoal and mineral fertilizer were applied compared to plants grown on soils that received only mineral fertilizer. In the second, third and fourth harvest the Ferralsol and soil amended with only charcoal failed to produce any biomass altogether.

Foliar nutrient content of plants was also influenced by the type of amendment. Foliar K contents of plants grown on soils amended with both mineral fertilizer and charcoal was higher than that of plants that were grown on soils that were only amended with mineral fertilizer. Besides, cumulative nutrient uptake (N, P, K, Ca and Mg) was higher in plants on soil that was amended with both mineral fertilizer and charcoal compared to plants grown on soils with only mineral fertilizer.

Lehmann *et al.*, (2003) found increased shoot biomass of cowpea (*Vigna unguiculata* L. Walp.) grown in an Amazonian Ferralsol amended with 10% charcoal high in nutrients and a Terra Preta compared to a non-amended Ferralsol.

A significant increase in shoot biomass was found for plants grown in the Terra Preta and the Ferralsol amended with charcoal compared to plants grown on the non-amended Ferralsol. The root biomass, however, was significantly higher in the Terra Preta compared to the non-amended Ferralsol and the Ferralsol amended with charcoal.

Plants grown on the Ferralsol amended with charcoal had a significantly lower N and Mg content compared to the Ferralsol without charcoal addition. The lower N content was most likely caused by decreased availability due to the high C/N ratio. The P and Ca content were also lower, but not statistically significant. The K and Cu content was significantly higher. Increased biomass production was mainly the result of direct nutrient additions, especially K, but also P, Ca, Zn and Cu.

The higher crop growth in the Terra Preta was attributed to increased P availability, although no significant difference in P uptake of the plants was found. The plants grown on the Ferralsol had a significantly lower N , K and Mg content compared to the Terra Preta, but the Ca, Zn and Cu content was significantly higher from which the plants may have benefitted.

The total N content of the Terra Preta was higher than of the Ferralsol, but the N availability was lower due to the higher C/N ratio. However, the low N availability did not seem to reduce crop growth.

Higher crop growth (shoot biomass) was also found after the addition of both charcoal and mineral fertilizer. However, this was lower than shoot biomass in the Ferralsol amended with only charcoal, although not statistically significant. No difference in nutrient content between only charcoal addition and charcoal in combination with mineral fertilizer was found.

In a different study (Topoliantz *et al.*, 2005), charcoal and manioc peel were added together to an acid sandy clay loam tropical Oxisol. Yard-long beans (*Vigna unguiculata Sesquipedalis*) were cultivated on the soil. The plants grown in soil with the amendment had more pods and significantly higher shoot weight and shoot/root ratio. After the trial the soil with manioc peel and charcoal had significant increased exchangeable Ca and Mg, and significantly lower Al availability, alleviating the possible toxic effects of Al on plant growth.

Decreases Al availability was attributed to the high surface area of charcoal which confers with the high adsorptive capacity for chemical compounds and not to liming effect of charcoal since the charcoal had scarcity in nutrients.

A synergistic effect is suspected between charcoal, with its higher surface area and sorptive capacity, and manioc peel with high P content.

Tyron (1948) performed a plant experiment with white pine (*Pinus strobus* L.) in a greenhouse with three non-tropical soils with different texture (sand, loam, clay) and three different amounts of charcoal addition (15, 30 and 45%).
The percentage of seed that germinated decreased with charcoal addition. Tyron explained the high concentration of soluble salts, which decreases the capacity of seeds to adsorb water.
The length of the shoots and total weight decreased with charcoal addition, but this was not statistically significant. The weight of the shoots and roots and the shoot/root ratio shows no difference between the treatments.
Charcoal application increased the amount of available P in the loam and sand soils. The amount of available potash (K_2O) increased 3.2 times in the loam soil and 16.6 times in the sand soil after charcoal addition of 45%. The available Ca increased 15 times in the loam soil and 10 times in the sand soil. The available Mg also increased, but to a lesser extent than Ca. The available forms of N (NO_3^- and NH_4^+) were too small to detect and probably taken up by the seedlings as soon as they became available.

Besides influences on crop growth, plant nutrient and nutrient availability, charcoal addition can also influence nutrient retention of the soil. Nutrient retention in soils can be increased by the presence of more electrostatic adsorption sites (Lehmann *et al.*, 2003), but also through retention of soil water in micro and mesopores. If water percolation is decreased, nutrient leaching will also decrease. Nutrients that are normally leached very easily can be retained by this mechanism (Glaser *et al.,* 2002).

Lehmann *et al.,* (2003) found that charcoal addition to a highly weathered Ferralsol in a leaching experiment significantly increased K content of the soil by nine times. No significant differences were found in other nutrients. Leaching of NH_4^+, Ca and Mg was reduced and NO_3^- and K increased after charcoal addition to the Ferralsol. The ratio of uptake to leaching increased for all nutrients after charcoal was added. This indicates a high efficiency of nutrients applied with charcoal and shows that charcoal amendments can aid in retaining nutrients. The leachate in the Terra Pretas without fertilization had extremely low concentrations of nutrients, while nutrient availability was high compared to the Ferralsol. The soil content of P and Ca was significantly higher in the Terra Preta than in the Ferralsol. The Mg content was lower, while the K content remained the same. The cumulative leaching of NH_4^+, K, Ca and Mg was lower for the Terra Preta compared to the Ferralsol. However, leaching of NO_3^- was higher .

Steiner *et al.*,(2008) reported increased N retention and uptake and concluded that charcoal amendments improve the efficiency of mineral N fertilizer. Novak *et al.*, (2009) found that charcoal addition increased the Ca, K, Mn and P content of the soil after a leaching experiment .However, the S, Mg and Zn content of the soil decreased and the Cu, Mg and Na did not change. The leachates contained more K and Na after biochar application, but less Ca, P, Mn and Zn.

Lehmann *et al.*, (2003) concluded that the increased nutrient efficiency was the result of increased adsorption sites, since charcoal addition did not decrease water percolation, but did significantly increase CEC after charcoal addition to the Ferralsol. However, no significant difference was found between the Ferralsol and the Terra Preta.

Charcoal has oxidized functional groups that originate from oxidation of charcoal itself or from adsorption of partially oxidized charcoal or other materials. This surface oxidation is the cause of the increased CEC and nutrient retention (Liang *et al.*, 2006).

Novak *et al.*, (2009) also reported a slight increase in CEC after 2% charcoal application. Rondon *et al.*, (2007) and Steiner *et al.*, (2007) both found increased CEC although this was not statistically significant.

2.5 Influences of charcoal on physical soil properties of non-tropical soils

Research on charcoal addition to the soil has focused on chemical properties and influence on crop growth in the tropics. No specific research has been found on physical properties of soils in the tropics, but Tyron (1948) performed greenhouse experiments on the influence of charcoal on physical soil properties of non-tropical soils with different textures (sand, loam and clay).

The results of these experiments are described below.

2.5.1 Moisture equivalent

The moisture equivalent is the percentage of water which a soil can retain after a centrifugal force 1000 times that of gravity.

The addition of 0, 15, 30 and 45% charcoal resulted in a significant linear increase in moisture equivalent in a sand soil with values of 10.11, 10.82, 11.77 and 12.89% respectively. Fine pieces (1 mm) of charcoal were more effective in increasing the moisture equivalent in the sand soil.

No significant changes in moisture equivalent after charcoal addition to the loam soil.

In the clay soil the moisture equivalent caused a significant linear decrease from 31.57, 28.90, 27.70 to 26.52% respectively with increased charcoal content. Coarse pieces (2-5 mm) were more effective in decreasing the moisture equivalent in the clay soil.

2.5.2 Wilting point

The moisture content at wilting point significantly increased at a linear rate with increased charcoal addition from 3.33, 3.73, 3.96 to 5.13% in the sand soil. In the loam soil wilting point also increased, though at a lower rate from 5.55, 5.68 to 6.04% percent. In the clay soil the wilting point significantly decreased at a linear rate from 14.03, 12.96, 12.36 and 12.01%.

Soils that contained coarse charcoal pieces tend to hold more moisture when wilting of plants occurs than soil that contain fine pieces. The moisture held by coarse pieces is less available for plant uptake, since roots do not penetrate the charcoal pieces and the moisture is held more tightly by capillarity than in fine pieces.

2.5.3 Available moisture in the soil

The available moisture in the soil is the difference between moisture equivalent and wilting point. The available moisture in the sand soil increased with increasing charcoal amounts in the soil from 6.7, 7.1, 7.5 and 7.9%. In the loam soil the available moisture in the soil remained the same at 10.6%. While in the clay soil the available moisture in the soil decreased from 17.8, 16.6, 15.4 to 14.2%.

2.5.4 Rate of evaporation

The increase of charcoal amounts in the soil leads to a decrease in evaporation from the soil for all three soils. However, this affect is greater in the sandy soil than in the clay soil. No explanation for this phenomenon was given.

2.5.5 Time required to reach wilting point

Charcoal increases the wilting point of coarse textured soil and decreases the wilting point of fine textured soils and reduces the rate of evaporation of all three soils under greenhouse conditions. If the evaporation of all treatments were equal (false assumption) wilting point of fine textured soils that contain charcoal would be reached later. However, the wilting point of coarse textured soils would be reached more quickly when charcoal is added since charcoal increases the wilting point of coarse textured soils.

3 Area description

3.1 The Negev

Horvat Haluqim is an Iron Age village that is situated in the central Negev Highlands in Israel (Figure 1) (Bruins, 1986). The Negev Highlands are situated within the Sahara-Arabian desert belt (Avni, 2005). The elevation ranges from 450-1000 m above sea level (Singer, 2007). Inside the Negev Highlands, the main wadis drain northwest to the Mediterranean Sea and northeast to the Dead Sea Basin (Evenari *et al.*, 1961; Avni *et al.*, 2006).

The regional bedrock consists of marine sediments, mainly limestone, dolomite, chalk and chert, of Upper Cretaceous to Tertiary Age (Zilberman 1981, Zilberman 1991; Avni 1991 in Avni *et al.*, 2006).

The northern part of the central Negev Highlands is composed of a series of parallel anticlines and synclines that run in northeast-southwest direction (Avni *et al.*, 2006; Singer, 2007). The anticlines are composed of hard carbonate rocks (limestone and chert) of Cenomanian-Turonian age. Soft carbonate rocks and chert are exposed in the synclines of Senonian-Paleocene age (Arkin and Braun, 1965; Zilberman,1991 in Avni *et al.*, 2006). Most of the valley bottoms are filled with Late Pleistocene to Holocene sediments deposited during the last glacial interval (Avni, 1991; Zilberman, 1992 in Avni *et al.*, 2006). The southern part of the central Negev Highlands consists of undulating plains, mesas and buttes built of Eocene and Mesozoic limestone, chalk, soft shales and flint beds (Singer, 2007). The largest part of the Negev, 60-65%, is composed of rocky desert with bare rocks and desert lithosols. Around 5-10% are loessial plains with soils that are characterized by secondary carbonate formation. The remainder is composed of sedimentary plains or plateaus covered by a desert pavement, sand dunes or ephemeral stream channels and alluvial fans (Bruins, 1986).

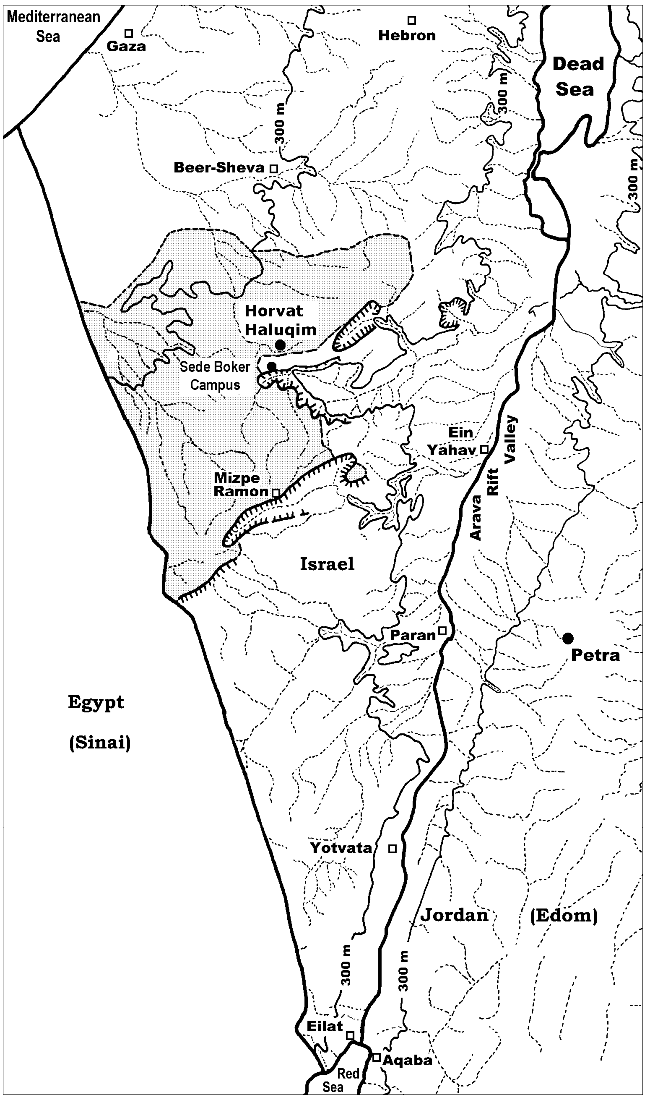

Figure 1 The central Negev Highlands (shaded area) Source: (Bruins, 2007)

The climate conditions are arid with the typical climate of a winter rainfall desert (Bruins, 1986). The rainy season is from October until April, but most precipitation falls in the months December to February (Avni, 2005).

In Sde Boker (a kibbutz approximately 2 km southwest of Horvat Haluqim), the average annual rainfall is less than 100 mm per year, with interannual fluctuations of 30.9 mm to 167.3 mm in the years 1951 to 1980. The average annual temperature is 18.2º C. The average temperature is the coldest month, January, is 3.9º C at night and 15.4º C during the day. The average temperature in the hottest month, August, is 17.8º C at night and 32.8º C during the day. The average amount of rainy days is 26 (from 1951 to 1980) (Bruins, 1986). Most precipitation falls in low-intensity rainstorms of less than 5 mm h^{-1} (Sharon, 1972; Sharon and Kutiel, 1986 in Avni *et al.,* 2006). About half of the rainy days have less precipitation than 1 mm d^{-1}. More than 10 mm d^{-1} only occurs on around three days per year. A rainfall of 25 mm d^{-1} is only expected once every two years (Bruins, 1986). Occasionally there are short-lived, small scale (10-50 km^2), but intense rainstorms with an intensity of 30-120 mm h^{-1} for several minutes that can cause floods (Sharon, 1972; Sharon and Kutiel, 1986 in Avni *et al.,* 2006).

The annual evaporation ranges from 2000 to 2500 mm and the P/EPT ranges from 0.04-0.07 (Avni, 2005), making this an arid zone according to the aridity classification of UNESCO (UNESCO, 1979).

Soils in the central Negev are calcareous and saline (Singer, 2007). They are influenced by the influx of aeolian dust and salt that originates from the Sinai Desert (Evenari *et al.*, 1982; Bruins, 1986). Low annual precipitation prevents the salts from leaching which leads to an accumulation in the soil profile (Singer, 2007). Soils in the Negev are loess soils and at Horvat Haluqim they contain approximately 60% silt (Bruins, 1986).

3.2 Run off farming practices

In the Negev desert there are relatively large areas where the soil is suitable for agriculture and the only missing requirement is water, since arid and hyper arid climates are too dry for normal rainfed agriculture (Evenari *et al.*, 1961; Bruins, 1986). In the Negev, loessial soils of 1-2 meters in depth have accumulated in not too steep wadis, floodplains and depressions (Evenari *et al.*, 1961).

To be able to perform sedentary agriculture it is necessary to use the small amount of precipitation to its maximum (Evenari *et al.*, 1961), since springs and wells in the Negev are few and the amount of water that can be tapped from them is very limited. Besides, their water is sometimes slightly brackish and their potential for irrigation agriculture has always been negligible. Therefore, alternative sources of water had to be used (Bruins, 1986).

An alternative that was practiced in the Negev in the past is run-off farming. A run-off farm consisted of cultivated fields and a surrounding catchment basin. Normally, the small amounts of precipitation are only enough to wet the soil to a very shallow depth and the soil will dry through evaporation before the plants can use it. However, loess soils tend to form a slaking crust when they become wet. This decreases the infiltration rate and increases run-off. The loessial hillslopes become impermeable after wetting and these hillsides were used as catchment area to produce run-off that was directed to the small area with cultivated fields (Evenari *et al.*, 1961).

There are different types of run off farming, but in Horvat Haluqim the terraced wadi system was used. In this system the agricultural fields are situated in the valleys (wadis), where run-off tends to concentrate naturally (Bruins, 1986). Inside the wadis dry stone check-dams at right angles of the wadi were constructed. These man-made structures stabilized the soils in the wadis and increased their thickness through sedimentation against the check-dams. The terraces retained water flow and conserved the water for infiltration into the soil, allowing it to be stored for use by agricultural crops. With this method it was possible to collect sufficient water to ensure crops (Evenari *et al.*, 1961; Bruins, 1986; Rubin, 1991; Singer, 2007).

In the past hundreds of wadis were terraced with check-dams in the Negev desert (Bruins, 1986).

3.3 Horvat Haluqim

The village of Horvat Haluqim consisted of an oval fortress (21 x 23 m), seven four room houses, several other buildings and four cisterns to collect run-off water for human consumption. The village was built along three parallel wadis with terraced fields (Figure 2). The three wadis are of the first or second order tributary wadis that drain in southward direction to Nahal Haroa (Bruins, 1986; Bruins and Ore, 2009).

Horvat Haluqim is situated at the Haluqim Anticline, about 50 km south of Beer Sheva. Stratigraphic radiocarbon dates show that the site was used for agriculture as early as the Middle Bronze Age (2200-1550 BC) (Bruins and Van der Plicht, 2007), although the lowest part of the anthropogenic terrace soil is much older, indicating that the beginning of run-off farming in the region predated the Bronze Age. Agriculture continued until the Early Arab Period (634-1099 AD) (Bruins and Ore, 2009).

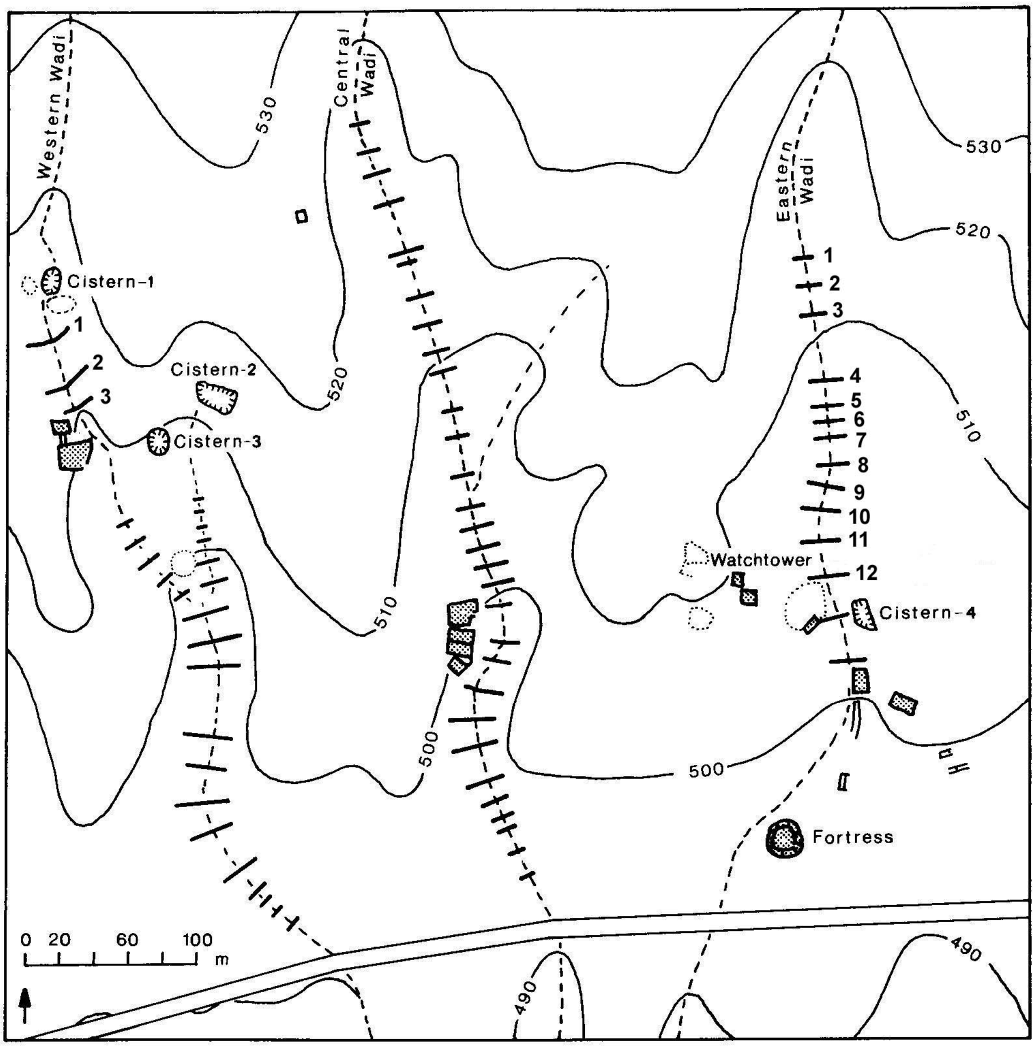

Figure 2 Map of the three wadis, with the location of the terraces, cisterns and various buildings, at Horvat Haluqim
Source: (Bruins and Ore, 2009)

At Horvat Haluqim distinct evidence of past soil manuring and run-off farming practices have been found. Small pieces of animal bones and charred organic matter (including charcoal) have been found in anthropogenic soil layers. The presence of large amounts of spherulites strongly suggests the use of animal dung as manure (Bruins and Van der Plicht, 2007). The presence of tiny pieces of charcoal and bone particles indicates that the local inhabitants also used home refuse to manure the soil in order to increase fertility, which is normally low in a desert environment (Bruins, 2007).

Field work was conducted in the eastern wadi (Figure 3). This wadi contains 13 terrace walls and agricultural fields. The catchment size of this wadi is approximately 8 ha. The length of the wadi is ca. 500 m and the width is on average 160 m. The hillslopes along the wadi are concave with slopes ranging from a few degrees at their upper parts (near the water divides) and up to 30° near the wadi. The altitude ranges from 490 m in the south to 546 m in the north (Bruins and Ore, 2009). The lithology of the hill consists of well bedded hard limestone and minor chalk layers. At the lower part of the slopes the bedrock of poorly bedded limestone is exposed (Bruins, 1986).

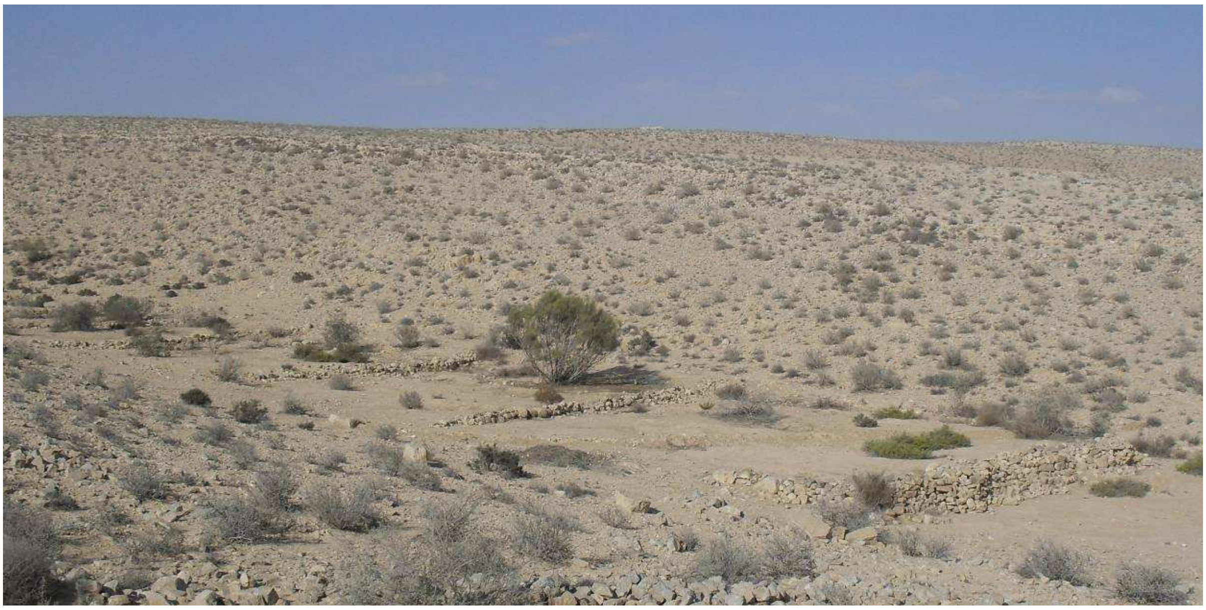

Figure 3 Eastern wadi of Horvat Haluqim

The soil cover on the hillsides of the wadi is limited, patchy and shallow. Bare rock outcrops occur frequently (Bruins, 1986). Behind terrace walls a significant amount of soil has accumulated, especially in the middle of the terraces where the depth to the bedrock is largest. The soil depth was sometimes more than 2 meters. The dominant soil textures are loam and silt loam.

4 Materials and methods

4.1 Field work

To answer the first research question, field work was conducted at Horvat Haluqim to determine the soil properties of the dark anthropogenic horizons and non-anthropogenic horizons. In the eastern wadi of Horvat Haluqim 10 soil pits were dug. This wadi was chosen for practical reasons. Since Horvat Haluqim is an archeological site, field work can only be conducted on locations for which the Israel Antiquities Authority has given permission.

The soil pits were named according to the terrace (T) in which they were dug, followed by a specification of the area (A) that identifies different pits in the same terrace. For example, soil pit number 1 in terrace 10 is named T10A1. The location of the pits was based on permission of the Israel Antiquities Authority to dig in certain terraces, as well as the spatial distribution of the terraces throughout the wadi and the spatial distribution and condition of the soil surface (erosion, height, vegetation etc.) within a specific terrace.

Five soil pits were chosen for analysis of chemical and physical soil properties. These were T10A1, T12A3, T12A7, T13A1 and T13A3 (Figure 4). These soil pits were chosen, because they had clearly observable dark anthropogenic horizons and because of differences in the intensity of the colour and the depth at which the anthropogenic A horizon was found.

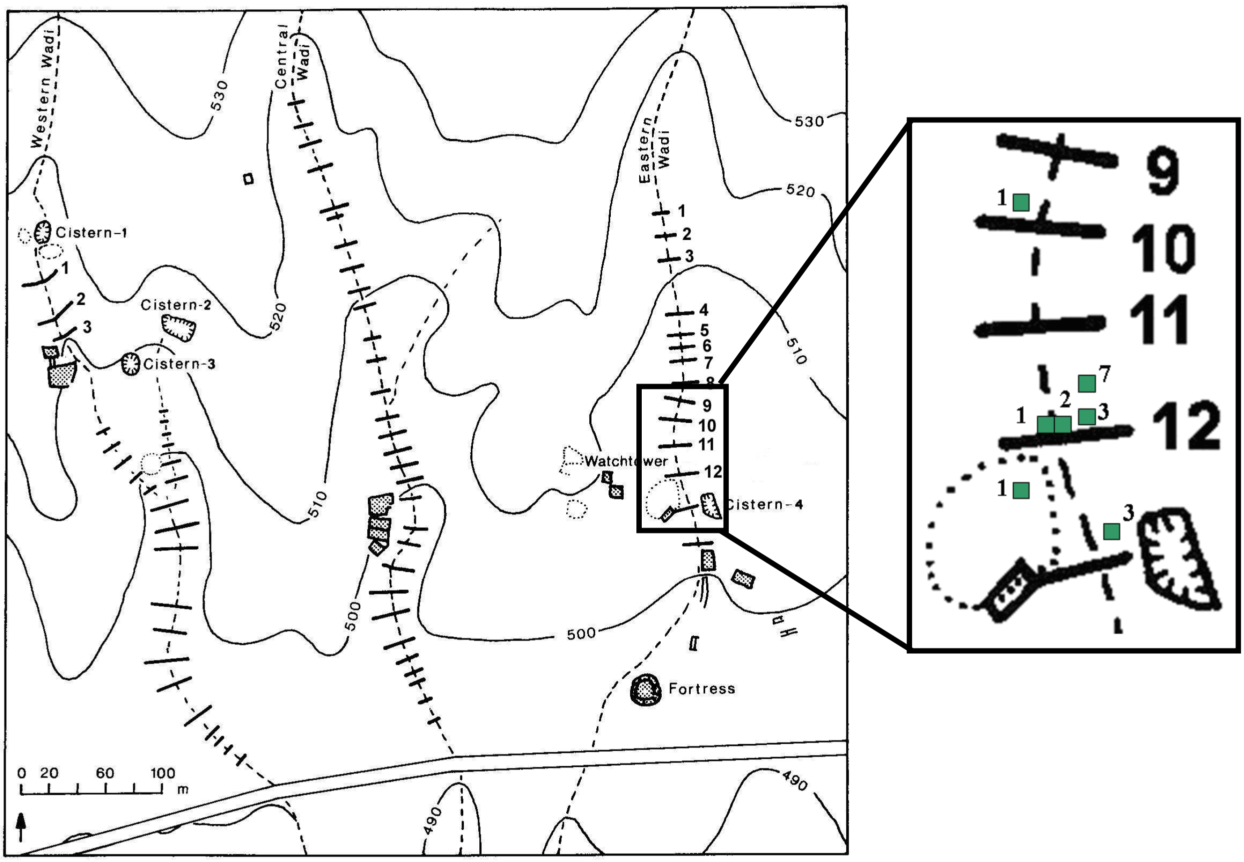

Figure 4 Location of the analyzed soil pits in the eastern wadi. Soil pits T12A1 and T12A2 were dug by Bruins (1986)
Adapted from (Bruins and Ore, 2009)

Soil colour using Munsell colour charts was used to distinguish between anthropogenic soil horizons (Aa) and non-anthropogenic soil horizons (C). Soil pits were described in the field at different parts of the day which influenced the way the soil colour is perceived. This resulted in soil horizons from different pits with the same colour, but with a different classification. Therefore, the colour of all soil horizons was determined again when samples where taken from the field.

In this study, horizons with the Munsell colour 10YR 7/6 (yellow), 10 YR 7/4 (very pale brown), and 10YR 6/4 (light yellowish brown) were classified as non-anthropogenic horizons (C), since these are normal colours of the loess in the Negev desert (Bruins, 2009 pers. com.). Soil horizons with the darker colours 10YR 7/3 (very pale brown), 10YR 7/2 (light gray), 10 YR 6/3 (pale brown) and 10 YR 6/2 (light brownish gray) were classified as anthropogenic soil horizons (Aa).

The analysis of chemical and physical soil properties described below were performed on all soil horizons of the above mentioned soil pits, except for the bulk density and saturated hydraulic conductivity. The bulk density was not determined for soil horizons that were very thin (5 cm), because it was not possible to collect large enough aggregates. From T10A1 only the most distinct soil horizons were chosen, because of time constraints.

4.1.1 Chemical analyses

pH

The pH was determined on air dried soil in a 1:2 soil/water suspension (m/V) with a glass electrode as described in the 'Guide to laboratory establishment for plant nutrient analysis' (Motsara and Roy, 2008). It was determined in duplicate and afterwards the average was calculated. The pH was determined from a bulk monster taken from the whole depth of the soil horizons. pH data of Bruins (1986) of two additional soil pits, T12A1 and T12A2, were also used to analyze possible differences in pH between Aa and C horizons. The respective colours of these soil horizons were not published in Bruins (1986), but the original soil horizon classification was used.

Electrical conductivity

The EC was determined with a conductivity meter in the same soil/water suspension that was used for pH measurement. It was determined in duplicate and afterwards the average was calculated.

EC data of T12A1 and T12A2 (Bruins, 1986) were also used to analyze possible differences between Aa and C horizons.

Charcoal content

The charcoal content of the soil was determined using peroxide/weak nitric acid digestion (Kurth *et al.*, 2006). This method is described in detail by Van Asperen (2010).

The analysis was done in duplicate. To analyze possible differences between soil horizons the average charcoal content was used. The charcoal content was determined from a sample that was not taken over the whole depth of the described soil horizons. To analyze the relation between charcoal content and other soil properties it was assumed that the charcoal content of the whole horizon was uniform. When the charcoal content was determined from different samples taken from different depth of the same soil horizon, the average charcoal content was used.

The charcoal content of T12A3 at 60-70 cm depth is based on one value, because one sample was disturbed during the analysis and was therefore omitted.

4.1.2 Physical analyses

Soil structure and colour

The soil structure was described according to the Guidelines for Soil Description of the FAO (FAO and ISRIC, 1990). To describe the soil colour, the Munsell colour (Munsell Color Company, 1992) was determined on dry soil, because differences in colour were more pronounced in dry soils than in wet soils.

Particle size distribution and texture class

The particle size distribution was determined with the hydrometer method. For this a ASTM 152H (Bouyoucos style) hydrometer was used.

Before particle size distribution analysis, the soil samples were oven dried for 72 h at 105° C, after which the soil was crushed and stones were removed through sieving with a 1000 μm sieve.

To cause dispersion of soil aggregates 100 mL of 2.5% sodium pyrophosphate ($Na_4P_2O_7.10H_2O$) solution was diluted with 300 mL of deionized water and 50 g soil was added. The suspension was stirred mechanically for 30 min.

After dispersion of the soil aggregates the procedure as described in the ‘Guide to laboratory establishment for plant nutrient analysis’ of the FAO was followed (Motsara and Roy, 2008)

The texture classes were classified according to the USDA texture diagram (USDA Soil Survey Staff, 1994).

Bulk density

The bulk density was determined with the intact clod method (Cresswell and Hamilton, 2002). This was done because it was not possible to use the core method, because during the collection of core samples the soil was crumbled and fell out of the cores.

The intact clod method involves coating of soil aggregates with paraffin wax in order to allow the measurement of volume by displacement of water.

This method is based on Archimedes’ principle which states that an object submerged in a fluid is buoyed up by a force equal to the weight of the displaced fluid. An object submerged in water weighs less than and object weighed in the air. This is because water exerts a buoyant upward force that partially counters gravity. The buoyant force depends on the density of the fluid and the volume of the object. The difference in weight of an object in air and water equals the weight of the displaced water. The volume of the completely submerged object can be calculated from its known weight of displaced water. The volume equals the mass of the displaced water divided by the density of the water.

In order to determine the bulk density a fine cotton thread was attached around the aggregates after which the soil aggregates were weighed in the air on a balance (W_1). The weight of the thread was assumed to be negligible. The aggregates were dipped into a bath with molten wax and quickly withdrawn to prevent penetration of wax into the aggregates. The clods were checked for blisters and imperfections. If necessary they were inserted into the wax bath again and minor repairs were made using drops of molten wax. After the wax had cooled down, the coated aggregates were again weighed in air (W_2).
The volume of the aggregates was determined through submersion in water. A beaker with water was weighed (W_3) and the coated aggregates were suspended from a fixed support and totally submerged in the water. The difference in weight is equal to the weight of the displaced water (W_4). The volume of the object equals the weight of displaced water, divided by the density of the water (1.0 g/cm^3).

To determine the gravimetric water content of the aggregates the wax was peeled of carefully and the aggregates were reweighed in the air (W_5) and dried in the oven for 72h at 105° C. The removal of small amounts of soil from the aggregates is assumed not to influence the water content of the aggregates, because the water content distribution through the aggregates was assumed to be uniform, since the soil had a very low water content. Afterwards the oven-dry weight was determined (W_6).

For every soil horizon, the average bulk density of three aggregates was determined.

Calculations

Weight of wax (g) $$W_{wax} = (W_2 - W_1)$$

Volume of wax (cm^3) $$V_{wax} = \frac{W_{wax}}{\rho_{\mathrm{wax}}}$$

Water content of clod (-) $$\theta_g = \frac{(W_5 - W_6)}{W_6}$$

Dry weight of original clod (g) $$M_s = \frac{W_1}{1 + \theta_g}$$

Volume original clod (cm^3) $$V = V_{clod+wax} - V_{wax} = \frac{(W_4 - W_3)}{\rho_w} - V_{wax}$$

Bulk density of original clod (g cm^{-3}) $$\rho_d = \frac{M_s}{V}$$

The density of paraffin wax (ρ_{wax}) was determined at 0.92 g cm^{-3}.

Differences in bulk density between Aa and C horizons were analyzed with the independent t-test.

Infiltration capacity and saturated hydraulic conductivity

The saturated hydraulic conductivity and cumulative infiltration were determined with a single ring infiltrometer with a diameter of 30 cm that was inserted 10 cm into the ground. The maximum water ponding depth was 5 cm and the minimum water ponding depth was 3 cm. When the minimum water depth was reached the water level was manually raised to 5 cm. The infiltration capacity was measured with increasing intervals, starting with intervals of 1 minute and ending with intervals of 5 minutes. The experiment was ended when the infiltration capacity more or less reached a quasi steady state and no longer seemed to decrease.

The infiltration experiment was done twice, once in an Aa horizon and once in a C horizon. The Aa horizon of T12A3 was chosen for practical reasons, since it was relatively close to the surface and dark in colour. The experiment was repeated on the C horizon at the surface in terrace 12 close to area 3.

The field saturated hydraulic conductivity (K_{sf}) is assumed to be steady state infiltration capacity (q_s) (Reynolds *et al.*, 2002).

4.2 Pot experiment

To answer the second research question a pot experiment was performed in which wheat (*Triticum aestivum* L. Yuval 1225, from Agridera Seeds & Agriculture Ltd) was grown on five different soils and under two different water regimes. Wheat was chosen because it is relatively fast growing, suitable for semi-arid conditions (Agridera, year unknown) and because wheat was most likely grown in the wadis of Horvat Haluqim in the past.

The pots contained soil from the Aa horizon from Horvat Haluqim or normal loess soil from the C horizon, with or without addition of charcoal or ash (Table 3).

Table 3 Soil types in pot experiment

Soil types	Abbreviation
Loess (control)	L(0)
Loess + 7.5% charcoal (w/w)	L(7.5)
Loess + 15% charcoal (w/w)	L(15)
Anthropogenic soil	A
Loess + 7.5% ash (w/w)	B

The loess soil was collected from terrace 12 in the eastern wadi of Horvat Haluqim. The top 45 cm of the soil was collected from T12A3 and homogenized. This soil has a silt loam texture, a pH of 8.7 and an EC of 0.3 dS/m.
The anthropogenic soil was collected from T12A3 at a depth of approximately 50-90 cm, because the anthropogenic layer was darkest at this depth. This soil also has a silt loam texture, a pH of 8.9 and an EC of 0.2 dS/m.

Lump charcoal was obtained from the local supermarket and mixed throughout the whole soil in the pot after it was crushed to dust and pieces smaller than 1 cm in size. The ash was received from a Bedouin family living in the region. This Bedouin family has a traditional fire place for cooking and heating water, using local vegetation from dead shrubs and also wood, originating from various sources, usually from outside the region. It contained mainly ash and a few tiny pieces of charcoal, but also some other pieces of household waste such as nails, some other pieces of metal, pieces of glass and a cigarette end. These pieces were removed from the ash as much as possible before mixing it with the soil.

The plants were also subjected to two different water regimes. The first treatment (W) was well watered to approximate field capacity. Plants in the second treatment (D) stopped receiving water after 20 days.

The plants were grown in 1 m long PVC pipes that are 10 cm wide (81 cm^2) and open at the bottom to allow drainage to take place. This gave the soil a water pressure head of -100 cm (pF 2). This set up is chosen because the local loess soil contains around 60% silt and needs a

sufficient amount of negative pressure to release enough water to obtain moisture conditions that allow plants to grow without hindrance from too wet conditions.
The bottom of the pipes were covered using 2 mm mesh wire (horrengaas) that was folded several times and taped to the outside of the pipes. A piece of felt was inserted at the bottom of the pipe to prevent soil from draining away.

The plants were grown at approximate field capacity. This was determined with the gravimetric moisture method. After the pots had been filled with soil, the soil was saturated with water. The pots were left to drain for 3 days. It was assumed that the soil had now reached field capacity.
After germination the plants were thinned so three seedlings per pot remained to avoid competition for light and space. After sowing the pots were well watered for 20 days. The pots were weighed every two days to determine the amount of water that was lost through evapotranspiration and drainage. The amount of lost water was replenished with tap water to the determined approximate field capacity.
On the 22^{nd} day the two different water regimes were applied. The pots in the well watered treatment (W) continued to be watered once every two days, while the pots in the water deficit treatment (D) received no more water. This way of imposing drought stress was chosen, because this is the physiological correct way of imposing drought stress in plants, since this resembles what happens in an agricultural field (Blum, year unknown). The experiment lasted 40 days.

The experiment was done in triplicate for every combination of soil type and water regime. In total there were 30 pots. The pots were placed in a greenhouse according to a randomized design.
The pots were named according to their treatment. The first letter indicates the water regime (W or D). The second letter indicates the soil type (L(0), L(7.5), L(15), A or B) and the digit indicates a specific pot in a specific treatment.

Plant analysis

There are several crop growth characteristics, such as cumulative growth, shoot and root biomass and the ratio between root and shoot biomass that can be used to compare crop performance of plants grown under different circumstances. They can also indicate whether plants are suffering from stress (Grundon, 1987). If plants show reduced growth this is a sign that growth conditions are below optimal and growth characteristics of different plants can be used to give information about the suitability of growing conditions.

These characteristics can also be used to give information about the possible causes of differences in growth.

To compare crop growth of the plants grown in different treatments, several growth characteristics were analyzed.

Cumulative crop growth

This was determined by measuring the length of the plants every two days

Dry shoot and root biomass, shoot/root ratio

Biomass was dried at 65º C for 48h and weighed

Statistical analysis

To test whether differences in cumulative crop growth within the two moisture regimes are statistically significant it was analyzed with One-Way Independent Post Hoc ANOVA.

Post hoc tests compare all different combinations of treatment groups. It is different from performing t-tests for each pair of groups in that the familywise error can be controlled.

Bonferroni's test was chosen, because this test has absolute control over the Type I error (test shows a statically significant effect, while there is not). However, there is always a trade off between the Type I error and the statistical power of a test. Bonferroni's test lacks statistical power, it is a conservative test. This means that the probability of a Type II error is high (test shows no significant effect, while in fact there is) (Field, 2009).

The differences in mean crop height were rather large, between the treatments in which differences in crop height were expected. That is why Bonferroni's test was chosen.

To make sure not to violate the assumptions of parametric tests the data of the W treatment were transformed. This was done by taking the square root of the log transformed data (√log (crop height)). The data of the D treatment did not have to be transformed.

To test whether differences in cumulative crop growth between the two moisture regimes are statistically significant the Independent t-test was used. This was done with the cumulative crop growth at the end of the experiment and with the cumulative crop growth on the 22nd day, when the plants in the D treatment received no more water for the first time. This was done to make sure that any statistically significant differences at the end of the experiment did not already exist before the water treatments were applied.

The data of some of the combinations had to be transformed in order not to violate the four assumptions of parametric tests. To perform a t-test on the data at the end on the experiment the data of WA and DA were transformed by taking the square root of the crop height and the data of WL15 and DL15 had to be transformed trough reciprocal transformation (1/Xi).
In the t-test at the end of the experiment a 1-tailed test was used because it was hypothesized that plants in the W treatment would perform better than those in the D treatment.
For the t-test at the onset of the water regimes only the data of WL(0) and DL(0) had to be transformed. This was also done trough reciprocal transformation (1/Xi).
In the t-test at the onset of the two moisture regimes a 2-tailed test was used because no specific difference between the W and D treatment were hypothesized.

In both ANOVA and the independent t-test a standard criterion of .05 was used.

It was not possible to perform statistical analysis on the biomass data, since the biomass of the three plants in one pot were dried together and not enough data was available to perform statistically meaningful analysis.

In the analysis of cumulative growth and biomass, the data of plants in pot DB3 were not included, because these plants germinated 6 days later compared to the plants in other pots and the plants did not have the time to catch up in there cumulative growth and biomass production.

5 Results

5.1 Soil properties of anthropogenic and non-anthropogenic soil horizons

The charcoal content of samples taken at different depths in different soil pits (Van Asperen, 2010) are displayed in Table 4. The charcoal content is very low, ranging from 0.06 to 0.19%.

Table 4 Charcoal content of different soil horizons at Horvat Haluqim

Soil Pit	Depth (cm)	Charcoal content (%)
T10A1	140*	0.163
T10A1	170*	0.146
T10A1	>205	0.056
T12A1	51-56	0.060
T12A3	0-3	0.170
T12A3	25-29	0.100
T12A3	50-57**	0.190
T12A3	60-70**	0.146
T13A3	26-32	0.101

* and ** belong to the same soil horizon

No consistent difference exists in charcoal content between the charcoal content of Aa and C horizons (Figure 5). In T10A1 the Aa horizon has a higher charcoal content than the C horizon, while in T12A3 the C horizon has the highest charcoal content compared to the Aa horizons even though the difference in colour is quite distinct (Figure 6)

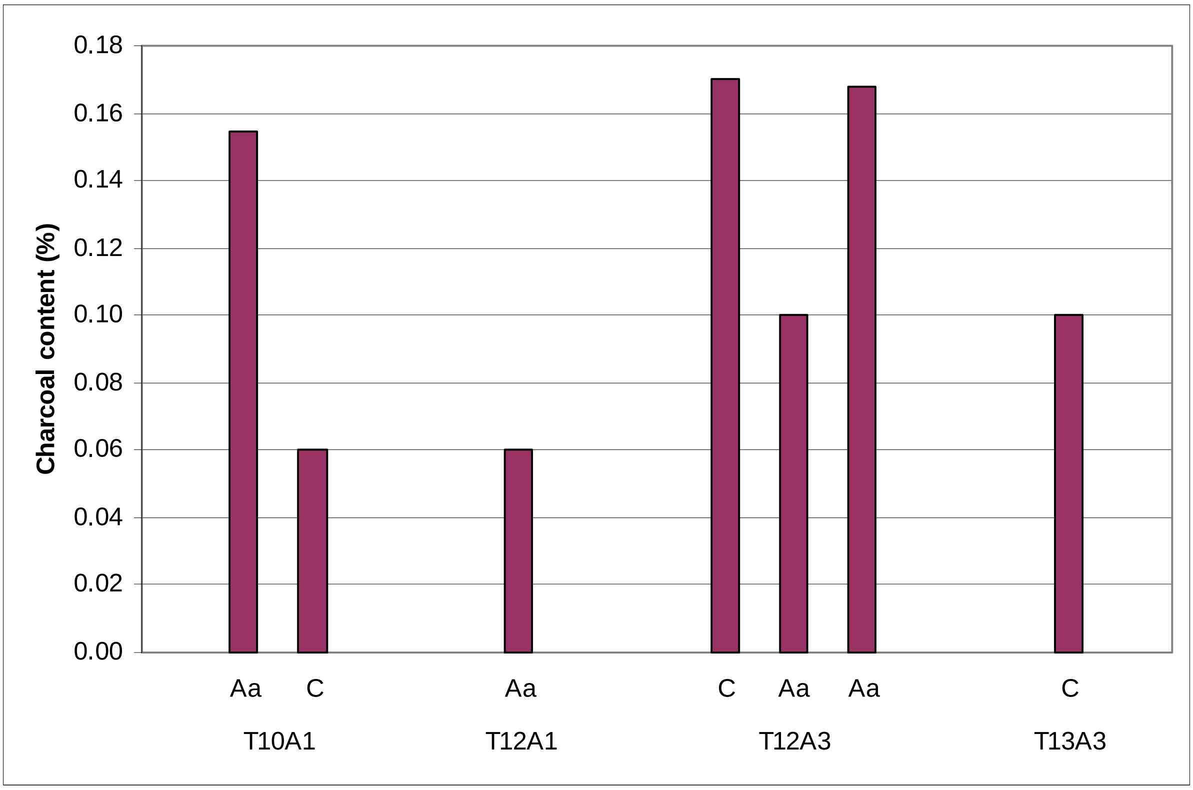

Figure 5 Charcoal content of different soil horizons


Figure 6 Difference in colour between the dark Aa horizon and the light C horizon in T12A3

Differences in other soil properties are described below. The complete database of determined soil properties can be found in Appendix A.

5.1.1 Soil colour

The soil colour does not seem to be related to the charcoal content of the soil (Figure 7). Soils with a darker colour do not consistently have a higher charcoal content than soils with a lighter colour. This is especially apparent in the soil horizons with value 7. The two soil horizons with colour 10 YR 7/4 have both the lowest and the highest charcoal content. Although, it must be mentioned that the charcoal content of all horizons is very low.

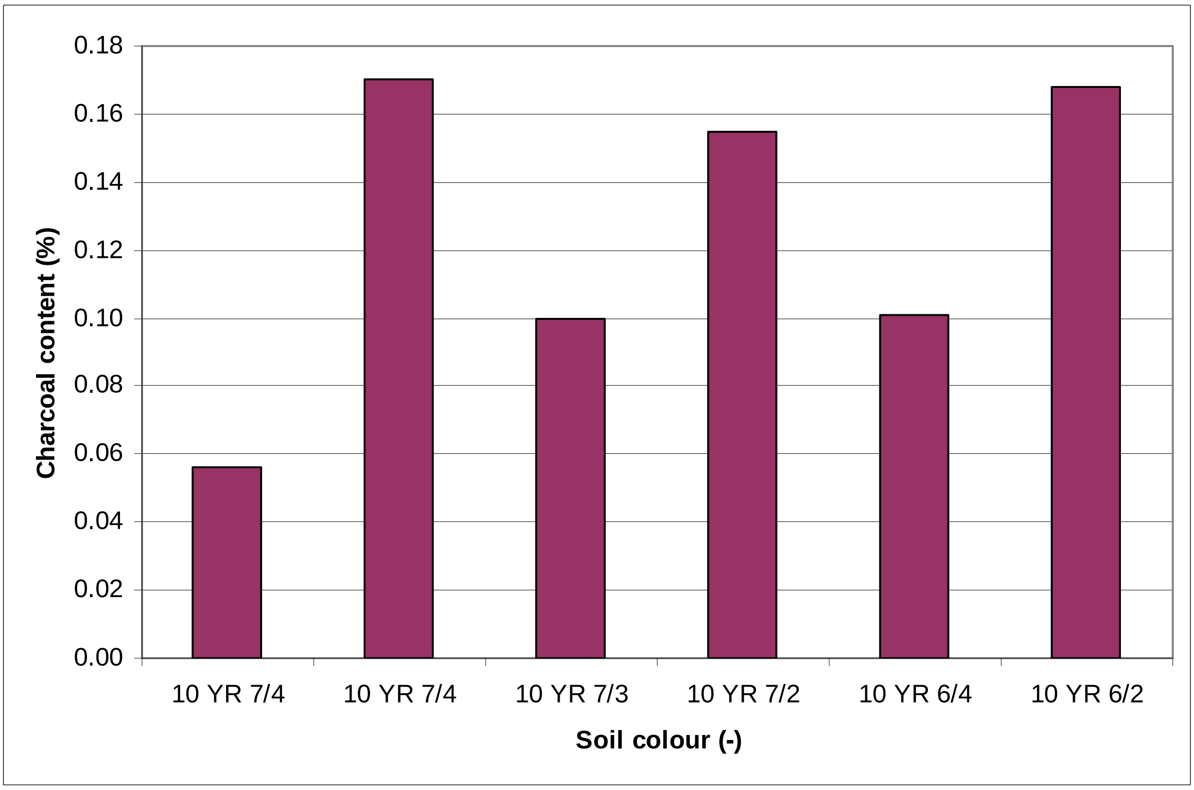

Figure 7 Charcoal content of soil horizons with different soil colour. From left to right the soils become increasingly darker.

5.1.2 pH

There is quite some variation in the pH of the soil in the eastern wadi of Horvat Haluqim.

The pH ranges from 7.4 in all horizons of T12A1 to 9.3 in the calcic horizons of T12A7 and T13A1 (Appendix A). According to the soil reaction ratings of the FAO the soil is moderately to strongly alkaline (Motsara and Roy, 2008).

The pH of soil pit T12A1 and T12A2 were determined by Bruins (1986) using a 1:1 soil/water solution, while the pH of the other soil pits was determined using a 1:2 soil/water solution.

Part of the difference in pH measured by Bruins (1986) and the pH of the other soil pits could be due to the different soil water ratios. In general, a more dilute suspension leads to a higher pH measurement in both acid and alkaline soils (Jackson, 1958). To compare the difference in pH measured by the different methods, the pH of horizon IIIA of T12A1 was also determined in a 1:2 soil/water solution. Both measurements gave a pH reading of 7.9. Therefore, it may be assumed that the difference between both methods is small and that the difference in determined pH of soil pits T12A1 and T12A2 and the other soil pits is caused by a genuine difference in soil pH and not by a different method of determination.

There is variation between the pH of different terraces, between soil pits in the same terraces and within in soil pits (Figure 8).

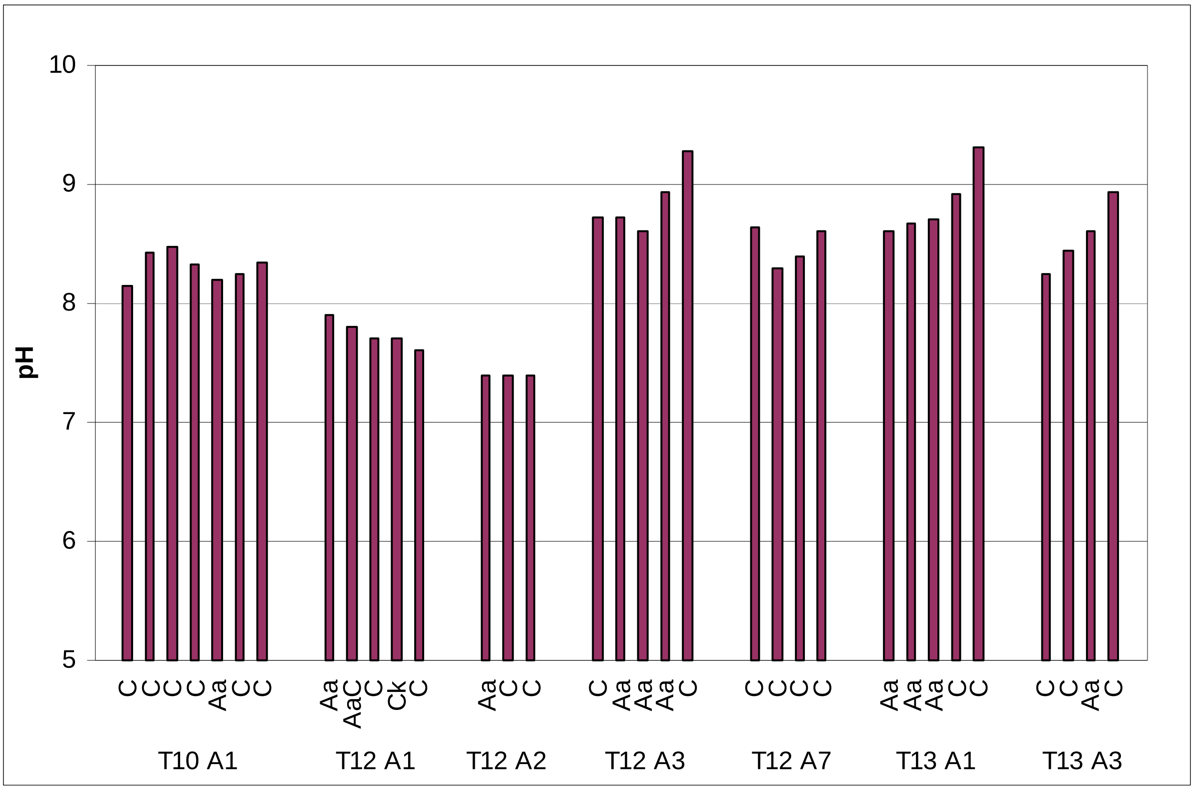

Figure 8 pH of soil horizons of different soil pits

Soil pits T12A1 and T12A2 have a lower pH than the other soils pits. The pH of soil pit T10A1 is higher. Soil pits T12A3 and T12A7 have even higher pH that is comparable to T13A1 and T13A3.
A possible explanation for this pattern is the location of the soil pits in relation to the slopes of the surrounding hills. T12A1 and T12A2 are both located in the middle of the terrace, while the other soil pits are situated in closer proximity of the edge of the terraces and therefore closer the surrounding hills (Figure 4). These locations on the terrace could receive more freshly eroded sediment from the surrounding limestone, which could be a cause of the higher pH.
Within the soil pits there is also variation in the pH. Some soil pits show slightly decreased pH with depth, while others show increased pH with depth. The pH of T12A2 does not change with depth.
The soil pH of T12A1 at a depth of 50-65 cm is 7.8, while in T12A2 at a depth of 50-62 cm it is 7.4. This soil pits are located in close proximity to each other. This shows the variation that can occur within small distances.

The pH of Aa and C horizons does not show any consistent difference between the two horizons within different soil pits. The C horizon has a higher pH in some soil pits, while in others the Aa horizon has a higher pH. There also does not seem to be a relation between charcoal content of the soil and pH (Figure 9). A soil horizon with a higher charcoal content does not always have a higher pH compared to other horizons.

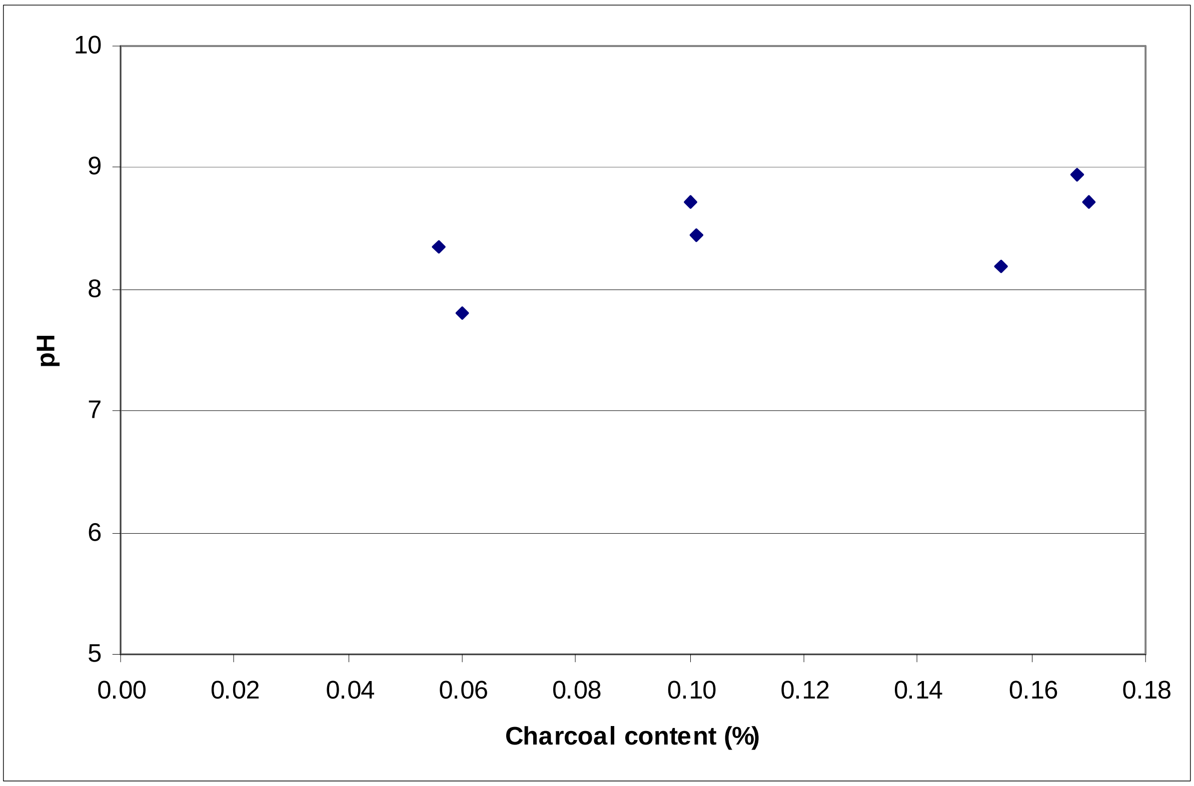

Figure 9 pH of soil horizons with different charcoal contents

The mean pH of the Aa horizons is 8.4 and the mean pH of the C horizons is 8.3. It was not possible to perform an independent t-test because the data of the Aa horizon was not normally distributed even after transformation.

The pH of the soil horizons seems to be more related to spatial location then to be influenced by the presence of constituents inside the anthropogenic layer.

Texture is probably also not a cause of difference in pH, since both soil horizons with low and high pH have varying clay and sand content, ranging from relatively low to high (Appendix A).

5.1.3 Electrical conductivity

The EC of soil pits in Horvat Haluqim is very variable. It ranges from 0.2 to 18.5 dS/m (Appendix A). The EC varies between the soil pits, but also within soil pits (Figure 10).

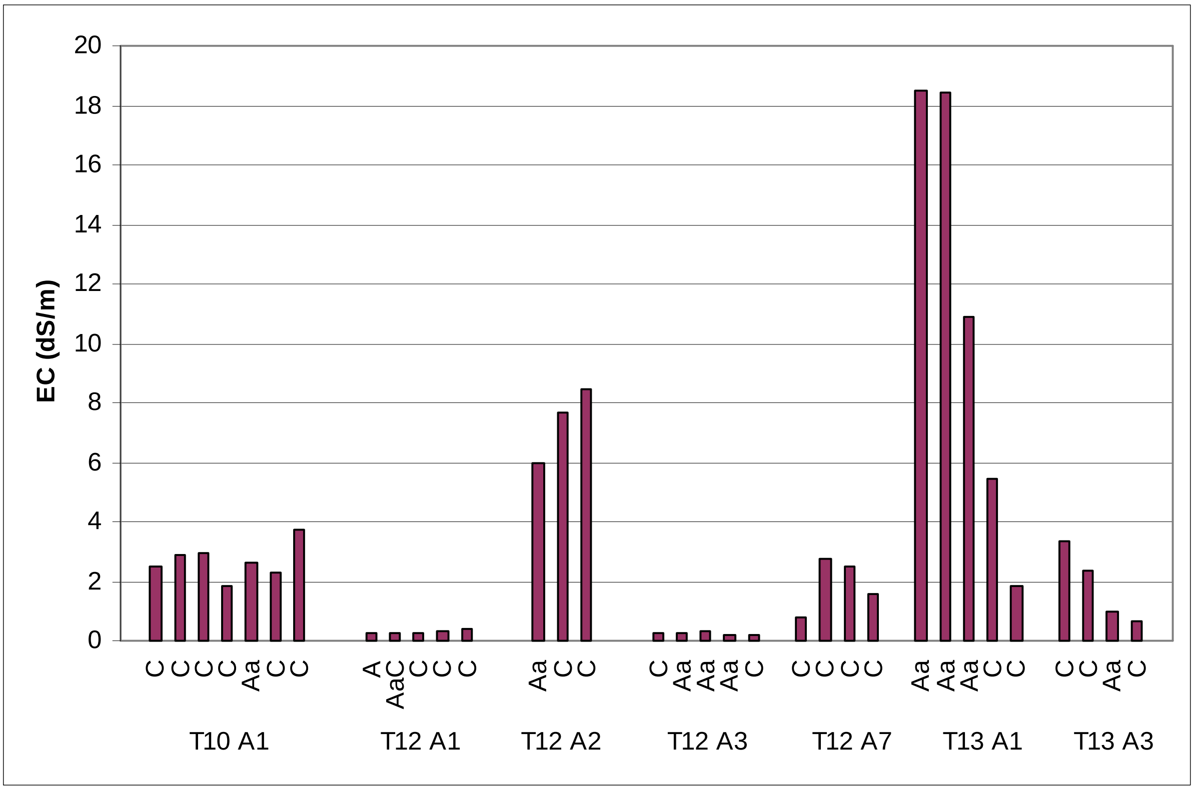

Figure 10 Electrical conductivity of soil horizons of different soil pits

The highest EC is found in T13A1. According to the classification of the FAO (Abrol *et al.*, 1988) the topsoil is very strongly saline (Table 5). The soils in the other pits are classified as moderately or slightly saline and non-saline.

Table 5 Soil salinity classification of the FAO

Soil salinity class	EC (dS/m)	Effect on Crop Plants
Non-saline	0-2	Salinity effects negligible
Slightly saline	2-4	Yields of sensitive crops may be restricted
Moderately saline	4-8	Yields of many crops are restricted
Strongly saline	8-16	Only tolerant crops yield satisfactorily
Very Strongly saline	>16	Only a few very tolerant crops yield satisfactorily

The EC does not differ consistently between Aa and C horizons, but is related to topographic position in the landscape.
Terrace 13 is highly eroded and has a pronounced erosion gully in the lowest parts of the terrace. After a rainfall event run-off water will collect in the erosion gully and flow to terrace 14. The soil on the terrace on either side of the erosion gully has a slope that promotes formation of run-off. Soil pit T13A1 is located furthest from the erosion gully, close to the edge of the terrace. It is situated on one of the highest points of terrace and under a slope. This prevents rain water infiltration and consequent leaching of salts. Soil pit T13A3 is located on a lower topographic position than T13A1 and under a less steep slope. Infiltration of rainwater is most likely higher on this location. This can explain the difference in salt content.
Soil pit T12A3 is located on the lowest parts of terrace 12. During floods this landscape position will collect runoff water and infiltration and leaching of salts can take place. This explains the low salt content in this soil pit. Soil pit T12A7 is located in same line as T12A3 in the length direction of the terrace. This means that it is also located in the lowest section of the terrace, although it is a little bit higher than T12A3, since the terrace has a slight slope towards terrace 11.
Soil pits T12A1 and T12A2 were dug, sampled and described by Bruins (1986). He reports that the terrace wall was slightly affected by erosion and that a very shallow erosion channel is located near T12A1, which suggests that accumulated salts have leached by run-off stream flows. T12A2 has a higher topographic position compared to T12A1. After a rainfall event T12A1 is more likely to be flooded and undergo consequent leaching of salts than T12A2.
The salt content of T10A1 can also be explained by its topographic position. It is situated on a terrace that is fairly unaffected by erosion.

Not only the current state of the terrace can be used to explain differences in salt content. Leaching of salts does not have to be recent. The accumulation of salts in soil may require considerable time, whereas leaching may occur within a few years (Yaalon, 1964; Dan and Yaalon, 1982 in Bruins, 1986). Thus, soil on terraces that are now (partly) eroded, but were not in the relatively recent past, a lower salt content would still be expected since there was not enough time to accumulate salts in considerable amounts.
According to Singer (2007) soil salinity usually starts within 20-50 cm depth and decreases with depth in soil in the central part of the Negev. This is not generally observed in the soil pits that were analyzed. A possible explanation is the influence of past management practices on the natural soil processes.

The EC of Aa horizons is not consistently different than that from the C horizons. In some soil pits the EC of the anthropogenic horizon is higher, while in others it is lower. There also does not seem to be a relation between the charcoal content of the soil and the EC (Figure 11).

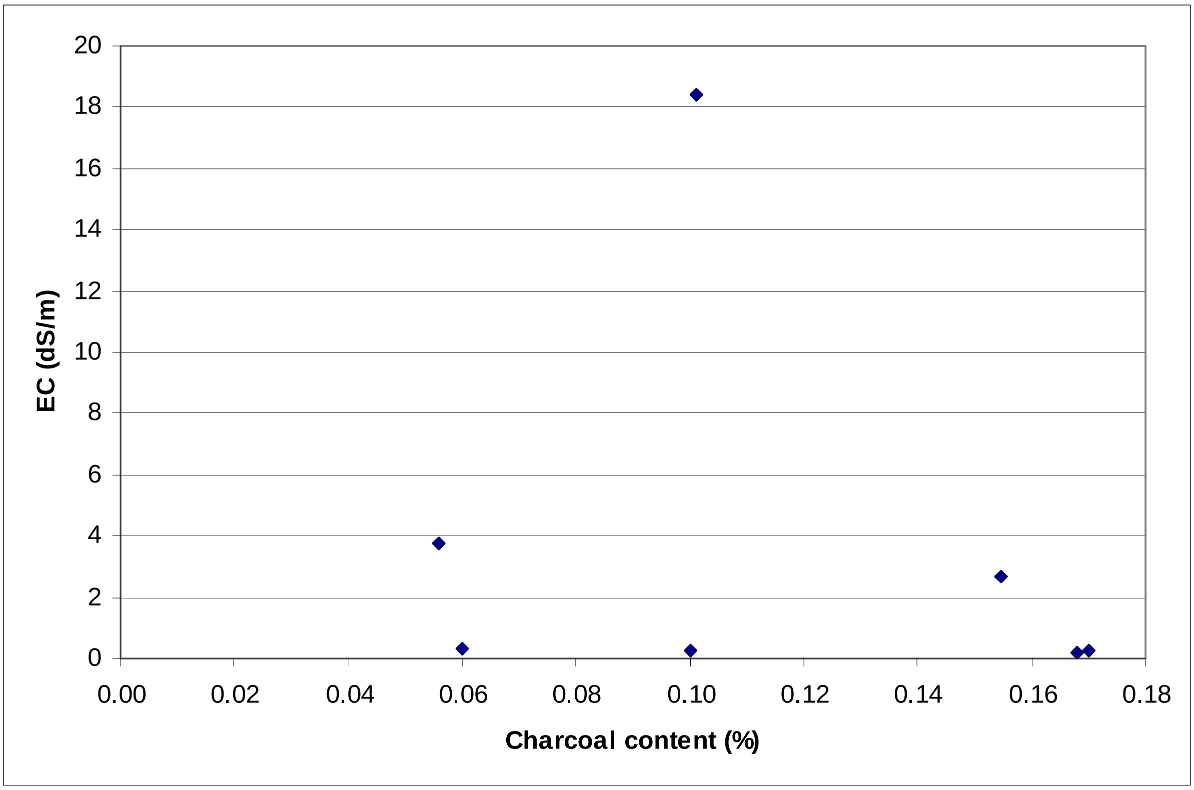

Figure 11 Electrical conductivity of soil horizons with different charcoal content

5.1.4 Soil structure

The soil structure of the soil at Horvat Haluqim ranges from strong to very weak (Appendix A). Table 6 shows the percentage of Aa and C horizons with different structure grades. No consistent difference in structure can be found between the Aa and C horizons. Both have structures ranging from weak to strong. Most Aa horizons do have a weak structure, but so do some C horizons. The difference in structure is therefore probably not a result of the presence of some constituents that are exclusively or more present in the Aa than in the C horizon.

Table 6 Percentage of Aa and C horizons with different structure grades

Horizon	Weak	Moderate	Strong	Σ
Aa	75.00	12.50	12.50	100
C	18.75	43.75	37.50	100

Figure 12 shows that soils with a higher charcoal content do not always have the weakest structure.

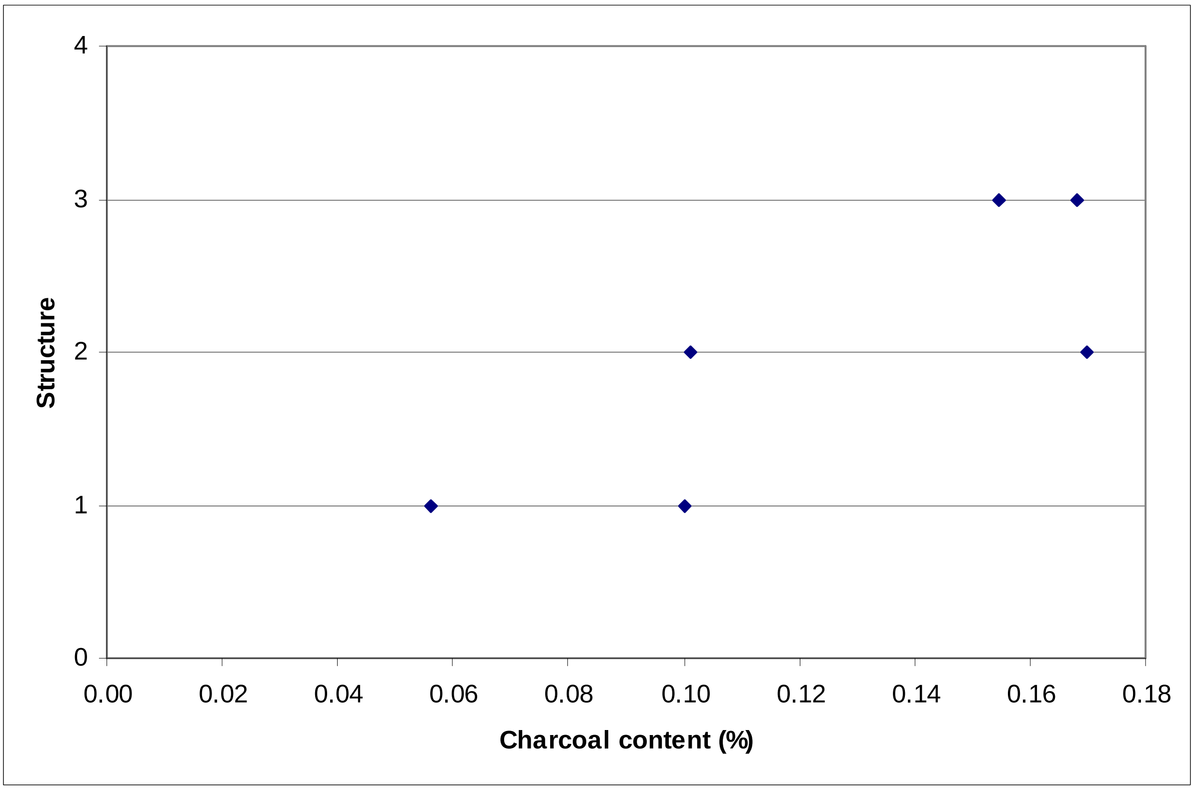

Figure 12 Structure of soil horizons with different charcoal content

The difference in structure can not be explained with the soil texture, since the horizons with a weak structure have both relative low and high clay and sand content (Appendix A).

5.1.5 Bulk density

The soil bulk density at Horvat Haluqim ranges from 1.12 g cm^{-3} to 1.59 g cm^{-3}. The bulk density does not differ much between different soil pits (Figure 13). However, the Aa horizons usually have a lower bulk density than the C horizons within the same soil pit.

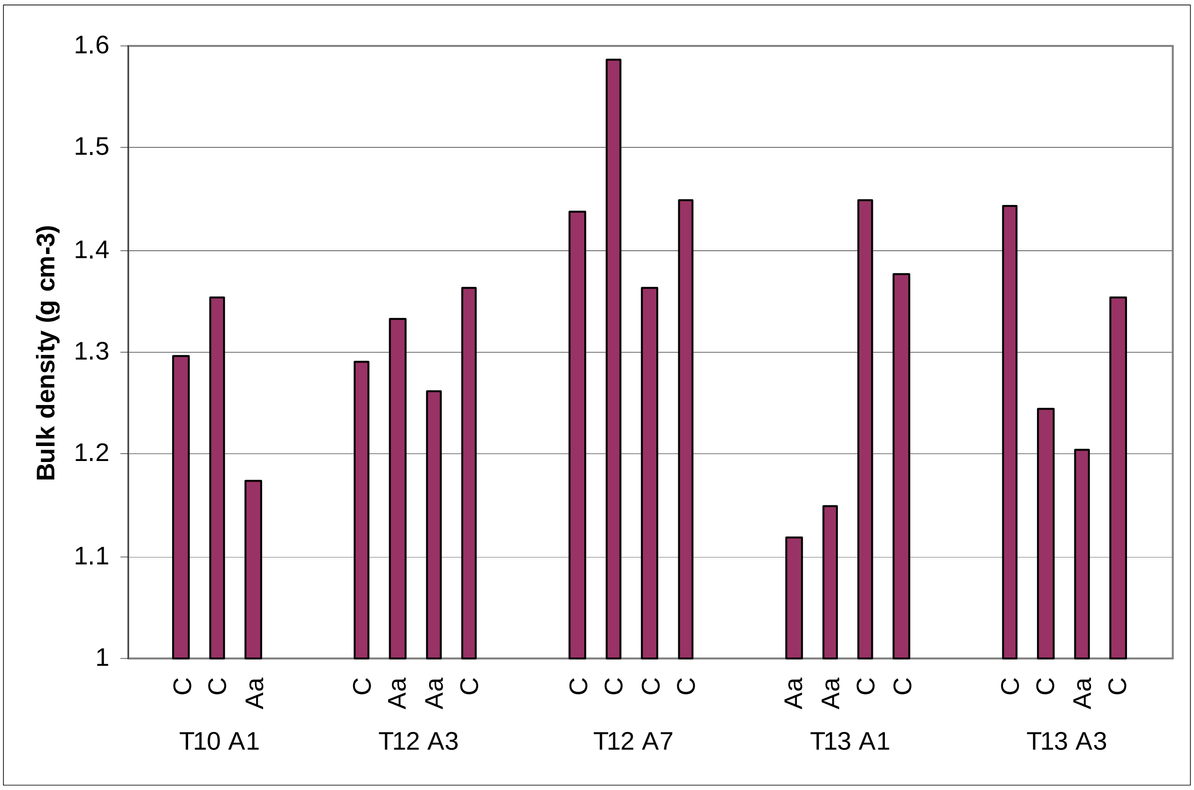

Figure 13 Bulk density of soil horizons of different soil pits

An independent t-test was performed on the Aa and C horizons and the anthropogenic horizons showed a significant lower bulk density of 0.18 g cm^{-3} of the Aa horizon. The average bulk density of the Aa horizons is 1.20 g cm^{-3} and the average bulk density of the C horizons is 1.39 g cm^{-3}. Details of the independent t-test can be found in Appendix B.

Decrease in bulk density could be influenced by the presence of tiny amounts of charcoal in the soil, since charcoal has low bulk density and can decrease the bulk density of a soil when it is applied. However, the charcoal content is very small and bulk density is not consistently lower with increasing charcoal content (Figure 14).

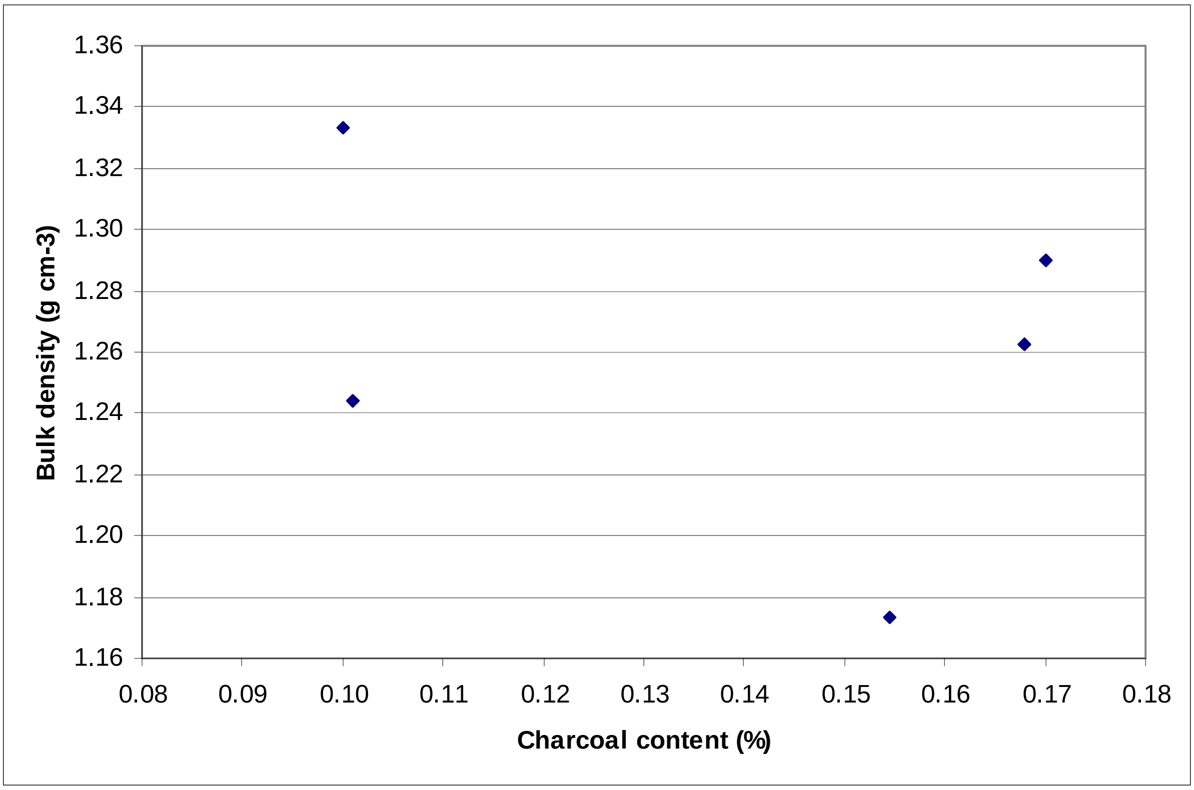

Figure 14 Bulk density of soil horizons with different charcoal content

Soil structure and bulk density do not show a strong correlation. Soils with a weak soil structure do have the lowest soil bulk density, but also relatively high bulk density.

Texture is most likely not the cause of differences in bulk density, since horizons with low bulk density have both the highest and lowest clay and sand content compared to other horizons in the same soil pit (Appendix A).

5.1.6 Saturated hydraulic conductivity and cumulative infiltration

The infiltration capacity of the Aa and C horizon increases rapidly and shows a very fluctuating pattern at the end of the experiment (Figure 15). This makes it impossible to determine the approximate steady state infiltration capacity and therefore the saturated hydraulic conductivity. A cause of this fluctuating pattern can be disturbance of the soil surface when the ponding depth was elevated to maximum ponding depth, because soil particles at the soil surface came into suspension.

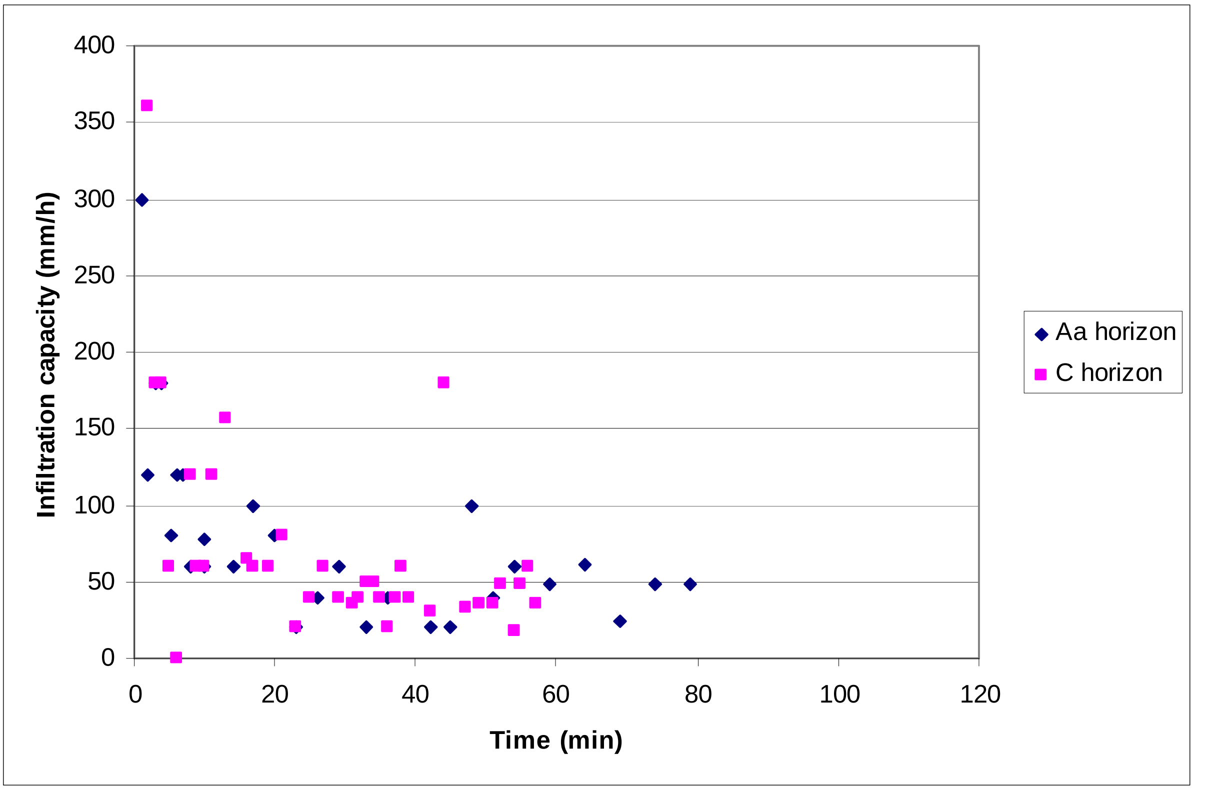

Figure 15 Infiltration capacity of the Aa and C horizon of T12A3

The cumulative infiltration has a much smoother pattern (Figure 16). The experiment in the Aa horizon was stopped earlier than the experiment in the C horizon. However, at the end of the experiment in the Aa horizon the cumulative infiltration between the two horizons is almost the same. The cumulative infiltration of the C horizon is 70 mm, while it is almost 73 in the Aa horizon.

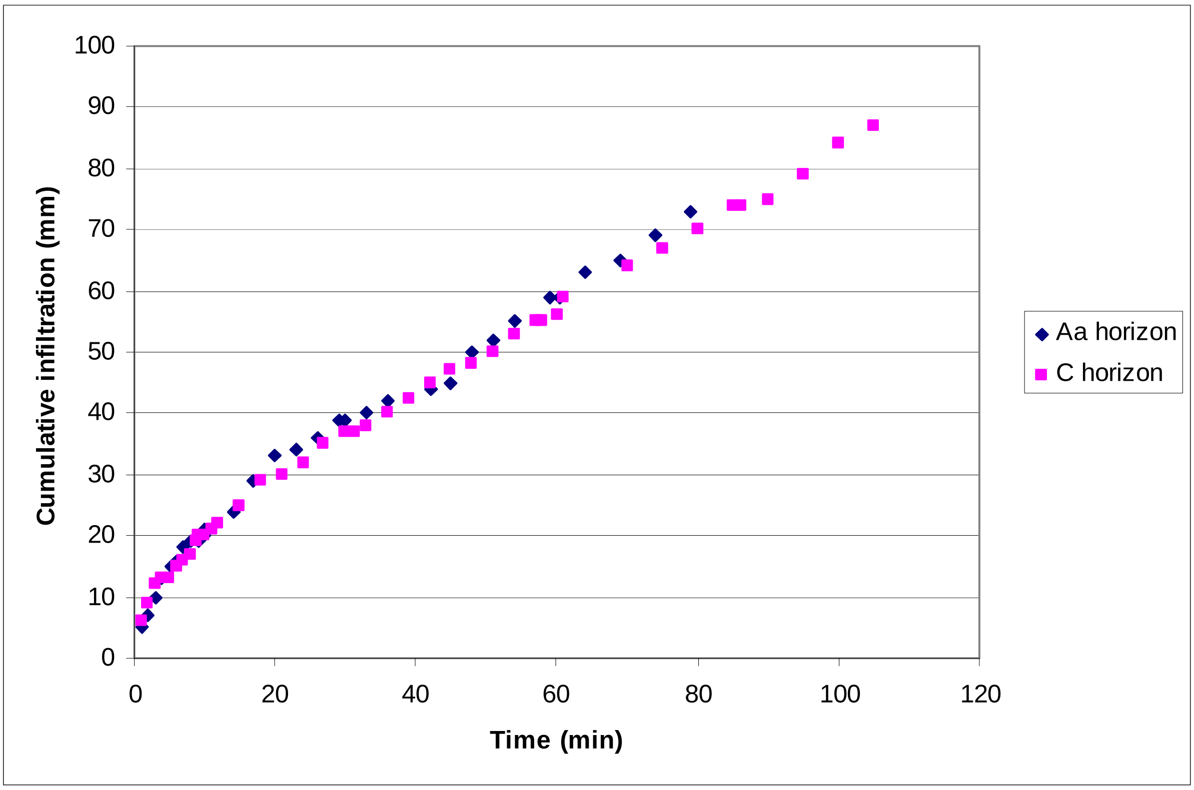

Figure 16 Cumulative infiltration of the Aa and C horizon of T12A3

The soil properties of both horizons are very similar (Appendix A). The Aa and overlying C horizon have almost the same pH, ED, bulk density and texture. The only difference between the two horizons is colour and structure.

This experiment showed no difference in cumulative infiltration.

5.2 Influence of charcoal and ash on soil properties

5.2.1 pH

In the pot experiment ash and freshly produced charcoal were added to the loess soil. The pH of the loess soil (L(0)) before the start of the experiment was 8.7 and the pH of the anthropogenic soil (A) was 8.9. The pH of the soils at the end of the experiment (after 40 days) is shown in Table 7. As expected the pH of the anthropogenic soil and the loess soil are almost the same. The pH of the soil in the L(0) and A treatment was a little bit higher at the end of the experiment, but this could be due to natural variation in the soil.

The pH of soil in the L(7.5) and L(15) treatment increased slightly compared to the pH of the loess soil before the start of the experiment. This could be due to natural variation, but also to the presence of a small amount of ash that is present in charcoal.

The soil pH of the B treatment is the only one that has a marked increased in pH after the amendment with ash. This effect is often described in literature and attributed to the presence of highly soluble oxides, hydroxides and carbonates of Ca, Mg, Na and K in ash.

Table 7 pH soils in pot experiment

Treatment	pH
A	9.0
B	9.6
L(0)	8.9
L(7.5)	9.0
L(15)	9.2

5.2.2 Electrical conductivity

The influence of charcoal and ash on salinity can be deduced from the EC measurements of the soils that were used in the pot experiment.

The EC before the start of the experiment of the L(0) soil was 0.25 dS/m. At the end of the experiment the EC was 0.28 dS/m. This difference can be ascribed to natural variability. The EC of the charcoal amended soils increased slightly (Table 8). Charcoal always contains a certain amount of ash and can increase the EC through the presence of soluble salts. It would be expected that the EC of the soil in the L(15) treatment would be higher than that of the soil in the L(7.5) treatment. However, this is not the case. This is probably also due to natural variability.

Table 8 EC of soils in pot experiment

Treatment	**EC (dS/m)**
A	0.29
B	0.49
L(0)	0.28
L(7.5)	0.34
L(15)	0.32

The EC of the A soil is almost the same as that of the control. This result was expected, since both soil have been collected from T12A3 in which all horizons have low EC. The EC of the soil in the B treatment is the only one that is markedly increased. This can be attributed to the addition of ash, which contains soluble salts that have shown to increase the EC in the short term in many studies.

5.2.3 Moisture retention

Unfortunately no pF curves could be established to determine the difference between water retention of Aa and C horizons of Horvat Haluqim. However, some indication can be gained from observations of moisture content of the soils used in the pot experiment. At the end of the experiment the soil was taken out of the pots to isolate plant roots. During this process marked differences between the water content of the soils was observed.

The soil of the B and L(0) treatment had retained the most water. The soil was very wet and sticky throughout the whole length of the pots. However, in the bottom the soil showed signs of reduction. The soil had reduction spots and a distinct smell.

The soil of the A treatment was drier than that of the B and L(0) treatment, less sticky and had a more loose structure. The soil showed no signs of reduction.

The soil in the L(7.5) and L(15) treatment were drier than the other three soil, with the L(15) being the driest and the loosed structure. These soils also showed no signs of reduction.

These observations suggest that charcoal application to the soil decreases moisture retention. This is probably due to the porous structure of charcoal, which influences the soil structure. This effect was also observed in the anthropogenic soil of Horvat Haluqim even though the soil contained only 0.15% charcoal. The structure of this soil probably caused the decreased water retention. Though it is unlikely this is caused by the presence of such a small amount of charcoal.

5.3 Influence of charcoal and ash addition on crop growth

5.3.1 Cumulative crop growth

At the end of the experiment clearly visible differences in crop growth were observed between plants grown in different soil types (Figure 17).

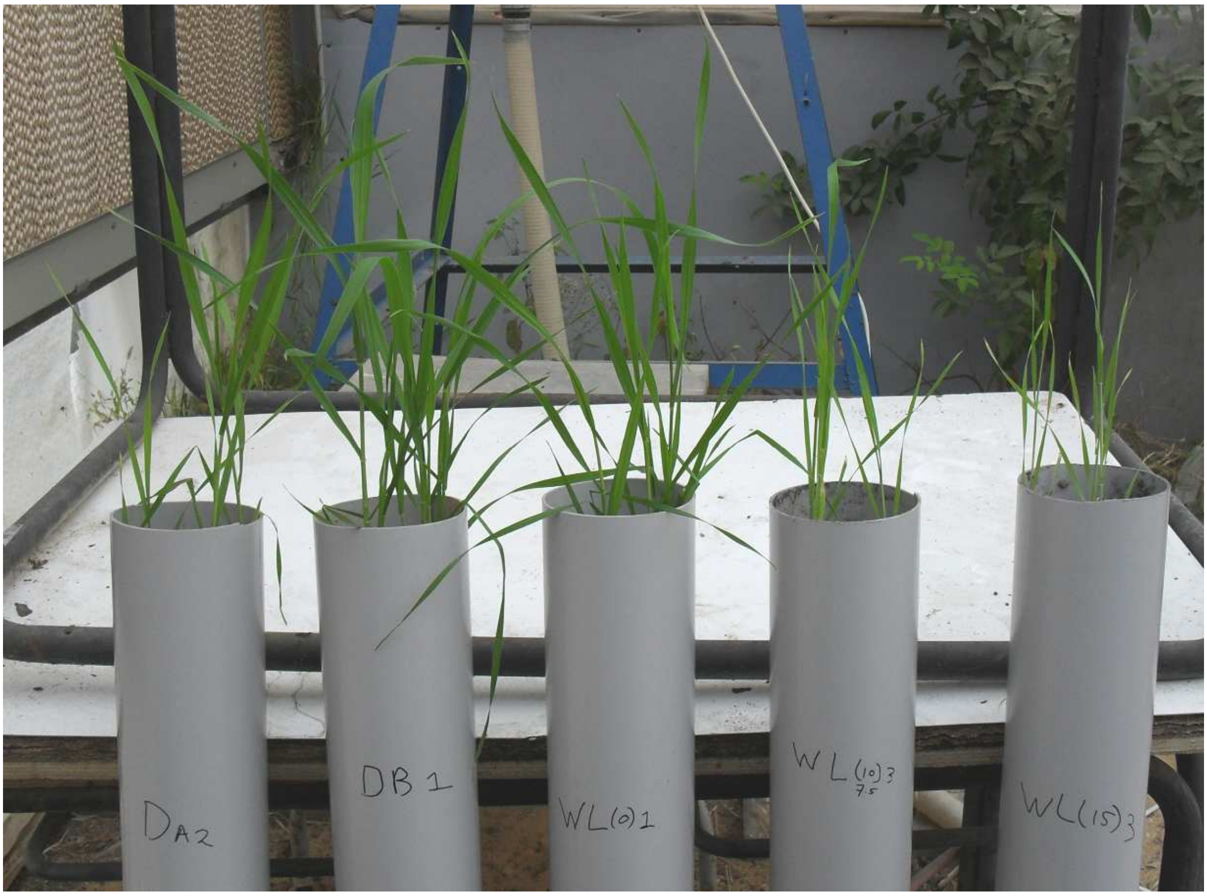

Figure 17 Pots with plants grown on different soil types. From left to right: anthropogenic soil, non-anthropogenic soil amended with 7.5% ash, non-anthropogenic soil, non-anthropogenic soil amended with 7.5% charcoal and non-anthropogenic soil amended with 15% charcoal.

The cumulative crop growth of the plants in the well watered (W) treatment is displayed in Figure 18. There is a marked difference in crop growth between plants grown in different soils. Cumulative crop growth of the plants in the A, B and L(0) treatment follows a similar pattern and plants have approximately the same height throughout the experiment, except for the last few days when the growth of plants in the A treatment starts to lag behind. Compared to plants grown in the other soils, the plants grown in soil amended with charcoal show reduced growth. The plants grown on L(15) show reduced growth compared to plants grown on L(7.5). The growth of plants on both soils slows down around the 18th day of the experiment and two days later these plants started to develop chlorosis that started at the tip of the leaves and gradually spread to the whole leave, after which some of them died. At the 36th day growth rate increased again due to the formation of new leaves. The pattern is most clearly observed in the L(15) treatment.

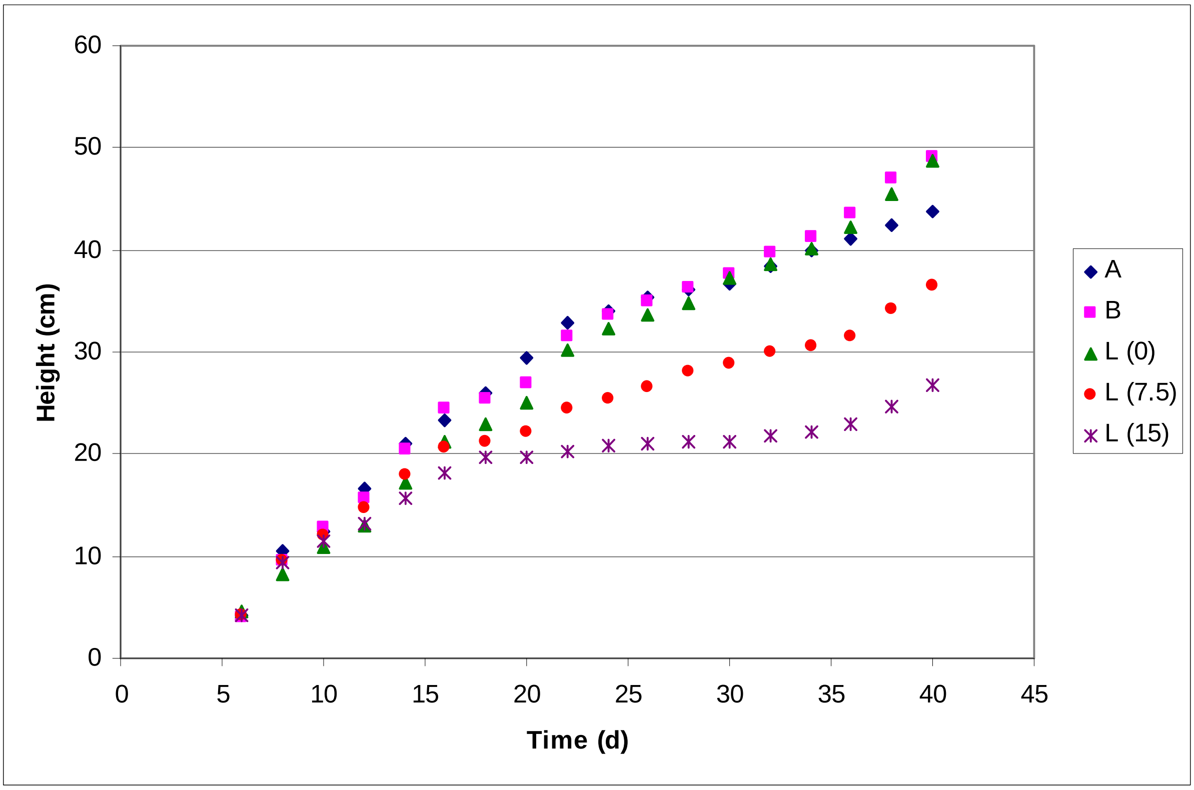

Figure 18 Average cumulative growth of plants grown in the W treatment

The cumulative crop growth of the plants in the water deficit (D) treatment is displayed in Figure 19. The pattern is different from that in the W treatment. The plants in the B treatment have a marked larger cumulative crop growth than the plants in the A and L(0) treatment.

The plants in the L(7.5) and L(15) treatment show the same pattern as in the W treatment. The growth is lower than the other three treatments, with plants in the L(15) treatment again being the smallest of the two. Growth seems to stop around the 18th day and starts to increase again at the 24th day for plants grown in soil amended with 7.5% charcoal and at the 26th day for plants grown in soil amended with 15% charcoal. Around the 28th day the growth of the plants in the L(15) treatment seems to decrease again, but it increases again around the 36th day.

The cause of periods of reduced growth also coincides with chlorosis and the formation of new leaves results in increased growth.

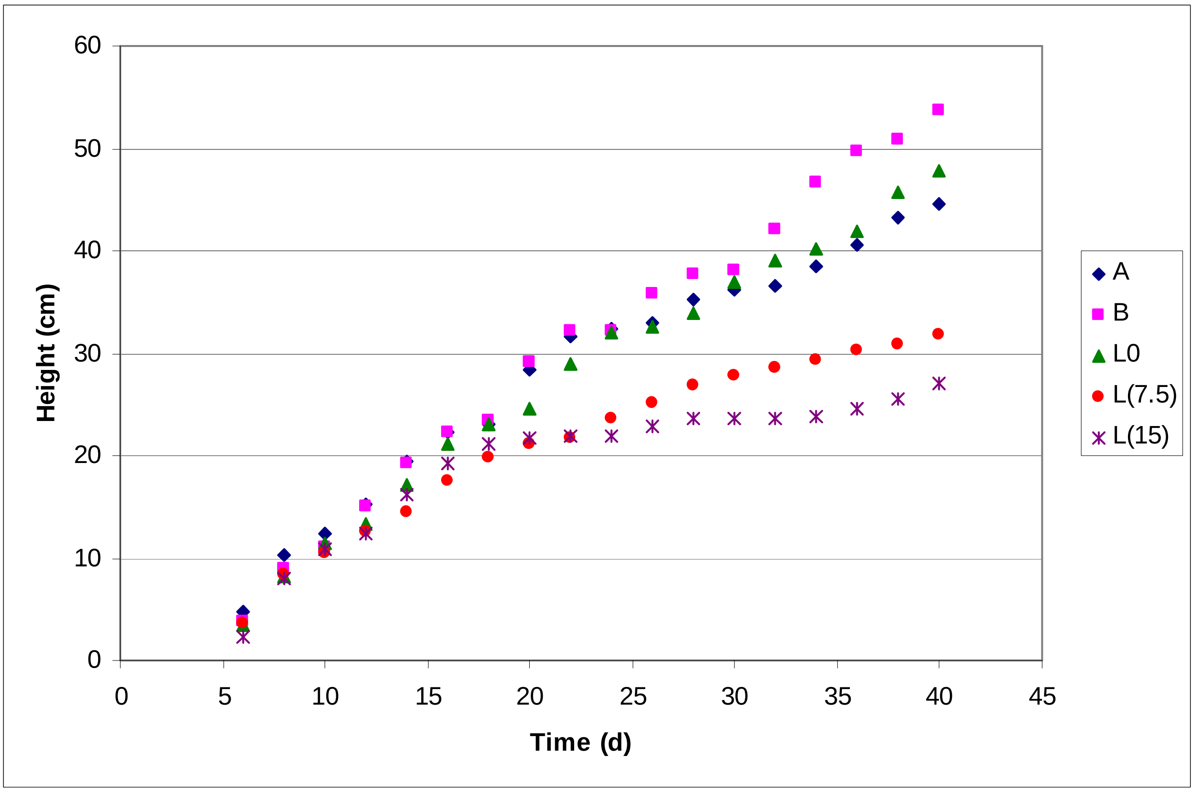

Figure 19 Average cumulative growth of plants grown in the D treatment

Differences between different soil types in same moisture regime

The mean cumulative crop growth of plants grown in different soil types and the same water regime was analyzed with post hoc ANOVA (Bonferroni).

The mean cumulative growth at the end of the experiment of plants in the W treatment of the A, B and L(0) treatments do not differ statistically significant. However, mean cumulative growth of plants in the L(7.5) and L(15) treatment are statistically significant different from each other and from to the other three treatments (Table 9). Details of the ANOVA can be found in Appendix C.

Table 9 Mean cumulative crop growth at the end of the experiment

Soil type	Mean crop length W treatment (cm)*	Mean crop length D treatment (cm)*
A	43.8^{a}	44.5^{a}
B	49.1^{a}	53.7^{b}
L(0)	48.7^{a}	47.8^{ab}
L(7.5)	36.4^{b}	31.9^{c}
L(15)	26.7^{c}	27.1^{c}

* Values in one column indicated by the same letter are not significantly different at p <0.05

The mean cumulative crop growth of plants in the D treatment is given in Table 9. The plants of the B treatment are the tallest. The cumulative growth of plants in the A and L(0) and the B and L(0) treatments are not significantly different, while the difference between the A and B treatment is significant. The difference between plants in the L(7.5) and L(15) treatment is also not significant. However, they are significantly lower from the plants in the other three treatments. Details of the ANOVA can be found in Appendix D.

Difference between same soil type in different water regimes

The mean cumulative crop growth of plants grown in the same soil type, but in different water regimes was analyzed with the independent t-test.

Comparison of mean crop height at the end of the experiment shows that the plants in the A, B and L(15) treatment have a higher mean in the D than in the W treatment. For the plants in the L(0) and L(7.5) treatment this is the other way around (Table 10). However, this difference is only statistically significant for the L(7.5) treatment with a mean difference of 4.5 cm. Details of all the t-tests can be found in Appendix E.

Table 10 Mean cumulative crop growth at the end of the pot experiment

Soil type	Mean crop length W treatment (cm)	Mean crop length D treatment (cm)	Significance
A	43.8	44.5	0.392
B	49.1	53.7	0.064
L(0)	48.7	47.8	0.326
L(7.5)	36.4	31.9	0.034
L(15)	26.7	27.1	0.368

In order to find out whether there were any differences before the onset of different water regimes, the mean cumulative growth on the last day (22nd day) before the onset of the different water regimes, was also analyzed. The plants grown on the A, L(0) and L(7.5) soil had a larger cumulative growth in the W treatment compared to the D treatment. For the other treatments this is the other way around (Table 11). However, none of these differences is statistically significant. Details of the analysis can be found in Appendix F.

Table 11 Mean cumulative crop growth at the onset of the two water regimes

Soil Type	Mean crop length W treatment (cm)	Mean crop length D treatment (cm)	Significance
A	32.9	31.7	0.644
B	31.6	32.3	0.136
L(0)	30.1	29.0	0.843
L(7.5)	24.4	21.7	0.409
L(15)	20.3	21.8	0.098

To compare changes in crop height that have occurred from the 22nd day to the end of the experiment the differences between the W and D treatments are presented in Table 12. This table shows that from the onset of the water regimes to the end of the experiment the cumulative growth of the plants in the D treatment increased relatively to the W treatment for the A, B and L(0) treatment. In the other treatments it is the opposite.

Table 12 Difference in mean crop length between the W and D water regimes at two times during the experiment

Soil Type	Difference on 22nd day (cm)	Difference at end (cm)
A	1.2	-0.7
B	-0.7	-4.5
L(0)	1.1	0.8
L(7.5)	2.7	4.5
L(15)	-1.5	-0.4

5.3.2 Biomass

<u>Shoot biomass</u>

The pattern of the amount of biomass of plants grown in different soil types is similar for the W and D treatment (Figure 20). Plants in the B treatment have the highest shoot biomass, followed by A, L(0), L(7.5) and L(15) has the lowest shoot biomass. This pattern largely follows the cumulative crop growth at the end of the experiment. However, plants in the A treatment have the third largest cumulative growth, while it has the second largest shoot biomass. For plants in the L(0) treatment this is the other way around.

If the dry period of the D treatment would have been long enough to cause differences in biomass due to water shortage, it would be expected that the plants in the D treatment would have a lower shoot biomass compared to the W treatment. This is only the case in A, L(0) and L(7.5). The differences between plants in the A and L(0) treatment are small, but the difference between plants in the L(7.5) treatments is quite large. This difference corresponds with the statically significant difference of the cumulative growth of plants grown in the L(7.5) treatment.

The biomass of plants in the DB treatment is remarkably larger than that of the WB treatment and the biomass of the DL(15) is slightly larger than that of the WL(15) treatment.

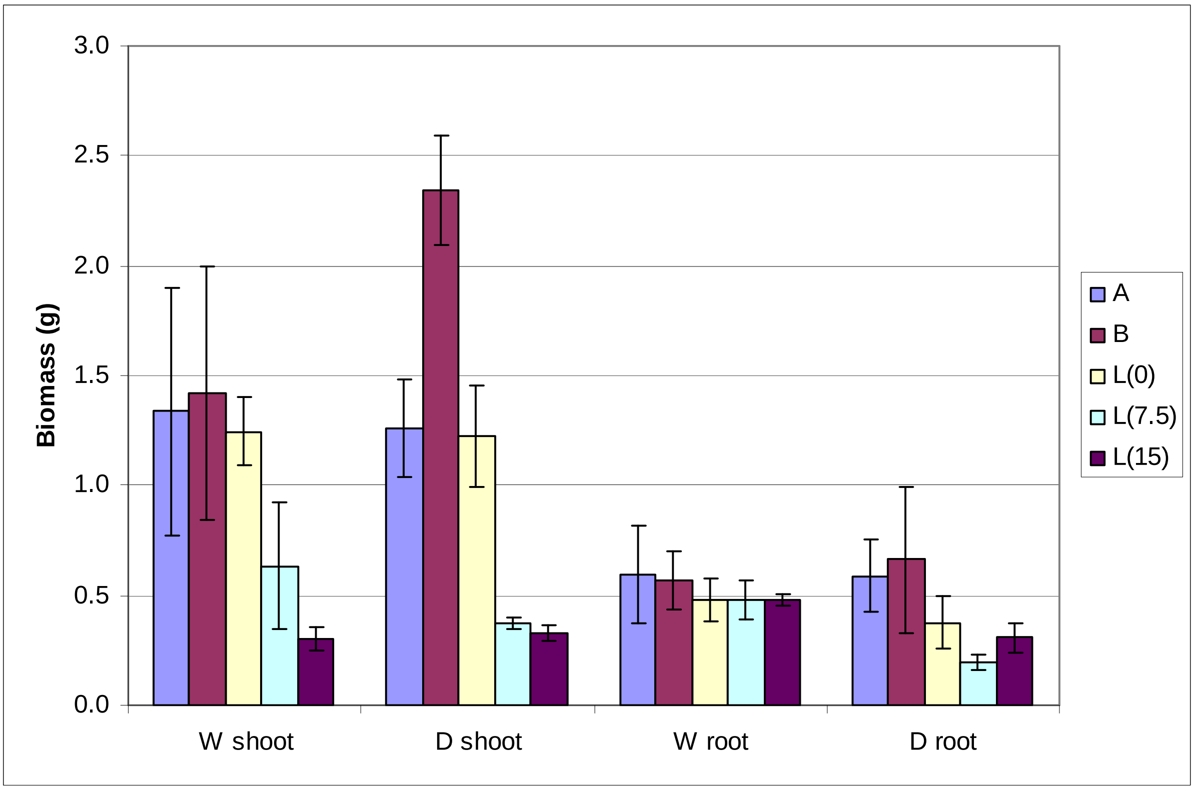

Figure 20 Average biomass of plants grown in different soils and under different moisture regimes

Root biomass
The differences in root biomass do not follow the same pattern as that of the shoot biomass (Figure 20). In the W treatment plants in the A treatment has the highest root biomass, followed by B, L(0), L(7.5) and L(15). In the D treatment B has the highest root biomass, followed by A, L(0), L(15) and L(7.5).
In both the W and D treatment plants in the A, B and L(0) treatment have the three highest root biomass and also the highest shoot biomass. In order to accumulate shoot biomass a well developed root system must be present to extract water and nutrients from the soil.
The difference between the root biomass is similar for all soil types.

Shoot/root biomass ratio
The shoot/root biomass ratio in the W treatment is lowest for the L(15), followed by
A and L(7.5), B and L(0) (Figure 21). The shoot/root biomass ratio in the D treatment is lowest for the L(15), followed by L(7.5), A, L(0) and B.

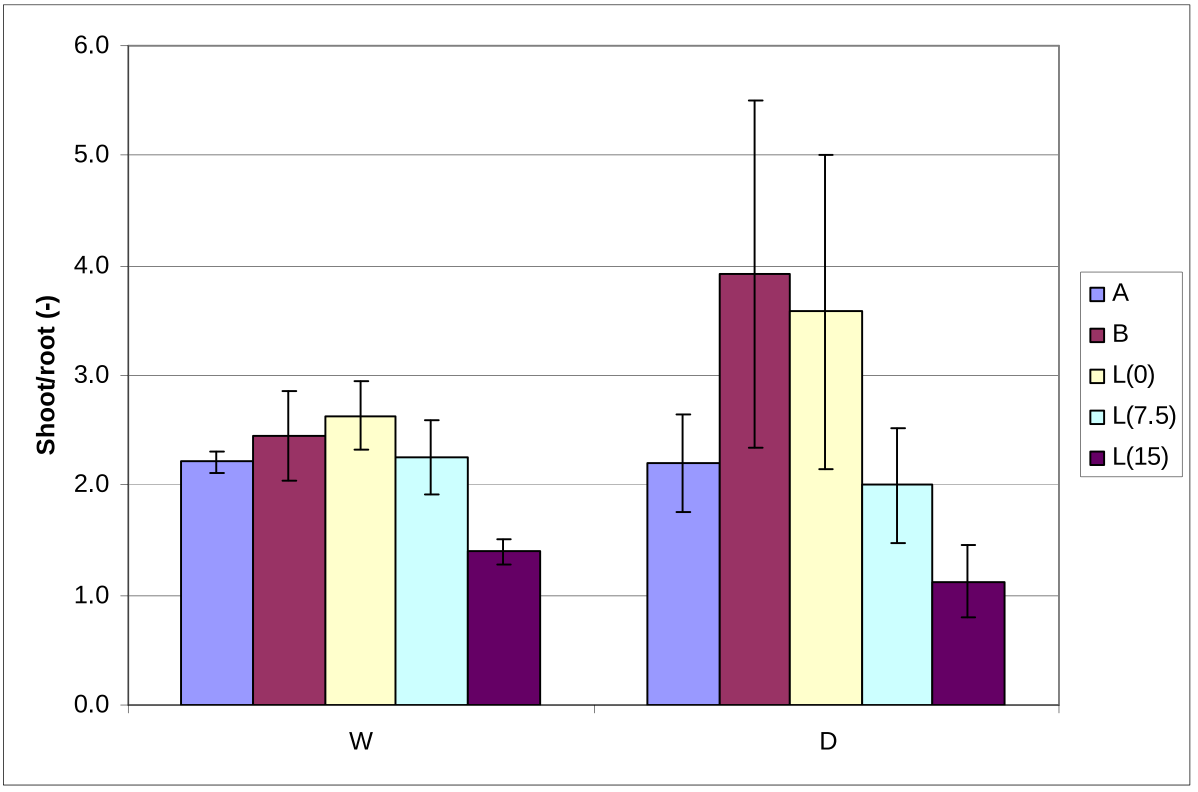

Figure 21 Average shoot/root ratio of plants grown in different soils and moisture regimes

6 Possible causes of reduced crop growth after charcoal addition

From cumulative crop growth and biomass analysis it is obvious that the plants were negatively affected by charcoal addition to the soil. In both the W and D treatment cumulative crop growth of plants in the L(7.5) and L(15) treatment was statistically smaller than from the L(0), A and B treatments.

Apart from reduced growth, the plants also showed chlorosis. This started at the tips of the older leaves and gradually the whole leaf turned yellow and died (Figure 22). Later new leaves emerged which were not (yet) affected by chlorosis.

When plants are not growing as well as they could under optimal conditions, there are a number of different possible causes, such as water (Jones, 1992; Ehlers and Goss, 2003) or nutrient deficiency (Grundon, 1987) and toxicity (Karataglis *et al.*, 1991; Athar and Ahmad, 2002).

Figure 22 Plants in pot DL(15) 1 with leaves affected by chlorosis

Nutrient deficiency

There are 19 elements that are essential for healthy growth of plants. These elements are divided into macronutrients (C, H, O, N, Ca, P, K, Mg and S) and micronutrients (Fe, B, Zn, Cu, Mn, Na, Mo, Cl, Co and Si) (Grundon, 1987).

The elements C, H and O are obtained from the air and water, while the other elements are obtained from the soil. When plants are not able to acquire these elements in sufficient amount, they grow poorly and develop an abnormal appearance (Grundon, 1987).

The symptoms of deficiency are generally typical for a certain nutrient. Therefore, it is possible to use the visual appearance of a plant to diagnosis the cause of the disorder (Grundon, 1987).

In Table 13 characteristic symptoms of different nutrient deficiencies are displayed. Some disagreement exists about the characteristics of deficiency of some elements. However, taking into account the symptoms of the plants grown on soil amended with charcoal, only N, P, and K deficiency could be the cause stunted growth and lack of biomass production.

Table 13 characteristic symptoms of nutrient deficiencies

Nutrient	Grundon (1987)	Snowball and Robson (1991)	General characteristics of deficiency according to Grundon (1987)	General characteristics of deficiency according to Snowball and Robson (1991)
Ca	Young	Middle	Chlorosis and dying and curling of shoots	Necrosis in middle of leaves
Cu	Young	Young	Wilting, dying and curling of shoots	General wilting, dying and curling of shoots
Fe	Young	Young	Longitudinal interveinal chlorosis	Longitudinal interveinal chlorosis
Mg	Old	Young	Longitudinal interveinal chlorosis	Chlorosis, unopened new leaves
Mn	Young	Young	Irregular interveinal chlorosis and flecking	Irregular interveinal chlorosis and flecking
N	Old	Old	Chlorosis, beginning at leave tip that advances in a broad front down the shoot	Chlorosis, beginning at leave tip
P	Old	Old	Chlorosis, beginning at leave tip that advances in a broad front down the shoot. If the deficiency is severe or persists, a purple suffusion combines with the yellow colour to give a orange-yellow or orange-purple chlorosis	Chlorosis, beginning at leave tip
K	Old	Old	Chlorosis at tips and margins of leaves sometimes followed by necrosis	Mottled chlorosis
S	Young	Young	Chlorosis	Chlorosis
Zn	Middle	Middle	Necrotic spots extending to the margins	Necrotic spots extending to the margins
Bo	-	Young	-	Splitting of leaves close to the midriff, unusual indentations along length of leave
Mo	-	Old	-	Longitudinal yellow striping on middle leaves and after some time necrosis of tips and margins of old and middle leaves

More detailed inspection of the symptoms of N, P and K deficiency showed that N is the most likely nutrient that could have caused the symptoms. The other two nutrients result in additional symptoms that were not displayed by the plants in the pot experiment. P deficiency causes red-purple or purple striping on the stems and leafs even when the deficiency is mild. During K deficiency chlorosis stars on the tip of the leave and advances along the margins towards the base (Grundon, 1987). This was not a symptom that was displayed by the plants in the pot experiment. All the symptoms of N deficiency did fit the symptoms displayed by the plants in the pot experiment. Therefore, if nutrient deficiency caused the stunted crop growth, reduced biomass and chlorosis of plants grown in soil with 7.5% and 15% charcoal, N is the most likely nutrient.

Apart from reduced growth, N deficiency may also cause assimilate partitioning in favour of roots (Ehlers and Goss, 2003) which results in decreased shoot/root ratio. The plants of the L(7.5) treatment had a shoot/root ratio that is slightly lower than the other treatments, but the shoot/root ratio of the L(15) treatment was much lower. This also indicates N deficiency.

A possible explanation for N deficiency is the high C/N ratio of charcoal. The C/N ratio is often used as an indicator of the ability of organic substrates to mineralize and release inorganic N when it is applied to soil (Chan and Xu, 2009). A C/N ratio between of 20 to 30 is generally used as a critical limit above which immobilization of inorganic N by microorganisms occurs (Leeper and Uren, 1993; Sullivan and Miller, 2001; Chapin *et al.*, 2002). This means that the N applied with the substrate is not available for plants (Leeper and Uren, 1993).

The C/N ratios of charcoal vary widely. Chan and Zu (2009) reviewed charcoals from different feedstocks. The C/N ratio varied between 7 and 400 with a mean of 67. Based on the usually high C/N values of charcoals, most charcoals are expected to cause immobilization of inorganic N and possibly cause N deficiency in plants when applied to the soil. However, there is a degree of uncertainty whether the same criterion of C/N values applies to charcoal. On the one hand, the bulk of charcoal is made up of biologically very recalcitrant organic C, which his not easily mineralized. Thus, it would be expected that N immobilization is negligible despite the high C/N ratio. On the other hand, however, it is likely that the presence of a small portion of freshly produced charcoal is relatively easily mineralizable and may cause N immobilization, because of its high C/N ratio (Chan and Xu, 2009).

Studies on the influence of charcoal in the humid tropics have shown different reactions to the application of charcoal to the soil. Lehmann *et al.* (2003) reported that a Ferralsol amended with charcoal had a lower N availability due to an increased C/N ratio compared to a Ferralsol without charcoal. However, Steiner *et al.* (2007) reported increased N availability by showing that N uptake in crops and export with crop harvest was increased with biochar additions.

Water deficiency

The most obvious effects of even mild water stress in plants are reduced growth (Jones, 1992) and reduced of biomass production (Masinde *et al.*, 2005). Although plant growth rates are generally reduced under water limited conditions, shoot growth is often more reduced than root growth, which leads to a decrease of shoot/root ratio with increasing water deficits. This is not only due to a relative increase in root growth, but can also be due to an increase in absolute root growth (Malik *et al.*, 1979). These effects are the result of translocation of assimilates from the shoot to the roots. When the water supply is limited, first new growth is reduced and the growth of leaves that have already formed is slowed down. This makes it possible that assimilates that are not used in the shoot can be transported to the roots and root mass can increase significantly when water shortage prevails over a long period of time. However, the total biomass will decrease due to water stress (Ehlers and Goss, 2003).

Even though plants in the L(7.5) and L(15) treatment have reduced biomass and decreased shoot/root ratio compared to L(0), it is unlikely that water deficit was the cause. If water deficit would be the cause, it would be expected that plants in the D treatment would have had even more severely reduced growth or even have died after more than two weeks of drought, in stead of growth that was similar to that of the plants in the W treatment. In the last few days of the experiment the growth of the L(15) plants seemed to actually slightly increase.
Furthermore, at the end of the experiment when the pots were emptied the soil in both the W and D did not seems to have a marked difference in water content (Appendix G). Both soils were still quite wet.

Heavy metal toxicity

Inhibition of root growth is one of the characteristic features of heavy metal stress (Barcelo and Poschenrieder, 2004). Several studies have shown that heavy metal toxicity in wheat depresses shoot growth and dry biomass, but root growth and root biomass reductions were much larger (Karataglis *et al.*; Athar and Ahmad, 2002). Heavy metal toxicity has also been shown to increase shoot/root ratio of wheat plants (Mahmood *et al.*, 2007).

It is unlikely that heavy metal toxicity was the cause of reduced crop growth of the plants grown on soil amended with charcoal. In contrast to increased shoot/root ratio caused by heavy metal toxicity, the plants had smaller shoot/root ratio compared to plants grown on the other soils. Furthermore, heavy metal cations are generally most bio available under acid conditions (Alloway, 1990), while the pH of the different soils used in pot experiment was strongly alkaline.

Salinity

Based on their low EC, the soils used in the pot experiments were classified as non-saline according to generally recognized salinity classes. This makes it highly unlikely that crop growth and crop production of the plants grown in the L(7.5) and L(15) treatment were negatively affected by soil salinity. Especially, since the other treatments had similar EC values.

7 General Discussion

7.1 Interpretation of the results

The charcoal content of the Aa horizons in Horvat Haluqim is very low, ranging from 0.06 to 0.19% and is comparable to the charcoal content of C horizons. The soil colour is also not consistently darker with increasing charcoal content. The dark colour of the Aa horizon is therefore not the result of the presence of charcoal. However, if the measured charcoal content of the second horizon with colour 10YR 7/4 (Figure 7) is considered an exceptional outlier due to the presence of individual spots with more charcoal, there seems to be a relation between the charcoal content and the soil colour. The two horizons with the lowest chroma (10YR 7/2 and 10YR 6/2) have the highest charcoal content and soil horizons with a higher chroma and the same value have a lower charcoal content. However, there is no reason to assume that the second horizon with colour 10YR 7/4 is an exceptional outlier. Besides, it is unlikely that such low charcoal contents can cause such a dark soil colour. It must also be mentioned that the used method for charcoal quantification is not considered accurate for such low charcoal contents (Van Asperen, 2010).

It is not possible to compare the amount of charcoal in Horvat Haluqim with that of the Terra Pretas since few data is available and the data that is available is in different units. However, Sombroek (1966) found an average carbon content of light textured Terra Preta soils ranging from 0.5 to 2%. These soils are also very dark in colour, which was attributed to complex formation of organic matter and Ca^{2+}, which can form a coating around soil particles.

It is not likely that this is the cause of the dark colour of Aa horizons in Horvat Haluqim, since the soil of Horvat Haluqim is highly calcareous and contains around 30% $CaCO_3$ (Bruins, 1986) and agriculture was also performed on the C horizons, though be it in a different time period. A coating of organic matter and Ca^{2+} could therefore, be present in both horizons, but it is not.

The presence of ash in the soil is most likely also not the cause of the dark soil colour. If ash is still present in large amounts this would have resulted in systematically higher EC of Aa horizons compared to C horizons, but this was not the case.

More research is needed into the cause of the dark colour of the Aa horizons.

Few differences in soil properties were found between the Aa and C horizons of Horvat Haluqim. The soil bulk density of the Aa horizons is lower than that of the C horizons. The structure of Aa horizons is more often weaker compared to the C horizons, but all three structure grades (weak, moderate and strong) were observed in both horizons. Lower bulk density and structure grade can positively increase seed emergence and root penetration, although no problems were observed in the pot experiment. The workability of the soil is also positively influenced. The soil is more easily ploughed, especially when the soil is dried out after a prolonged period without rain or irrigation. The cause of this reduced bulk density and structure is not known. Soil with a higher charcoal content do not have a consistently lower bulk density or structure grade. The charcoal content of the Aa and C horizons is very low and comparable. Therefore, the differences are not caused by the charcoal content and more research is needed.

No differences were found in soil pH, EC and cumulative infiltration.

Charcoal addition to the soil can influence soil water retention and water availability. Tyron (1948) found no change in water retention and available moisture in a loam soil. The influence of charcoal on water retention of the soil of Horvat Haluqim was not quantified, but in contrast to the findings of Tyron (1948), the soil in the pot experiment that was amended with charcoal had a lower water retention than the soil that was not amended with charcoal.

In an arid region like the Negev desert this can have negative effects on crop growth. The water that is available needs to be retained in the soil for as long as possible so crops can benefit from it as much as possible. To quantify the decrease in water retention in the soil of Horvat Haluqim more research is needed.

Charcoal addition of 7.5 and 15% to non-anthropogenic soil decreased crop growth and biomass production compared to the non-amended loess soil. The most likely cause is reduced N availability due to increased C/N ratio and consequent N immobilization.

The pH and EC slightly increased after charcoal addition, but this could also (partly) be attributed to natural variability within the soil.

Plant growth on soil amended with ash was similar to plants grown on non-amended soil, even though ash contains large amounts of nutrients. Plant growth on the anthropogenic soil and the non-amended soil was also similar.

Although, a relative larger crop growth was observed in plants grown on the control, anthropogenic soil and soil amended with ash in the period that these plants received no water compared to the plants that did receive water. This could indicate that plant growth was limited by too much water. The increase was largest in the plants grown on the soil amended with ash which could indicate that ash can have a positive influence on crop growth through the addition of nutrients. The anthropogenic soil has a similar nutrient content than the non-anthropogenic soil (Bruins, 1986), which can explain why crop growth was similar for the plants grown on the anthropogenic soil and the non-anthropogenic soil.

The significant lower cumulative crop growth of plants grown in soil amended with 7.5% charcoal in the D treatment compared to the W treatment, suggests that the plants in the D treatment were affected by a shortage of water. This is corroborated by the fact that the soil of the L(7.5) treatment in both the W and D treatment lost the most water compared to the other treatments. If this was the result of charcoal addition the soil of the L(15) treatment should have lost more water, which was not the case. Water loss of the soil of the L(15) treatment was the lowest in the W treatment and more or less median in the D treatment. This indicates that the amount of loss was not due to the presence of charcoal, but due to some other factor, such as, for instance the density of packing of the soil. Besides, the soil of all pots was still very moist at the end of the experiment and water was still available for plants, even in the soils that had not received water during the last part of the experiment.

Charcoal addition in the humid tropics has the potential to influence crop production in the short term through direct nutrient addition and increase in pH and consequent reduced Al toxicity. The recalcitrant nature of charcoal can also ensure long term influences on soil fertility. It increases the CEC and nutrient retention of the soil. This is especially important in the acid, highly weathered tropical soils with low nutrient retention. These effects are probably less important in the alkaline loess soils of Horvat Haluqim.

In the past kitchen refuse was applied as fertilizer to the soil of Horvat Haluqim (Bruins, 2007). This consisted mainly of ash and small quantities of charcoal. This would result in short term pH and EC increase and increased nutrient content of the soil, but this effect would only be short term. The quantities in which kitchen refuse was applied at a time were probably small and these effects would be limited.
In the short term the application of ash is probably more effective in increasing soil fertility than the application of charcoal, since ash has a higher nutrient content. However, in alkaline soils nutrient availability may also decrease due to increased pH. Knowledge is lacking on the long term effect of charcoal to the soil properties and crop production.

If long term effects of charcoal would be beneficial for crop production and it were to be applied on a large scale, attention must be paid to the desired properties of this charcoal, which are highly variable and dependent on the type of biomass that is used and the production procedures in order to acquire charcoal with the right properties suitable for the purpose. Additional mineral fertilizer may be needed to combat the problem of N immobilization in the first period after the addition, but much more research is needed on the long term effects. Although it is questionable whether the beneficial effects will counterbalance reduced water retention.
The practicality of large scale application of charcoal in arid regions is also questionable. Charcoal from fallow vegetation and/or organic wastes can be easily produced by local farmers and also by those with a low income in the humid tropics (Glaser *et al.*, 2002). However, vegetation in arid regions is often scarce and this vegetation may be needed to combat land degradation, such as desertification and erosion.

7.2 Limitations of the methodology and research

The classification between anthropogenic and non-anthropogenic soil horizons is based on soil colour. The distinction between different colours is sometimes very difficult and also subjective. It was decided that soil horizons with normal Negev loess colours (10 YR 7/6, 7/4 and 6/4) were classified as non-anthropogenic. It could have been possible that, for instance, a soil with colour 10YR 7/4 was influenced by anthropogenic activities and the original colour was 10YR 7/6. No distinction could be made during this study. This problem might be overcome by making thin sections and the use of soil micromorphology to identify anthropogenic influence through the presence of bone pieces at microscopic level (Bruins, 2007).

The determination of structure grade (weak, moderate, strong) is also very subjective. Determination of the structure grade of different horizons in the same soil pit can be done relative to the other horizons. It is more difficult to determine structure of different horizons relative to soil horizons from other soil pits. If different classes were assigned this may have led to a better relation between Aa and C horizons and the structure.

For the determination of soil bulk density soil aggregates were collected from the field. These aggregates were carefully handled and wrapped in several plastic bags to prevent damage during transport and storage. However, small amounts of damage could not be prevented. Sometimes, small pieces of the aggregates broke of. These could have influenced the determined bulk density, but only to a small extent.

To determine bulk density it is better to use large soil aggregates so it is possible to capture more of the variation within a soil. The aggregates used in this study were usually very small (few cm in size), especially in soil horizons with a weak structure, since large aggregates easily broke into smaller aggregates. To capture natural variability the average bulk density of three soil aggregates of every soil horizon was determined.

To get a better indication of the saturated hydraulic conductivity of the soil a more accurate test needs to be done. From the single ring infiltrometer experiment it was not possible to determine the saturated hydraulic conductivity. The reason is not really known, but a possible explanation is that soil particles at the soil surface came into suspension after the addition of water when the water level had reached the minimum ponding depth.

Due to the fluctuating infiltration capacity it is also hard to say whether the infiltration experiment should have lasted longer.

The pot experiment lasted for 40 days, which was too short for plants to reach maturity. A longer experiment needs to be done to reach this stage in plant development and to assess possible differences in harvest, especially in the anthropogenic soil, the soil amended with ash and the non-amended loess soil, since no differences could be observed at the end of the experiment, but which might have occurred if the experiment would have continued for a longer period of time.
The time span of the experiment was also too short to assess how plants in the different soils react to drought. At the end of the experiment the soil of all five soil types was still sufficiently wet and the soil of the soil amended with ash and the non-amended soil were still saturated in the bottom of the pipes. A much longer period of drought is needed to allow the soil to dry out to a sufficient level to observe and analyze differences in plant growth and biomass production of plants grown on different soils.
It is possible that plant growth was limited by the high water content of the soil. After water addition stopped the plants grown in the anthropogenic soil, the non-amended soil and the soil amended with ash showed a relative increase in crop growth compared the plants that received water until the end of the experiment. The plants grown in soil with additional ash showed the largest increase. It could be possible that plant growth would have been different for these three treatments if the plants received less water.

The nutrient content of the charcoal, nutrient availability in the soil and nutrient content in the plants were not known. This information is needed to be able to conclude with certainty what caused the differences in crop growth of plants grown in different soils.

The long term effects on soil properties and crop production could not be assessed with this pot experiment. To assess the long term influence of charcoal on crop growth a long term experiment needs to be conducted over several growing seasons.

8 Conclusions

Soil properties

In the eastern wadi of Horvat Haluqim, anthropogenic and non-anthropogenic soil horizons were identified on the basis of their colour.

The anthropogenic soil horizons have significantly lower mean bulk density (1.20 g cm^{-3}) compared to non-anthropogenic soil horizons (1.39 g cm^{-3}). The anthropogenic horizons also have more often a weak structure compared to the non-anthropogenic horizons.

These differences are not related to the charcoal content of the soil horizons, because the charcoal content of the soil is very low, ranging from 0.06 to 0.19% and is comparable between the anthropogenic and non-anthropogenic horizons, even though there is a distinct difference in colour between both horizons, ranging from 10YR7/6, 7/4 and 6/4 in non-anthropogenic horizons to 10YR 7/3, 7/2, and 6/2 in anthropogenic horizons. Furthermore, the soil horizon with the highest charcoal content does not have the lowest bulk density or the weakest structure.

No differences were found in pH, EC and cumulative infiltration between the anthropogenic and non-anthropogenic soil horizons.

Charcoal addition to the soil in the pot experiment slightly increased soil pH and EC, but water retention decreased. The addition of ash to the soil increased the pH and EC to a larger extent than the addition of charcoal, but the changes remained small.

Charcoal additions to soils in the humid tropics usually lead to an increase in pH that is much larger than the increase that was observed in this study.

Crop growth

The addition of charcoal the Negev loess soil led to significantly lower crop growth and biomass production compared to the control. This was most likely caused by N deficiency, since charcoal has a high C/N ratio, which can lead to N immobilization.

The period without water was too short to find any differences between the two different moisture regimes caused by water deficit.

The addition of ash and the use the anthropogenic soil of Horvat Haluqim did not influence crop growth and biomass production compared to the control.

In contrast to what was found in this study, charcoal addition to highly weathered soils of the humid tropics often leads to increased crop growth and biomass production due to reduced Al availability and the addition of nutrients. In some cases reduced N availability has also been observed.

Overall conclusion

The dark colour of the anthropogenic soil horizons at Horvat Haluqim is not due to the presence of charcoal and in that sense they are not comparable to the Terra Pretas in the humid tropics. The creation of ‘Terra Pretas’ in arid regions with loess soils through addition of charcoal, as has been done in the humid tropics, shows no great potential, since it decreases water retention and can lead to N deficiency.

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Appendices

Appendix A

Table 14 Soil properties of soil pits at Horvat Haluqim

Soil Pit	Depth (cm)	Horizon based on field description	Horizon based on colour	Dry Munsell colour	Structure grade	Bulk density (g cm^{-3})	pH	EC (dS/m)	Clay content (%)	Silt content (%)	Sand content (%)	Texture class
T10A1	0-30	C	C	10 YR 7/6	moderate	nd	8.2	2.5	16.3	55.5	28.2	silt loam
	30-60	C	C	10 YR 7/6	strong	1.30	8.4	2.9	22.0	52.3	25.7	silt loam
	60-95	C	C	10 YR 7/6	strong	1.35	8.5	2.9	23.3	47.3	29.4	loam
	95-110	AaC	C	10 YR 7/4	moderate	nd	8.3	1.8	30.0	49.3	20.7	clay loam
	110-175	Aa	Aa	10 YR 7/2	very weak	1.17	8.2	2.7	12.3	56.7	31.0	silt loam
	175-205	AaC	C	10 YR 7/4	weak	nd	8.2	2.3	15.3	63.0	21.7	silt loam
	>205	Ck	C	10 YR 7/4	strong	nd	8.3	3.8	30.6	51.4	18.0	silty clay loam
T12A3	0-24	C	C	10 YR 7/4	moderate	1.29	8.7	0.3	12.2	54.7	33.1	silt loam
	24-45	C	Aa	10 YR 7/3	strong	1.33	8.7	0.3	13.2	58.0	28.8	silt loam
	45-50	AaC	Aa	10 YR 6/3	moderate	nd	8.6	0.3	14.2	63.0	22.8	silt loam
	50-92	Aa	Aa	10 YR 6/2	weak	1.26	8.9	0.2	12.2	56.0	31.8	silt loam
	>92	Ck	C	10 YR 7/4	strong	1.36	9.3	0.2	26.2	47.0	26.8	loam
T12A7	0-20	C	C	10 YR 7/6	moderate	1.44	8.6	0.8	24.9	44.0	31.1	loam
	20-50	C	C	10 YR 7/6	strong	1.59	8.3	2.8	18.9	50.0	31.1	loam/silt loam
	50-93	Aa	C	10 YR 7/4	weak	1.36	8.4	2.5	16.9	56.0	27.1	silt loam
	>93	C	C	10 YR 7/6	weak	1.45	8.6	1.6	24.9	42.0	33.1	loam
T13A1	0-5	Aa	Aa	10 YR 7/3	weak	nd	8.6	18.5	12.9	60.0	27.1	silt loam
	5 - 32	Aa	Aa	10 YR 7/3	weak	1.12	8.7	18.4	7.7	77.2	15.1	silt loam
	32-43	Aa	Aa	10 YR 7/3	weak	1.15	8.7	10.9	20.9	58.7	20.4	silt loam
	43-60	AC	C	10 YR 7/4	strong/weak	1.45	8.9	5.4	15.7	59.2	25.1	silt loam
	60->80	Ck	C	10 YR 7/6	stong	1.38	9.3	1.8	20.2	45.7	34.1	loam
T13A3	0-18	C	C	10 YR 7/4	moderate	1.44	8.2	3.3	18.3	51.7	30.0	silt loam
	18-40	AaC	C	10 YR 6/4	moderate	1.24	8.4	2.4	21.6	48.0	30.4	loam
	40-49	Aa	Aa	10 YR 6/3	weak	1.20	8.6	1.0	28.0	40.5	31.5	clay loam
	49-100	Ck	C	10 YR 7/4	moderate	1.35	8.9	0.6	24.9	43.9	31.2	loam

Appendix B

Table 15 result independent test between Aa and C horizons

Horizon	Mean	Std Error mean	t	df	Sig. (2-tailed)	Mean difference	Std. Error difference
C horizons Aa horizons	1.3875 1.2050	.02700 .03170	4.107	16	.001	.18250	.04444

Appendix C

Details of Post Hoc ANOVA (Bonferroni) analysis of cumulative crop growth of plants in the W treatment at the end of the experiment.

Table 16 Descriptives

Treatment	Treatment	N	Mean*	Std. deviation	Std. error
0	L0	9	1.2982	.01592	.00531
1	L15	9	1.1913	.03279	.01093
2	L7.5	9	1.2473	.02830	.00943
3	A	9	1.2793	.02587	.00862
4	B	9	1.2996	.01759	.00586
Total		45	1.2631	.04744	.00707

* SQRT (log (crop height)) transformed

Table 17 ANOVA

Treatment	df (between groups)	df (within groups)	F	Sig. (1-tailed)
W	4	40	29.828	.000

Table 18 Multiple comparisons

Treatment I	Treatment II	Mean difference (I-II)	Std. Error	Sig. (1-tailed)
0	1	.10690*	.01175	.000
	2	.05090*	.01175	.000
	3	.01884	.01175	.500
	4	-.00148	.01175	.500
1	0	-.10690*	.01175	.000
	2	-.05600*	.01175	.000
	3	-.08806*	.01175	.000
	4	-.10839*	.01175	.000
2	0	-.05090*	.01175	.000
	1	.05600*	.01175	.000
	3	-.03206*	.01175	.047
	4	-.05238*	.01175	.000
3	0	-.01884	.01175	.500
	1	.08806*	.01175	.000
	2	.03206*	.01175	.047
	4	-.02033	.01175	.457
4	0	.00148	.01175	.500
	1	.10839*	.01175	.000
	2	.05238*	.01175	.000
	3	.02033	.01175	.457

* the mean difference is significant at the 0.05 level

Appendix D

Details of Post Hoc ANOVA (Bonferroni) analysis of cumulative crop growth of plants in the D treatment at the end of the experiment.

Table 19 Descriptives

Treatment	Treatment	N	Mean	Std. deviation	Std. error
0	L0	9	47.822	3.1192	1.0397
1	L15	9	27.089	3.7257	1.2419
2	L7.5	9	31.889	3.5073	1.1691
3	A	9	44.544	5.1505	1.7168
4	B	6	53.650	5.3411	2.1805
Total		42	40.095	10.5791	1.6324

Table 20 ANOVA

Treatment	df (between groups)	df (within groups)	F	Sig. (1-tailed)
D	4	37	56.848	.000

Table 21 Multiple comparisons

Treatment I	Treatment II	Mean difference (I-II)	Std. Error	Sig. (1-tailed)
0	1	20.7333*	1.9639	.000
	2	15.9333*	1.9639	.000
	3	3.2778	1.9639	.500
	4	-5.8278	2.1957	.058
1	0	-20.7333*	1.9639	.000
	2	-4.8000	1.9639	.097
	3	-17.4556*	1.9639	.000
	4	-26.5611*	2.1957	.000
2	0	-15.9333*	1.9639	.000
	1	4.8000	1.9639	.097
	3	-12.6556*	1.9639	.000
	4	-21.7611*	2.1957	.000
3	0	-3.2778	1.9639	.500
	1	17.4556*	1.9639	.000
	2	12.6556*	1.9639	.000
	4	-9.1056*	2.1957	.001
4	0	5.8278	2.1957	.058
	1	26.5611*	2.1957	.000
	2	21.7611*	2.1957	.000
	3	9.1056*	2.1957	.001

* the mean difference is significant at the 0.05 level

Appendix E

This appendix shows the results of the independent t-test on cumulative crop growth between the W and D treatment for different soil types at the end of the pot experiment.

Table 22 Results of the independent t-test between plants in the W and D treatment in the A soil

Treatment	Mean	Std Error Mean	t	df	Sig. (1-tailed)	Mean difference	Std. Error Difference
WA	6.6032*	.17011	-.279	16	.392	-.06029	.21630
DA	6.6635*	.13360					

* square root transformed

Table 23 Results of the independent t-test between plants in the W and D treatment in the B soil

Treatment	Mean	Std Error Mean	t	df	Sig. (1-tailed)	Mean difference	Std. Error Difference
WB	49.144	1.7235	-1.632	13	.064	-4.5056	2.7601
DB	53.650	2.1805					

Table 24 Results of the independent t-test between plants in the W and D treatment in the L(0) soil

Treatment	Mean	Std Error Mean	t	df	Sig. (1-tailed)	Mean difference	Std. Error Difference
WL0	48.656	1.4887	.459	16	.326	.8333	1.8158
DL0	47.822	1.0397					

Table 25 Results of the independent t-test between plants in the W and D treatment in the L(7.5) soil

Treatment	Mean	Std Error Mean	t	df	Sig. (1-tailed)	Mean difference	Std. Error Difference
WL7.5	36.433	1.9972	1.964	16	.034*	4.5444	2.3142
DL7.5	31.889	1.1691					

* the mean difference is significant at the .05 level

Table 26 Results of the independent t-test between plants in the W and D treatment in the (15) soil

Treatment	Mean	Std Error Mean	t	df	Sig. (1-tailed)	Mean difference	Std. Error Difference
WL15	.0386*	.00218	.345	16	.368	.00098	.00284
DL15	.0376*	.00182					

* reciprocal transformed

Appendix F

This appendix shows the results of the independent t-test on cumulative crop growth between the W and D treatment for different soil types at the onset the different moisture regimes.

Table 27 Results of the independent t-test between plants in the W and D treatment in the A soil

Treatment	Mean	Std Error Mean	t	df	Sig. (2-tailed)	Mean difference	Std. Error Difference
WA	29.456	1.4089	.471	16	.644	.9889	2.0994
DA	28.467	1.5564					

Table 28 Results of the independent t-test between plants in the W and D treatment in the B soil

Treatment	Mean	Std Error Mean	t	df	Sig. (2-tailed)	Mean difference	Std. Error Difference
WB	26.933	.9677	-1.590	13	.136	-2.2167	1.3944
DB	29.150	.8865					

Table 29 Results of the independent t-test between plants in the W and D treatment in the L(0) soil

Treatment	Mean	Std Error Mean	t	df	Sig. (2-tailed)	Mean difference	Std. Error Difference
WL0	.0405*	.00173	-.202	16	.843	-.00043	.00216
DL0	.0410*	.00129					

* reciprocal transformed

Table 30 Results of the independent t-test between plants in the W and D treatment in the L(7.5) soil

Treatment	Mean	Std Error Mean	t	df	Sig. (2-tailed)	Mean difference	Std. Error Difference
WL7.5	22.244	.7625	.849	16	.409	1.0556	1.2439
DL7.5	21.189	.9828					

Table 31 Results of the independent t-test between plants in the W and D treatment in the L(15) soil

Treatment	Mean	Std Error Mean	t	df	Sig. (2-tailed)	Mean difference	Std. Error Difference
WL15	19.700	.7862	-1.754	16	.098	-1.9556	1.1147
DL15	21.656	.7902					

Appendix G

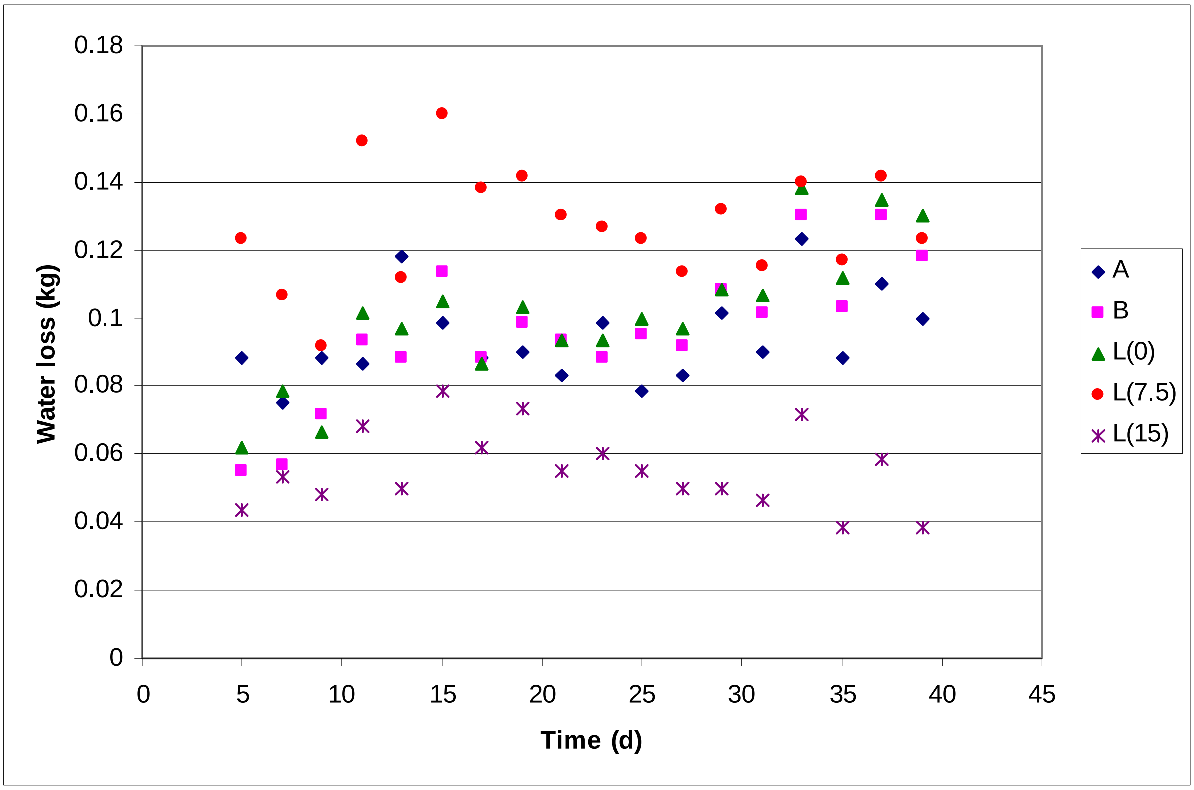

Figure 23 Average water loss of pots in the W treatment

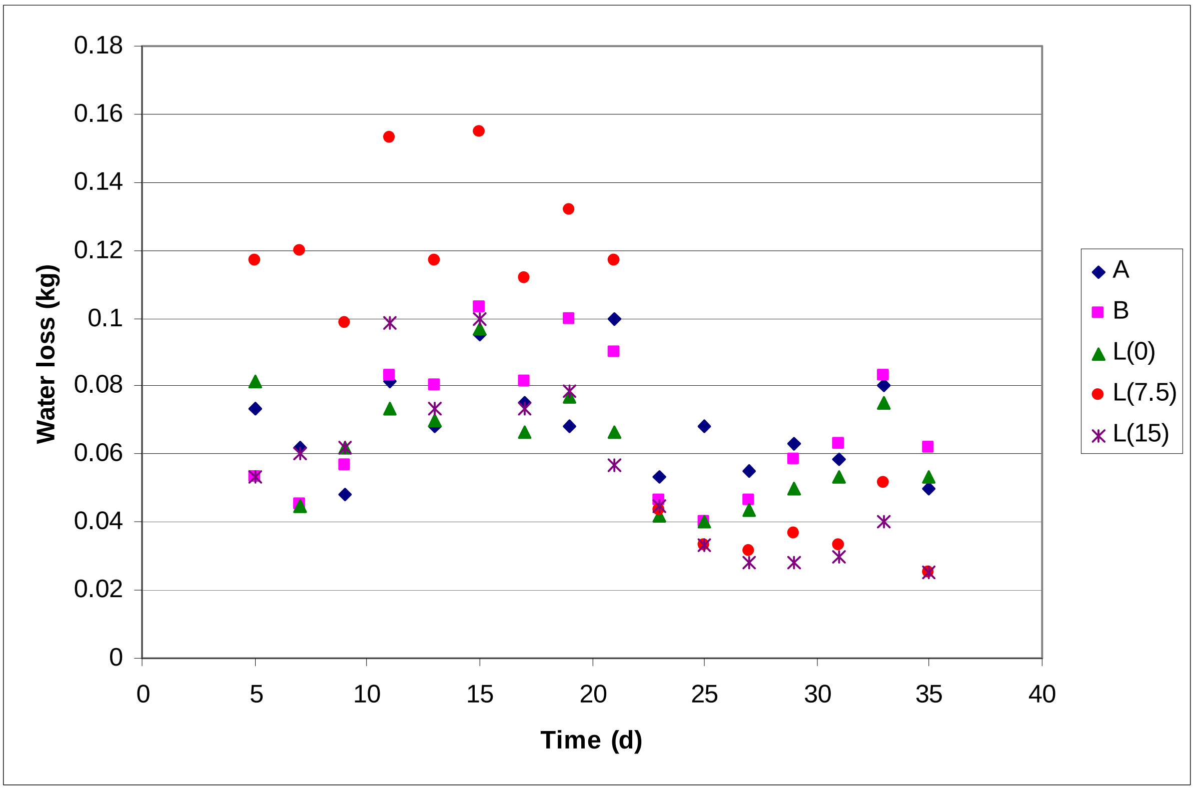

Figure 24 Average water loss of pots in the D treatment