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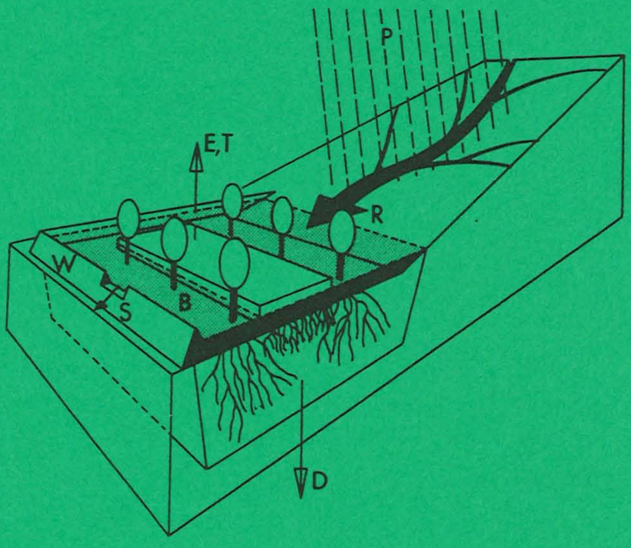
RUNOFF WATER AS A SOIL FORMING FACTOR IN ARID ZONES

Stefan Halldorf



Examensarbete
Handledare (Supervisors): Harry Linnér & Pedro Berliner

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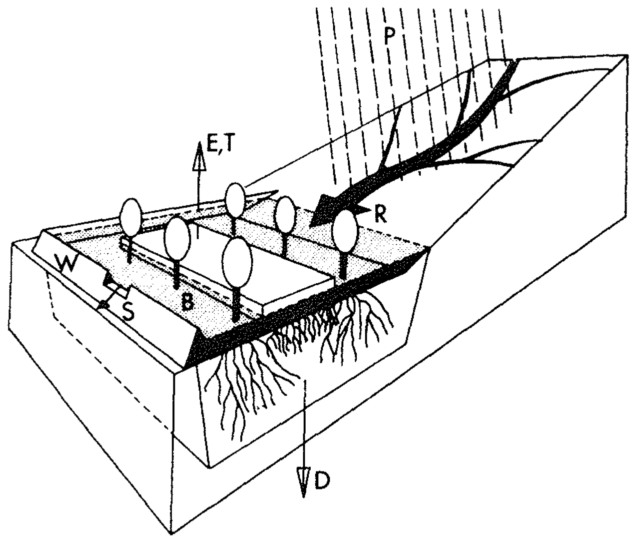

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This stay was made possible due to a scolarship from the Swedish University of Agricultural Sciences. I am most grateful to Karin Ericson and Åsa Elfström at the International Unit, who were very helpful in arranging this.

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CONTENTS page

ABSTRACT

Man-induced soil changes have been named *metapedogenesis* by the Israeli soil scientists Yaalon and Yaron. The present study deals with the effect of application of runoff water to fields surrounded by earth-walls, limans, and is thus a case of metapedogenesis.

Runoff agriculture has a long tradition in the Negev desert, and reached its most sophisticated level with the Nabateans during the Byzantine period. It was later abandoned for many centuries, but was reintroduced by the end of the 1950s by Professor M. Evenari and his fellow researchers N. Tadmor and L. Shanan. They established Wadi Mashash experimental farm in 1971, and here the liman system of rainwater harvesting has developed. In the present study, 6 limans of different age were investigated: 72/1, 79/2, 83/2, 83/7, 86/3 and 93/4. Olives grow in the first three, acacia and eucalyptus in the next two, and Sudan grass in the last. I investigated soil pH, electrical conductivity (EC), organic carbon content and particle size distribution.

Around 30 samples were taken from two depths, 0 - 20 cm and 20 - 40 cm, in each liman. The samples belonged to three locations: a) In rows (close to the trees, undisturbed land) b) Between rows (rotavated land) and c) Outside the liman (control). pH and EC was measured on all samples, while organic carbon and soil texture only in the upper layer.

The natural pH is very high. In the upper layer, all mean values, except one, lay between 7.7 and 8. The exception was 72/1, in the rows, which had a pH value of 7.1. In the lower layer there was no real variation, with a range from 7.4 to 8.2, and no clear trend. The main process for lowering the pH is thought to be the breakdown of litter in the limans, accompanied by release of organic acids.

The EC from control samples showed a very large variability, between 0.2 and 17 mS/cm. Inside the limans, the EC was without exception low, between 0.2 and 0.4 mS/cm. Liman 93/4 had only been flooded once, but showed comparable EC values to the others.

The mean of all control samples for organic matter was as low as 0.35 %. To raise the organic matter content in a hot climate is difficult, but the interaction of trees and grass is probably beneficial. Alteration of aerobic and anaerobic conditions can be important. No trend was detectable, but the average value for all limans, excluding 93/4, is 0.6 %. Earthworms were found in the sample with the largest individual value (1.2 %).

Particle size distribution is usually difficult to change, but in this case it is evident that eroded material has been transported into the limans. Liman 79/2, 83/7 and 86/3 showed a clear increase in the amount of clay and silt compared to their surrounding, while limans 72/1 and 83/2, which had the highest water income, showed none. Flooding of liman surroundings is maybe the cause. My calculations, based on data from the Sede Boker region, showed that the oldest liman could already have received about 4.5 cm of sediment, and would, at this rate, silt up in 150 years.

All observed changes of the studied properties were positive, and this type of runoff farming is, from the soil point of view, either harmless or beneficial.

INTRODUCTION

Can a soil be formed or changed during such a short time as 20 years? The question is highly relevant, since soil-forming processes normally act within much larger time-frames. The classical concept of a soil as a result of several influencing factors was established by Jenny in 1941 :

$$S \text{ or } s = f\,(cl, o, r, p, t\,...)$$

where S denotes the soil, s any soil property, cl the climate factor, o the biotic factor, r the topographic factor, p the parent material, t the time factor and the dots represent additional, unspecified factors (Birkeland, 1984; Goudie, 1990). One such factor could be man. Yaalon and Yaron (1966) call man-induced soil changes *metapedogenesis*. They argue that instead of seeing man just as a sixth factor, or part of the biotic factor, a new reference system should be created. In most cases, the soil has already reached a dynamic equilibrium before anthropogenic modifications start. The natural soil is thus the parent material, and a new zero time should be applied.

Recent reviews concerning human impact on soil are presented by Goudie (1990) and Russel and Isbell (1986). The latter authors describe the situation in Australia, where man, in a short time, has had a tremendous effect on the environment. Unfortunately man's activities have mostly been detrimental, and often at a fast rate: salinization, lateritization, compaction and, perhaps worst, soil erosion. Very little has been written about the effect of runoff farming on soil properties. What happens when you apply water (containing eroded material) to a soil which is normally dry? What processes are influenced? Has the vegetation any effect? These and similar questions are the basis for the current thesis. It is divided into a descriptive part concerning the Negev, runoff farming and earlier soil studies, and a second part describing my own investigation.

A few words about runoff agriculture or rainwater harvesting might be necessary already from the beginning. There have been several attempts to define it, but the basic idea is that rainwater is collected and conveyed from a catchment area to a lower-lying cultivated field without any intermediate storage. The size of the catchment area is usually many times larger than the cultivated plot, but this depends on the rainfall, topography and surface structure. Bruins et al (1986) definied rainwater harvesting agriculture as: "farming in arid regions by means of runoff rainwater from whatever type of catchment or ephemeral stream."

LITERATURE REVIEW

The Negev

Nowhere in the world is the transition between humid and arid climates more drastic than in Israel. It is only 450 kilometres in length, but encompasses almost all climatic zones. The Negev is the dry, southern region. In Hebrew, Negev means 'dryness', and it also implies 'south' (Hillel, 1982). The Negev is part of the largest desert belt on earth, stretching from the Atlantic coast of Africa all the way to India. Together with Sinai, it forms a land bridge between Africa and Asia. The Negev is criss-crossed by hundreds of valleys or ravines with ephemeral streams (Fig. 1). In Arabic such a valley is called a wadi, and in Hebrew, a nahal. Figure 1 shows the largest wadis in the Negev. In total they constitute about 5 % of the area. About 80 % is hillsides and slopes (Hillel, 1982). The Negev is mentioned several times in the Bible, first in connection with Abraham, Isaac and Jacob. In Swedish Bibles, the name is mostly translated as 'Sydlandet' (the southern country).

Geography and population

In the past, the Negev and Sinai were considered one unit. Only in this century were the boundaries delineated according to political considerations. The British and Turkish Governments demarcated the border between Sinai and the Negev in 1906, and when Transjordan was established in 1922 by the British Government, the eastern border was determined. (Stern et al, 1986) This is the only border with a clear physiographical justification, since it runs through the Arava valley. The northern limit is usually considered to run from Gaza to the Dead Sea, and it coincides most of the way with the 350 mm isohyet. However, in the north-east it is uncertain where the Negev ends, and where the Judean desert begins (Bruins, 1986). The total area is between 12,000 and 12,500 km^2. This should be compared with the whole of Israel: 20,700 km^2 excluding the West Bank, Gaza and Golan heights, and 28,200 km^2 including them (NE, 1993).

The total population of the Negev was 225.000 in 1981 (Fig. 2). This has increased considerably with immigration from the former Soviet Union in recent years. In 1981, 14 % were living in the rural areas. Most of them lived in kibbutzim and moshavim. The first kibbutz south of Beer Sheva, Revivim, was founded in 1943. The Bedouins live scattered throughout the region, and have become more and more sedentary. Large areas of desert are still uninhabited (Stern et al, 1986).

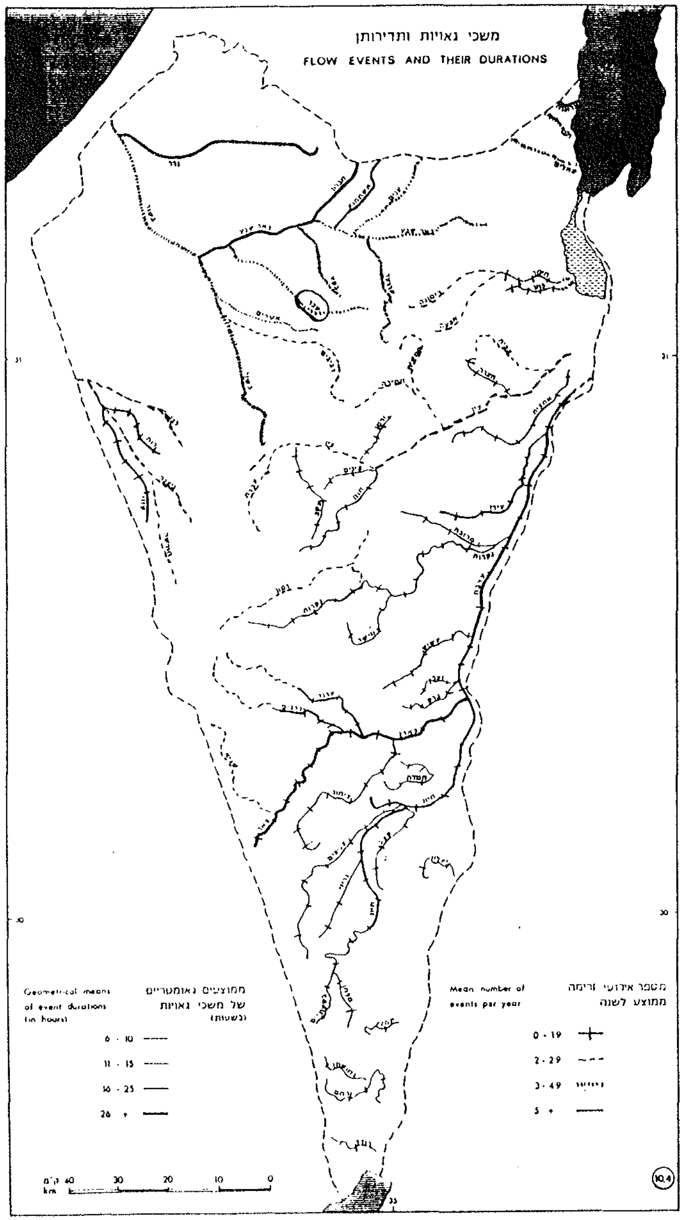

Figure 1. The main wadis in the Negev. Mean number of runoff floods are indicated. Wadi Mashash (Nahal Sekher) is encircled. (From Atlas of the Negev, 1986)

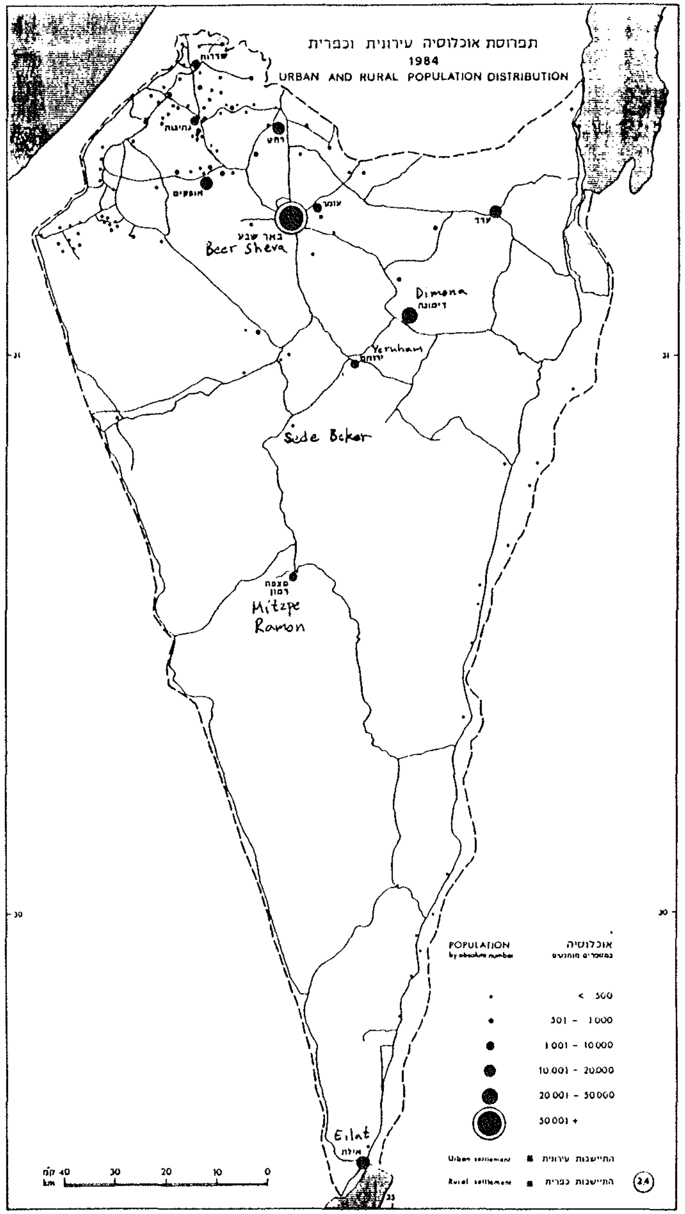

Figure 2. The population of the Negev. The smallest dots usually indicate a kibbutz. (From Atlas of the Negev, 1986)

Landforms

Evenari and his colleagues (1971) divide the Negev into four regions: The northern Negev, the central Negev, the southern Negev and the Arava valley. This section and the next one about climate come from them, unless other sources are mentioned.

The northern Negev consists of the narrow and sandy Gaza-strip, and the undulating inland. Hills and ridges separate the rolling plains. They are mostly composed by Eocene limestone as well as chalk with layers and concretions of black flint. The soil often consists of very fine sand and silt-sized particles, and show a sharp boundary to the underlying bedrock. This is an indication that the soil is not formed *in situ*. It is loess, generally believed to be wind-transported from surrounding deserts. It has almost no diagnostic horizons. Yaalon and Dan (1974) have described the accumulation and distribution of loess-derived deposits. They found that in the semi-arid region, the deposits are thicker on the north-facing (wind shadow) slopes, which indicates an origin in Sinai and Sahara. In the extreme arid region, the lack of vegetation prevents any accumulation. The annual accretion of dust is estimated to be between 50 and 200 g/m^2, which with a bulk density of 1.3 g/cm^3 would lead to an increase of soil depth of 0.02 - 0.08 mm per year, if half of the dust quantity is of local origin. The usual composition of the clay mineral free fraction in the dust is 25 - 45 % calcite, 10 - 20 % dolomite, 30 -50 % quartz and 3 - 10 % feldspars.

Some parts of the inland have more sandy soils. This is in fact often more favourable for plant growth in arid zones, since the soil has a higher infiltrability, the rainwater penetrates deeper and the evaporation losses are lower than from a more fine-textured soil (Hillel,1982).

The central Negev is mountainous, with elevations between 450 and 1000 m. It contains some spectacular landscape-formations: Makhtesh Ramon, Makhtesh Ha-Gadol ("The Large"), and Makhtesh Ha-Qatan ("The small") are three pseudo-craters, formed by erosion. They are several kilometres across, and several hundred meters deep. Nahal Zin and Nahal Neqarot are grandiose valleys opening up to plains facing the Arava. Half of the area has soils similar to the northern Negev, and the rest is covered by stone-paved regs and hammadas, where the finer material has been blown away. These features can only be formed under very dry conditions, and the vegetation is very sparse due to the thin soil between the stones and pebbles. This northern part of the central Negev covers almost the same area where runoff farming was practised during ancient times (Fig. 3), and is described in detail by Bruins (1986).

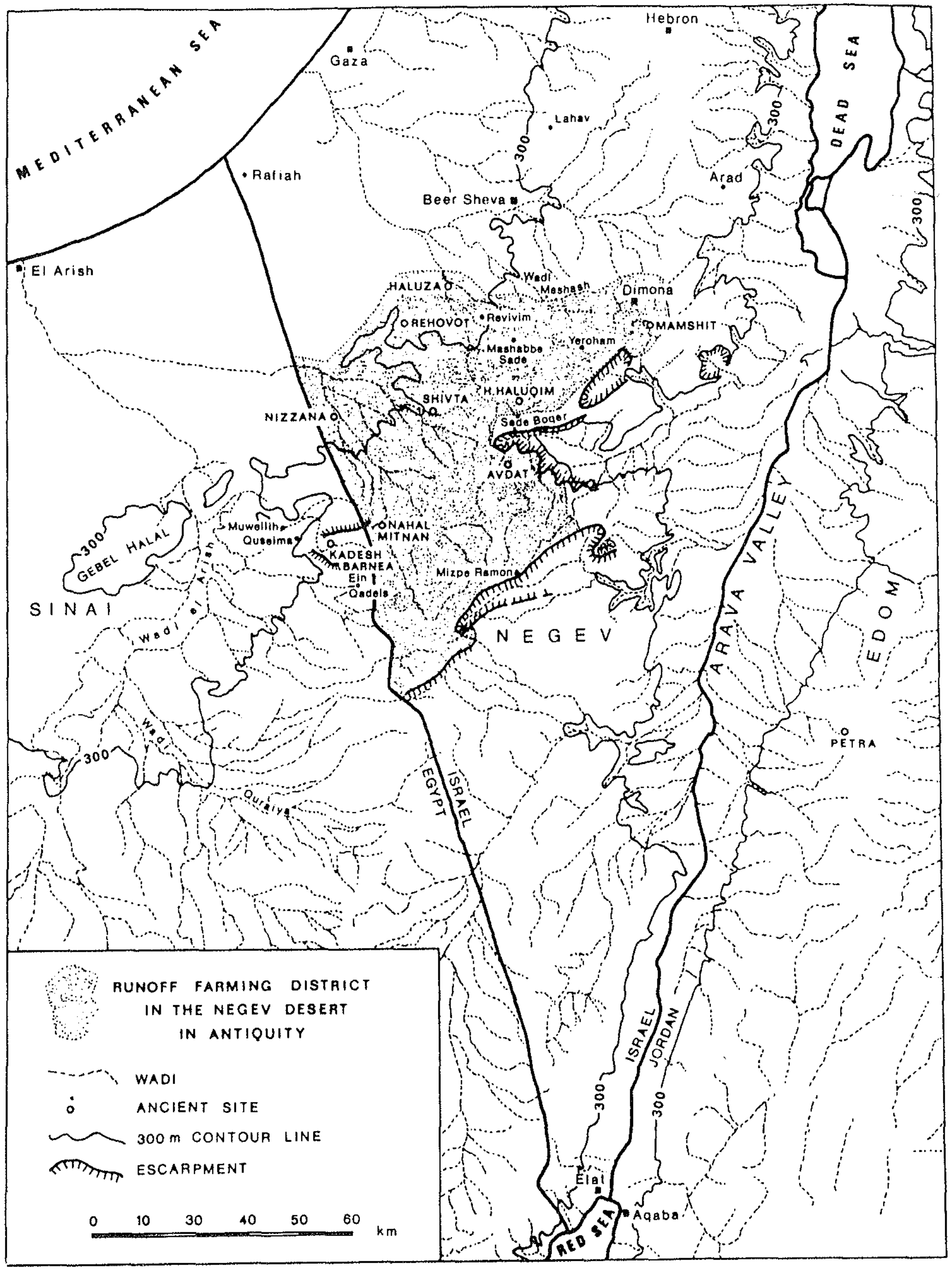

Figure 3. The Negev and the location of the runoff farming district (From Bruins, 1986).

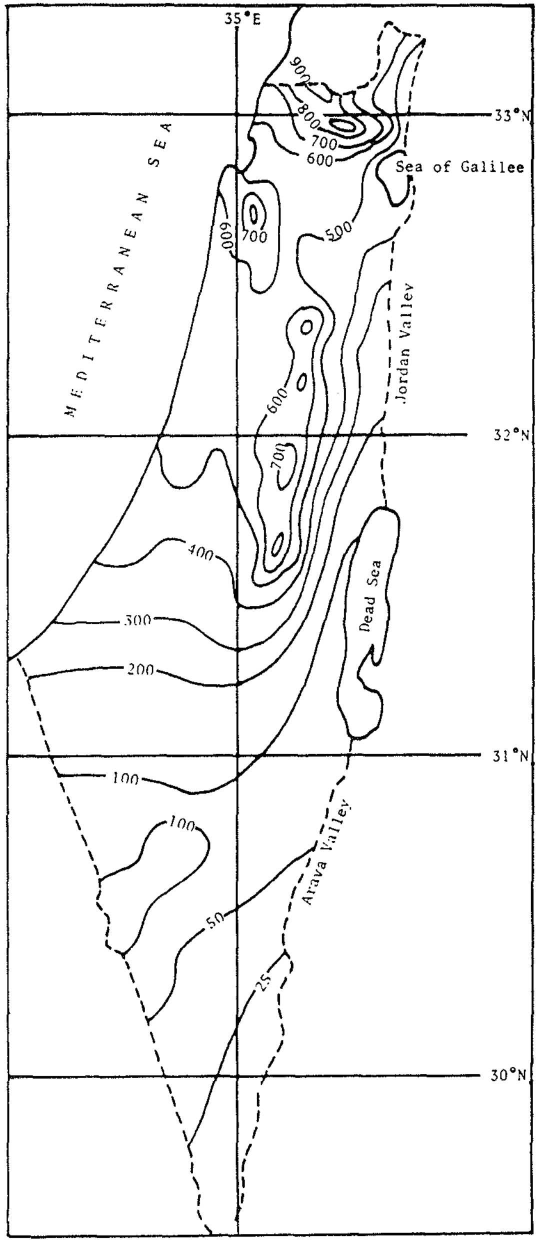

Figure 4. Rainfall map of Israel, with isohyets (lines of equal rainfall) marked in millimetres of mean annual rainfall. (From Hillel, 1982).

He points out that the region can be divided into three lithological groups: The **Judea group**, characterised by hard limestone and dolomite, the **Mount Scopus group** mostly made up of soft chalk and marl, and the **Avdat group**, composed of Eocene limestone and chalk with chert. South of Makhtesh Ramon, which more or less divides the Negev in the middle, elevations only reach between 100 and 400 meters. Barren regs cover the rolling landscape, and Nubian sandstone becomes more common towards the south.

The southern Negev, the area north of Eilat, consists of igneous and metamorphic rocks. Granite, diorite, gneiss and porphyry are also found. These rocks also make up most of the Sinai. Hamadas cover most of the flat land, but in the wadis desert alluvium has accumulated.

The Arava valley is part of the northern extremity of the Great Rift valley, running from Mozambique up through Africa and further on to Turkey. It is thought to have been formed tectonically, due to drifting apart of the continental plates. To the east, the Edumean mountains of Jordan rise to between 1000 and 1500 meters, and to the west lie the Negev highlands. The valley is 180 km long, and near to the centre is a watershed about 200 m above sea level. The southern end is, quite naturally, at sea level, while to the north it ends with the surface of the Dead Sea, -394 m, the lowest point on earth (Hillel, 1982). Most of the valley floor is covered with alluvium of stones and gravel. In depressions, smaller and larger salty areas are formed. Near the Dead Sea, the soils are composed of Lisan marls, a calcitic clay.

Climate

Several attempts have been made to divide the world into climatic zones. The limits for dry areas and deserts have been defined in different ways, but precipitation (P) and evapotranspiration (ETP) are almost always considered. One of the most recent systems is UNESCO'S map of the arid regions of the world (1979). Based on this, Bruins (1986) presented the classification of dry zones shown in Table 1. Since he also takes land use into account, the definitions are quite precise.

The rain in the Negev falls in the winter, between late October and early May, and the variation is large between years. The season 91/92 was extraordinarily wet, with snow falling three times in Sede Boker and a richness in spring flowers seldom seen, but in 92/93 the rainfall was far below the average. The rainfall pattern for all of Israel is shown in Figure 4. Since the variations are large, the isohyets in the Negev may be unreliable

(Hillel, 1982). At Sede Boker, there are 26 rainy days per year on average. Less than 1 mm is registered on about half of these rainy days, and more than 10 mm can only be expected 3 days a year (Bruins, 1986). The mean annual evapotranspiration in the central Negev, measured with a class A evaporation pan, lies between 1700 mm and 3000 mm (Lövenstein and Berliner, 1991).

The winters are cold and the summers hot and dry. The temperatures recorded at Avdat are as follows: maximum 46.4°C, minimum 0.2°C, mean of hottest month (Aug.) 25,7°C and mean of coldest month (Jan.) 10.8°C. Eilat has warm winters (15.9°C, mean of coldest month), extremely high evapotranspiration and very high summer temperatures (38.8°C mean of hottest month). Altitude also plays an important part in determining the local climate.

Table 1. Classification, characteristics and land-use of the dry zones (from Bruins, 1986)

Zone	Characteristics
HYPER-ARID zone:	- P/ETP ratio is smaller than 0.03
	- annual rainfall is very low
	- inter-annual rainfall variability up to 100 %
	- very sparse vegetation
	- no rain-fed agriculture or grazing
ARID zone:	- P/ETP ratio ranges from 0.03 - 0.20
	- annual rainfall 80 - 150 mm in winter rainfall areas
	200 - 350 mm in summer rainfall areas
	- inter-annual rainfall variability 50 - 100 %
	- scattered vegetation
	- nomadic livestock rearing is possible
	- agriculture based upon local rainfall only feasible through rainwater harvesting techniques: runoff farming
SEMI-ARID zone:	- P/ETP ratio ranges from 0.20 - 0.50
	-annual rainfall 200 - 500 mm in winter rainfall areas
	300 - 800 mm in summer rainfall areas
	- inter-annual rainfall variability 25-50 %
	- discontinuous vegetation with perennial grasses
	- rain-fed agriculture and sedentary livestock rearing are common

Two other phenomena in the Negev are the hamsin and dew. The former is the hot and dry desert wind, known under many names. When the hamsin is blowing, during spring and autumn, the temperature reaches peak values and the relative humidity drops to extremely low values, 10 % or less. Dew is important, since in very dry years it can even surpass the precipitation. Having witnessed heavy drops hanging and falling from the roofs in the middle of a cloudless night, this is not difficult to believe. The importance of dew for vegetation is, however, uncertain, except for lichens. It may also be a factor in the weathering process.

From Table 1, it is possible to deduce that all the dry zones are present in the Negev, from hyper-arid in the south to semi-arid in the north.

History

This section is mainly based on the chapter "Tides and ebbs of civilisations" in Hillel, 1982.

The Negev has a long history with several cultures flourishing. There have also been long periods when the area has been desolate, or only inhabited by nomads who left no trace behind them. There have certainly been climatic changes, but there is no evidence that these have been large enough during historical time to explain the rises and falls of civilisations. A summarised chronology is given in Table 2, which is taken from Bruins (1986).

The earliest settlements found in the Negev are from the late Chalcolithic Age, between 3500 and 3200 BC. Both stone and copper tools were in use, and there was a copper industry in the Beer Sheva area, probably supplied with ore from the Arava valley or the mountains of Edom. Grains were stored in plastered pits, and the dwellings were mainly dug into the loessial ground. The next finding is a fairly large city in Arad (North-eastern Negev) from Early Bronze Age, ca 2900 to 2700 BC. Egyptian pottery indicates trade with Egypt or Egyptian rule.

From the Middle Bronze Age numerous settlements have been discovered in the northern highlands. They are circular enclosures built of stone that probably served to shelter humans, who might have lived in tents. The Hebrew patriarchs Abraham, Isaac and Jacob, who lived a seminomadic life in the Beer Sheva region had this habit. Well-known authors like Nelson Glueck think that this period was the time of the patriarchs. At the end of the Middle Bronze Age, the Hyksos people invaded. They built fortified strongholds in the coastal area and in the western Negev.

During the 15th or 13th century BC, the famous exodus from Egypt took place, which brought the Israelites to the Negev. From Kadesh Barnea, the modern Ein el Qudeirat, situated just west of the Sinai-Negev border, Moses sent spies into Caanan. According to the book of Numbers, they came back and reported about the mighty people in the land, and told that the Amalekites were living in the Negev. The people were deterred from entering Caanan, but tried to do so, and failed miserably. This lead to the wandering for 40 years in the desert. Finally they crossed the southern Negev and the Arava, went round the Dead Sea and walked through the Jordan River near Jericho.

After conquering the Caananites, which seems to have been an extended process, the Israelite settlement began. Fortifications have been found in several places. During the middle and late Iron Age, the time of the Judean Kingdom, there was an intensive activity in the Negev.

Table 2. Archaeological and historical periods in Israel, with emphasis on the Negev (from Bruins, 1986)

Period		Approximate date BC or AD
Neolithicum		7500 - 4000 BC
Chalcolithicum		4000 - 3200 BC
Canaanite or Bronze Age	Early Bronze Age	3200 - 2200 BC
	Middle Bronze Age	2200 - 1550 BC
	Late Bronze Age	1550 - 1200 BC
Israelite or Iron Age	Early Iron Age	1200 - 1020 BC
	Middle Iron Age	1020 - 842 BC
	Late Iron Age	842 - 587 BC
Babylonian and Persian period		587 - 332 BC
Hellenistic period		332 - 37 BC
In the Negev:		
Nabatean period	Early Nabatean Period	300 - 100 BC
	Middle Nabatean Period	30 BC - 50 AD
	Late Nabatean Period	50 - 106+ AD
Annexation of the Nabatean kingdom to the Roman Empire		106 AD
Roman period		37 BC -324 AD
Byzantine period		324 - 634 "
Arab period		634 - 1099
Crusader period		1099 - 1291
Mamluk period		1291 -.1516
Ottoman period		1517 - 1917
Brittish mandatory period		1917 - 1948
State of Israel		1948 -

The Judean kings maintained villages, fortresses and trade routes throughout the Negev, and linked Judea with the copper mines of the Arava Valley and with the seaport of Eilat (Etzion Geber). The Second book of Chronicles mentions that King Uzziah "built towers in the wilderness and hewed out many cisterns." The latter achievement enabled the Judeans to construct settlements, not only close to springs and shallow ground water, but almost anywhere, utilising collected rainwater for domestic purposes. Runoff agriculture was also practised. With the fall of Jerusalem in 586 BC, and the Babylonian captivity, the Negev was laid to waste again.

It did not, however, take long before a new nation arose. The knowledge about these people, the Nabateans, has increased tremendously during this century. They probably came from the Arabian peninsula to the Negev in the fourth century BC, and started their career as nomads and brigands. Avraham Negev, an Israeli expert on the Nabateans, has written some articles in the summer -93 edition of Eretz magazine, from which the following comes.

According to Diodorus, the most important Greek historian to mention the Nabateans, they "do not plant any seeds, nor any fruit trees. There are no wine drinkers among them and they do not build houses." After gaining control of the southern trade route from Arabia and the Orient to the Mediterranean region (Fig. 5), this began to change. The Nabateans became wealthy through trade with spices and silks, ivory and incense, myrrh and medicinal herbs. Another commodity was asphalt from the Dead Sea, which was bought by the Egyptians for embalming. The traders had to have caravan bases, and some of the bases grew to become cities. Petra was the capital, and in the Negev there are six such cities, which can still be admired today: Avdat, Nitzana, Halutza, Shivta, Mamshit (Kurnub) and Rehovot (Ruheibe).

During the Hasmonean Kingdom of Judah, 167 to 37 BC, the Nabateans abandoned the Negev for several decades, but in 30 BC they were certainly resettled again. Trade with Rome flourished, but soon the Romans wanted power over the profitable trade themselves. A route through the Red Sea and Egypt was established, and the Nabatean economy collapsed. At the end of the first century AD, the Nabateans shifted over to agriculture, and became sophisticated desert farmers. The king at this time, Rabel II, was called "Saviour and Giver of Life to His People". At his death in 105 AD, the Nabatean kingdom became peacefully incorporated in the Roman Empire. In the Byzantine period, 324 - 634 AD, agriculture reached a peak level. One of the most important crops was grapes, and thus the last of the old taboos was broken. The water cisterns were much more effective than the earlier Judean ones. The Nabateans became Christians, and the beautiful churches in the Negev were built. They were burnt in the Muslim conquest in the year 634, and soon after, the laboriously constructed systems for desert agriculture were abandoned. Since this time, and up to this century, the Negev has only been inhabited by Bedouins.

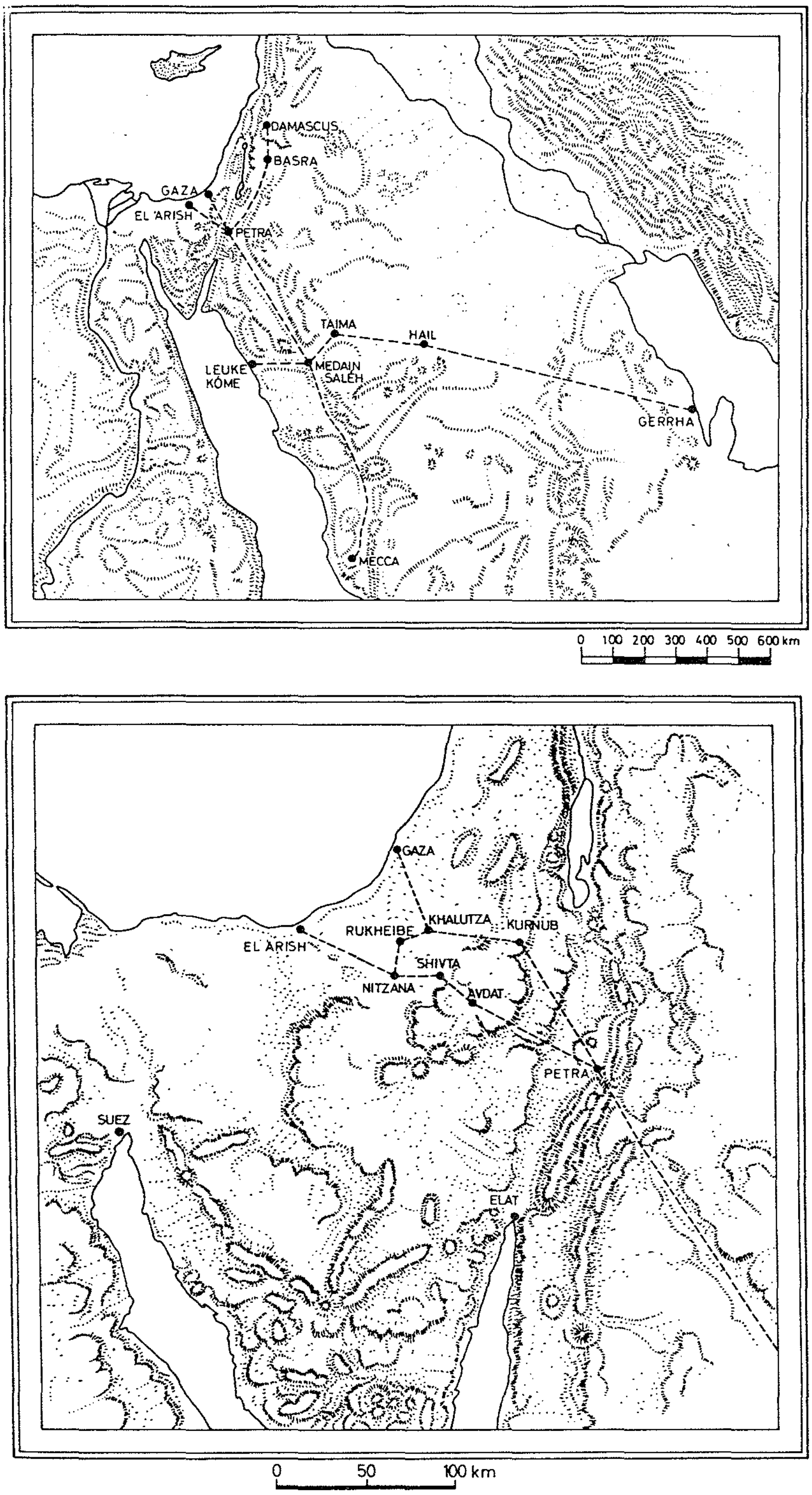

Figure 5. The main Nabatean trade routes (from Evenari et al, 1971).

Runoff farming

Requirements

In an arid zone, water is always a rare and precious liquid. Rain-fed agriculture is possible in semi-arid areas: with summer rainfall, the lower limit is 450 mm $year^{-1}$, and with winter rains down to 350 mm $year^{-1}$. When less water than this is available, irrigation is necessary to raise a crop. In many places, runoff irrigation is the most feasible possibility. Five criteria can be postulated for the ideal area for runoff agriculture:

1. The rain should come in heavy and intense showers, creating a lot of runoff.
2. The rain should fall in periods with low evapotranspiration (i.e. the winter), thereby minimising evaporation losses (Pacey & Cullis, 1986).
3. The soil or the surface of the catchment area should have a low permeability.
4. There should be clear differences in elevation, so the runoff water can easily be directed to the desired places.
5. The fields or plots of cultivation should have deep soils, with a good water holding capacity, a large part of the water available to plants, and an infiltrability high enough to prevent extended water logging.

In the Negev, at least the last four conditions are met. The loess soil has the ability to fulfill both of the seemingly contradictory requirements 3 and 5. When exposed to rainfall, it slakes and forms a crust which markedly increases the runoff. In a valley bottom, when the soil is thick enough, the water holding capacity is remarkably good. Plant available moisture is of the order of 15 - 20 % by volume. A normal clay has around 15 %, and a sandy soil perhaps only 3 - 5 %. The infiltration rate is also acceptable. A flooded field normally takes 1 to 2 days to infiltrate the surface water.

Definition and formation

The definition from the introduction may need some further comments. Runoff farming and rainwater harvesting are used synonymously, but even if the latter expression is accepted, the meaning of it is a bit obscure. Usually one can only harvest what has been sown, and with rainwater it implies that you harvest water from an area which has been treated in any way to "yield" more rainwater as runoff. This has been tried in experiments many times, especially in the US, but in actual practise it is not always the case. Harvesting is then reduced to a question of collecting the water. Both Evenari et al (1971) and Hillel (1982) deal extensively with a very common feature on the hillsides around the cultivated fields. Stone mounds and ridges in regular patterns can be found in large numbers, and they have puzzled earlier visitors. It now seems clear that stone-clearing and putting the stones in heaps was actually a way to increase runoff. The crust-forming soil then became exposed to the rain instead of the stones. The regular pattern may have practical and/or aesthetical reasons. Yair (1983) questions these conclusions of Shanan, Tadmor and Evenari. From his research on a slope near Sede Boker, he found a much higher runoff percentage from parts with bedrock than from those with more soil. He also points out that no traces of runoff agriculture are found on the larger loessial plains. The thickness of the soil probably plays a part, and bedrock certainly ought to have a high runoff percentage. Figure 6 shows an impressive runoff flood near Sede Boker.

Figure 6. A runoff flood in Nahal Zin creating a short-lived but powerful waterfall (from Evenari et al, 1971).

Runoff systems

Runoff agriculture is receiving more and more attention world-wide. For reviews dealing with systems all over the world, see Stenlund (1991), Reij et al (1988), Pacey and Cullis (1986) and Boers and Ben-Asher (1982). Bhushan et al (1992), Rees et al (1991) and Rapp & Håsteen-Dahlin (1990) present recent results.

Bruins (1986) differentiates five types of rainwater harvesting agriculture in the Negev. Systems in other places can probably fit into any of these categories. He puts them in an increasing geomorphic scale, but I prefer to present them in chronological order. The chronology is, however, not exact. The time of origin of both 'modern' systems is unknown, but they are at present the systems which receive most attention at the Runoff Agriculture Unit. The historical systems are also utilised today at suitable locations. The systems are:

1. Terraced wadi system
2. Hillside conduit system
3. Diversion system
4. Microcatchment system
5. Liman system

Quite naturally, the following descriptions are based mainly on Bruins (1986).

Historical systems

The large number of remnants of ancient agriculture in the Negev is truly amazing. In 1967 Kedar investigated the extent of ancient runoff farming systems, and Bruins (1986) relies mainly on him. It was found that the total area was about 2000 square kilometres. The cultivated fields were c. 4004 hectares in total. The location of the runoff farming district is shown in Figure 4. A precondition for this type of organised agriculture is a strong central power. This is one reason why nomads have practised runoff farming only to a very limited extent.

Terraced wadi system. The terraced wadi is probably the oldest system. It was practised by the Israelites, but also much later during the Byzantine period. A narrow wadi, a first-order catchment basin of the runoff from the hillsides, was crossed by several low check-dams. The dams were built from local stones. Each terrace was levelled to ensure proper water spreading and storage in the soil. This terracing made the valley look like a continuous stairway, each stair about 10-20 meters wide and 20-50 cm high. In the smaller wadis, spillways were not usually built in the check-dams, so the excess water flowed over the entire length of the dam. However, in the somewhat wider wadis, spillways are quite common. In all types of dams, it can be disastrous to try to catch too much water, and the spillways probably arose due to bitter experience. They are between 15 and 30 cm high, which means that the dam will hold between 150 and 300 mm of water when the terrace is filled with runoff water. Two or three such floods per year will normally give a reasonable yield.

Hillside conduit system. Where the wadis start to widen, a hillside conduit system might be very beneficial. The conduits are low walls built of stones and soil. They run along the hillsides, and direct the water to the cultivated plot. The conduits increase the catchment area, and divide it into smaller sub-catchments. The runoff water flows less as overland flow, and starts to flow in channels instead. This increases the velocity, and reduces the depression losses. The cultivated fields need check-dams to store the collected water. Where hillside conduit systems are found, remains of houses and farmsteads are also common (Evenari, 1971). The Avdat farm is a good example of this system. Seven conduit catchments ranging in size from 1 to 7 ha, and one natural catchment of 345 ha, supply water to the fields.

Diversion system. When large areas of suitable land have a higher elevation than the wadi-bed, a diversion system might be appropriate. A dam is built higher up in the wadi, and when the water level rises, it is diverted, often into a long diversion channel, towards adjacent fields. This system requires large, intricate structures, and is only found in some large wadis in the Negev. The largest runoff agriculture system in the world was of the diversion type. It was built and managed by the Sabeans, who lived more or less at the same time as the Nabateans, but in today's Yemen. The Great Dam in Ma'rib was an enormous structure: 680 m long and 16 m high. It was built in Wadi Dhana, which has a catchment area of at least 10 000 km^2. Below the dam, on each side, The North and South Oasis were cultivated, covering together 9600 ha. Like all other diversion dams, the biggest problem was silting-up behind the dam. A strong central power is needed to handle a system of this size. Both of these factors, a weak central power and silting up, led to the final collapse of the Great Dam in the beginning of the seventh century AD. It had been working for at least 1300 years, and judging by the depth of sediments in the cultivated fields, runoff irrigation might have been practised for at least 2500 years (Brunner and Haefner, 1986).

Modern systems

The microcatchment system. The term "microcatchment system" is used with a somewhat different meaning by different authors. Boers & Ben-Asher (1982) define all runoff systems with a flow distance of less than 100 m as a microcatchment system. Tauer & Humbourg (1992, 36-49, 182-183) call a system with a slope of less than 10 %, and the catchment area adjacent to the cultivated area, a microcatchment system. In the Negev, it usually refers to small plots of rhomboidal shape with a total area of less than 1000 m^2. The system seems not to have been practised in the Negev before Evenari, Shanan & Tadmor started their work in the 1960's, prompted by Yoel de Malach, one of the founders of kibbutz Revivim. He was the advisor in agricultural matters in Evenari's team. The idea came from North Africa. In the Negev each tree was given its own catchment area. Low earthen bunds are raised around each catchment, and at the lowest corner within this area a few square meters are dug out as the receiving area. This design was named "negarin" (negarim in plural) after the Hebrew word for runoff water, "neger". Figure 7 shows some negarim in Wadi Mashash.

Figure 7. Microcatchment system (negarim) at Wadi Mashash.

Runoff efficiency is larger in smaller catchments, and this system is simpler and cheaper than other. Shanan and Tadmor (1976) has described in detail how the negarim should be constructed. A lot of work was devoted to find the right size of the catchment area for different tree-species, but unfortunately this varies considerably in different locations. There seems also to have been large water losses when the water reached the receiving plot. The catchment area needs to be kept clear of vegetation, and the bunds between the plots prevent all mechanisation. This can however be achieved in microcatchment systems which run along a contour line, and where the slope above act as a catchment area. Several of these long fields will result in a more or less terraced slope.

The liman system. A liman is a field or plot with a rather large earth-wall surrounding it. It has generally two openings in the wall, an inlet and an outlet, but in several cases both the inlet and outlet are combined in one opening. They are best suited to broader valleys, which are known to carry runoff floods. The term liman is derived from the Greek word "Limne" which means lake. The "lake" is formed when a liman is filled up to the level of the spillway with water, and normally disappears in one to two days. In larger wadis, a series of limans may be built one after each other, the outlet of one liman being the inlet to the next.

Figure 8. Flooded liman at Sede Boker.

A requirement is of course that the large catchment area produces enough runoff water. The first limans in Israel were built at the end of the sixties by the road authorities, and were later improved in the Wadi Mashash experimental farm (A. Rogel, pers. comm. 1993). Figure 8 shows a filled liman at Sede Boker.

Earlier related studies

The only previous study found concerning runoff agriculture and soil changes was made by Sandor, Gersper and Hawley (1986 a, b, c). They examined the Sapillo valley in New Mexico, USA. The annual rainfall is in the range of 250 to 400 mm, mean annual air temperature 11 °C and summer temperatures of 18 - 21 °C. Runoff agriculture was practised between 1000 and 1150 AD., with a terraced wadi system. Annual crops were cultivated, with corn (*Zea mays* L.) the most prominent. The vegetation in the surrounding area is grass, mainly blue grama (*Bouteloua gracilis*). The fields were abandoned around 900 years ago, but several of them still lack a grass cover.

Sandor et al investigated several soil parameters, including micronutrients. The pH in the topsoil was around 6, with a somewhat higher value in the cultivated fields compared with the control. Below 50 cm depth, pH values up to 7.9 were found. The organic carbon content in the upper horizon in cultivated fields was 0.98 % by weight., while the mean in control plots is 1.8 %. Recent sediments were even richer in organic carbon (around 2.2 %). This loss of organic matter is in line with many other studies on cultivated fields, e. g. Russel et al (1984) about the Morrow plots, and among the possible explanations are an increased soil aeration under cultivation and direct loss of biomass in the conversion to cropland. The soil contains in the natural state much more clay than in the Negev, especially in the subsoil. A clear argillic horizon is found in many places. In the topsoil the clay contents are however comparable, 15 - 19 % in New Mexico and 16 - 25 % in the Negev. No statistical difference was found in the clay content of cultivated fields compared to control sites, except in the Bt horizon (20 - 50 cm in cultivated fields, 10 - 35 cm in control plots). Clear evidence of erosion was found, particularly the rills and gullies in cultivated plots, which often cut through the argillic horizon. The erosion began during the cultivation.

MATERIAL & METHODS

Wadi Mashash

Wadi Mashash was established in 1971 by Evenari, Tadmor and Shanan as their third research farm in the Negev. It is situated in a broad valley about 20 kilometres south of Beer Sheva. It is many times larger than the former farms Shivta and Avdat. The total area today is around 350 ha (Figure 9). The primary goal was to test the negarim system on a larger scale, but during the years the liman system has turned out to be more successful. Presently almost all research is carried out on the limans. The elder limans were planted with fruit-trees, but since 1983 only trees for fodder and fuel have been grown. For example, the famous *Leucena leucocephala* has been tried, but the result was very poor due to severe winters. To date, at least 30 limans have been erected. Figure 9 shows a map of Wadi Mashash at the time of the study. When the farm was established, a lot of grass seed was placed further up in the wadi, and was then transported with the water inside the farm. Today, all limans, and also the wadi in some places, have a lush grass vegetation after the floods. Table 3 shows the estimated water income in the different limans of the study. Notable is the sometimes large variations between them in the same year. 300 or 350 mm indicates a full liman (= one flood). Lower figures than this, except the zeros, may mean that there has been a break in the wall, and that most of a flood has been lost.

The different limans

Figure 10 shows the shape and size of each liman, with the inlet and outlet marked. Approximate locations of the different soil samples are also given. 1 dunam equals 1000 m^2 or 0.1 ha.

Liman 72/1

This is the oldest liman inside the Wadi Mashash farm, but older ones can be found outside along the road to Yeruham. It was planted with olive trees, and has for several years given a good yield. It has, together with liman 72/2, a catchment area of its own on the eastern hillside of Wadi Mashash, and is not connected to the main wadi. It has separate inlet and outlets, and the outlet leads to the inlet of liman 72/2. Figure 11 is taken from the inlet into this liman.

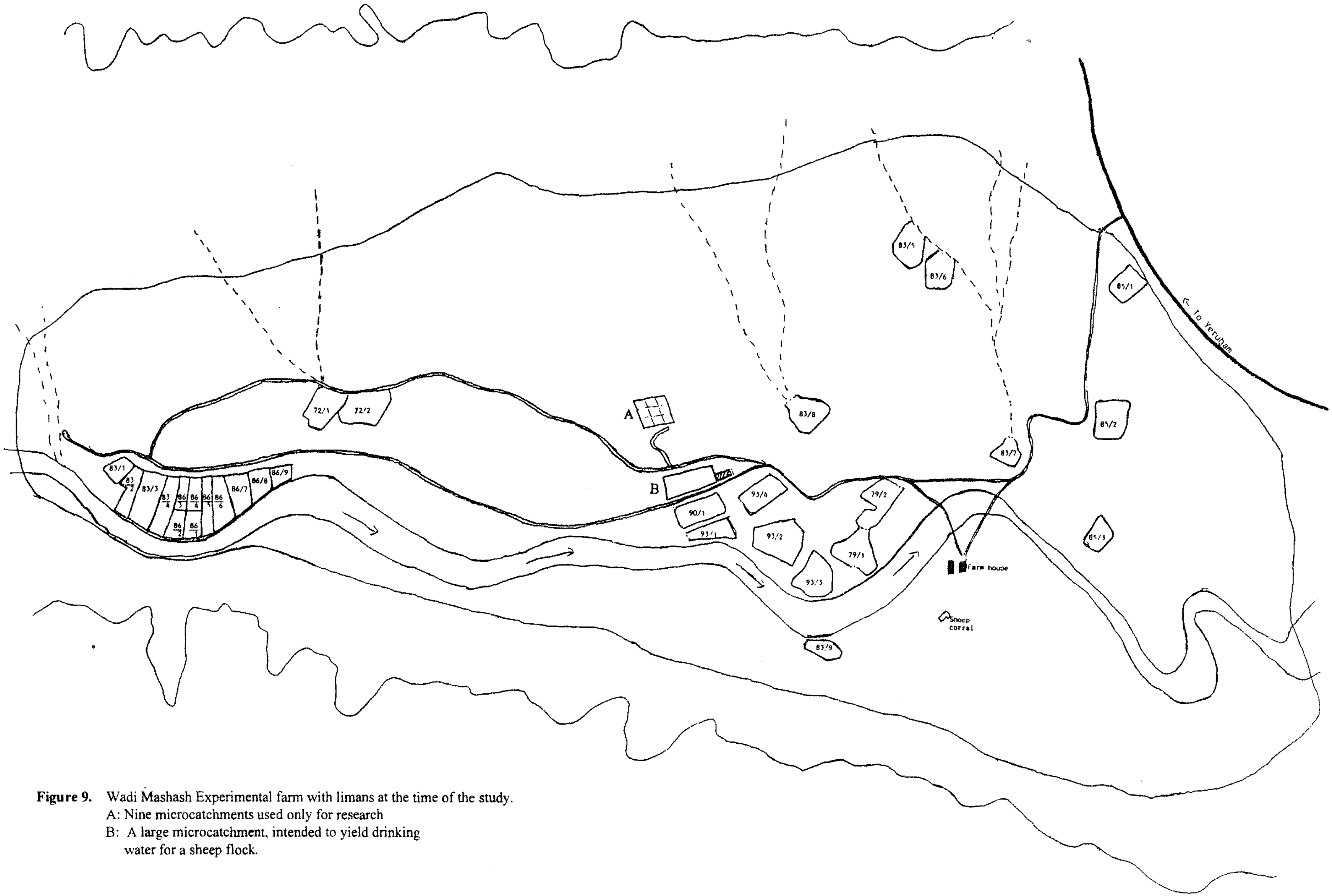

Figure 9. Wadi Mashash Experimental farm with limans at the time of the study.
A: Nine microcatchments used only for research
B: A large microcatchment, intended to yield drinking water for a sheep flock.

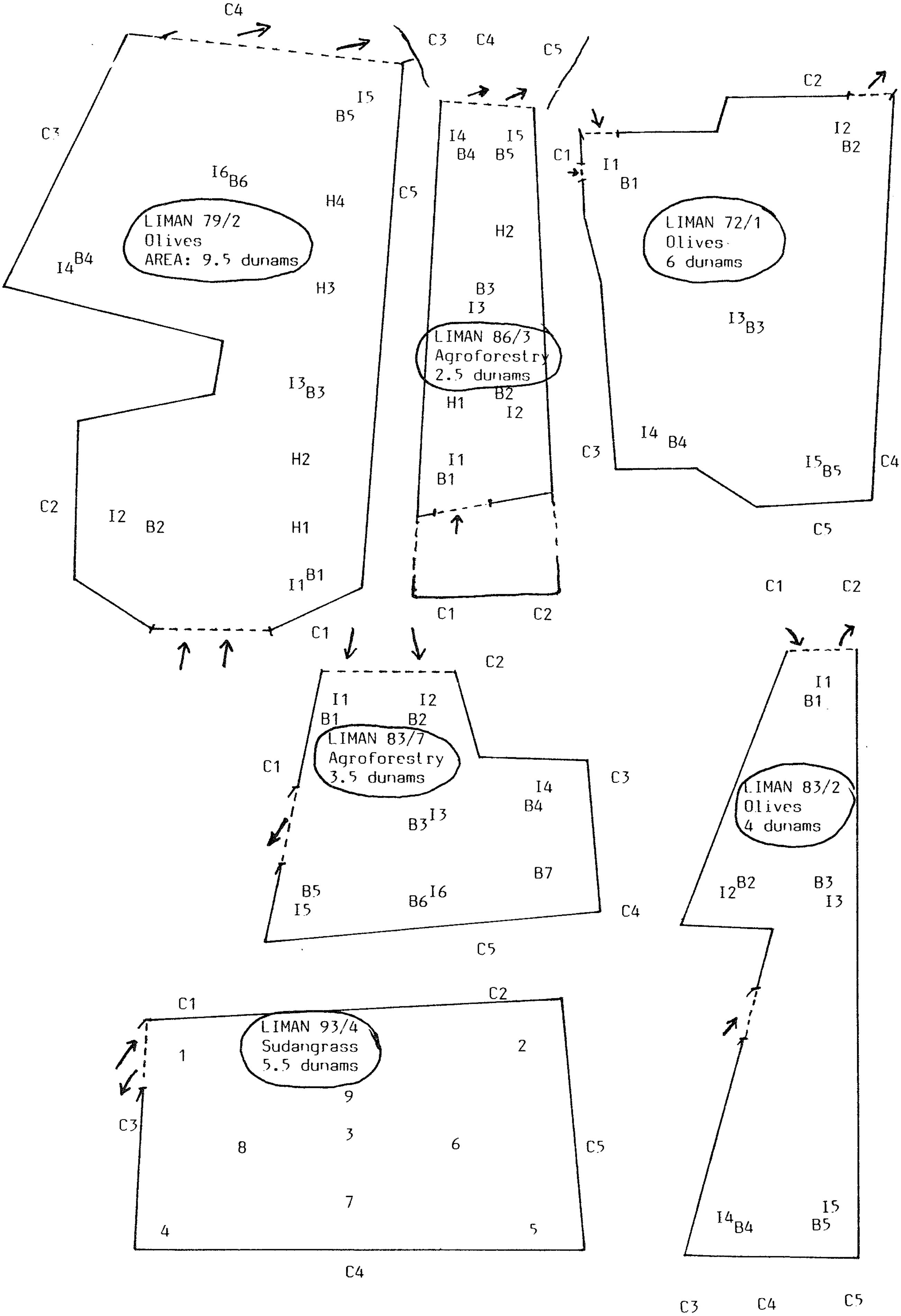

Figure 10. The shape, size and crop of the different limans. Inlets and outlets are indicated by arrows. Approximate sampling places are shown.

Table 3. Runoff water income, mm (=m^3/dunam), in the different limans. (The years 1971-82 after Bruins et al, 1986, and the rest from A. Rogel, pers. comm.)

Rainy season	72/1 Olives	79/2 Olives	83/2 Olives	83/7 Agrof	86/3 Agrof	93/4 Sudangr
1971 - 72	1000					
1972 - 73	0					
1973 - 74	400					
1974 - 75	300					
1975 - 76	0					
1976 - 77	200					
1977 - 78	150					
1978 - 79	500					
1979 - 80	1650	850				
1980 - 81	1000	500				
1981 - 82	100	0				
1982 - 83	680	850	1400	850		
1983 - 84	200	50	100	0		
1984 - 85	700	200	700	700		
1985 - 86	1250	1250	1500	1250	1100	
1986 - 87	550	370	1350	430	350	
1987 - 88	850	300	2050	350	1050	
1988 - 89	550	0	700	650	1000	
1989 - 90	400	400	650	150	850	
1990 - 91	300	450	1000	600	650	
1991 - 92	650	550	750	950	700	
1992 - 93	150	350	50	300	0	200
Total	11580	6120	10250	6230	5700	200
Average	526	437	932	566	712	200

Liman 79/2

This is one of the biggest limans in Wadi Mashash, and was extended to its present size in 1983. The runoff water comes from the main wadi, and the area of the liman was flooded several times before the establishment of the liman. The olive-trees in the liman grow well, and there are also some fig-trees planted where sample I2 (Fig. 10) was taken. Traces of an earthworm were found in sample I3. The inlet is the outlet of liman 79/1, but the outlet leads excess water to the wadi.

Figure 11. Liman 72/1 with olives.

Figure 12. Liman 86/3 with agroforestry. This is the second year after the second harvest.

Liman 83/2

This is one in the group of thirteen limans lying next to the main wadi. The inlet is however on the other side, since a man-made ditch, directing the water, has been constructed there. It receives water from liman 83/1, and passes the surplus on to 83/3. Together with 83/4 and 83/9, they were the last ones to be planted with olives.

Liman 83/7

This was one of the first limans planted for agroforestry purposes, and both acacia-, eucalyptus- and prosopis-species are found. It is not dependent on the main wadi, but probably drains into it. The catchment area is on the eastern hillside, but some 100 meters south compared to the catchment area of liman 72/1. In this liman, three earthworms were found, at samples I5 and I6 (Fig. 10), and they were all carefully replaced. This was a very unexpected finding, since the surrounding environment is definitely not suited for earthworms. The most likely source is the plant material, and the earthworms are a clear indication of how the micro-climate changes due to the runoff water and the trees.

Liman 86/3

This liman is also within the group of thirteen lying next to the wadi, and it forms together with limans 86/1, 86/2 and 86/4 a special group. It is planted with acacia and eucalyptus of different densities. It has been harvested two times. The inlet is from liman 86/2, and the water continues to liman 86/4. The water should therefore have a clear flowing direction, and a gradient in the clay content can in fact be seen here. Figure 12 shows this liman.

Figure 13. Liman 93/4 before any sudangrass has germinated.

Liman 93/4

This is one in a group of four limans which are intended to form a sustainable unit together with a sheep flock. The large microcatchment quite close to it is also intended to yield drinking water for the sheep in a pool at one end (Fig. 9). Sudan grass was sown after the first flood ever in this liman. The water comes from the main wadi, and the inlet and outlet are at the same place. Figure 13 shows the liman before any Sudan grass had germinated.

Sampling

The sampling pattern is shown in Figure 10. In general, 30 samples were taken from each liman, but from some limans with interesting features some extra samples were included. If the soil was wet enough a drill was used, otherwise a spade. The samples were taken at two depths, 0 - 20 cm (upper layer) and 20 - 40 cm (lower layer), and from three categories: in the tree-rows (I), between the tree-rows (B) and outside the liman (C). Sample nr 1 was taken as close as possible to the inlet, while nr 5 came from as far away as possible from the inlet. The numbers in between were spread evenly across the liman.

Analyses

As reference manuals for the laboratory work we used a Swedish student laboratory guide (Eriksson, 1986) and 'Lab guide for the Introductory course in Soil Science , Faculty of Agriculture, Rehovot, Israel'.

The de-ionised water at the Institute was unreliable, and had a fluctuating pH with values up to 10. Double distilled water was therefore used for all analyses except particle size distribution.

Electrical conductivity (EC) and pH was measured on all samples, while organic carbon and particle size distribution was determined on the samples of the upper layer. .

Electrical conductivity and pH

Electrical conductivity and pH was measured in a 1:1-extract. 30 g soil + 30 ml double distilled water was put in a shaker for one hour, and filtered. The two measurements were done almost simultaneously, and as the pH-meter had a thermometer, this temperature was used to adjust the EC-meter.

There is always a risk of salinization in an arid zone. The rocks weather, and there is too little percolating water to leach out the accumulated salts from the soil. Adding water, even if it is of good quality, enhances the danger. The evaporating water leaves the salt in the soil. The soils in the deserts therefore often have a high salt content, and the Negev is no exception. A common way to measure the total salt content is to study the electrical conductivity (EC) of a water extract of the soil. The higher the salt content, the higher the EC value. Up to a certain EC value the relationship is almost linear. Since the conductivity is the reciprocal of the resistivity with the unit ohm(Ω)/m, an early unit for the EC was mho/meter. It is still in use, while the new SI-unit is Siemens/meter. Swedish standard is now mS/m. The relation between some units in practise are:

$$100\ \text{mS/m} = 1\ \text{dS/m} = 1\ \text{mS/cm} = 1000\ \mu\text{S/cm} = 1\ \text{mmho/cm}.$$

EC is widely used in greenhouse-production in Sweden and elsewhere, to measure the nutrient status (=the salt content) in the growing medium. EC is highly dependent on temperature, but on newer EC-meters the values are compensated to 25°C.

Organic matter

Before analysis, we tried to separate and remove the fine roots in c. 5 g of soil, by means of the electro-static forces in a charged glass-rod.

To determine the organic carbon content, we used a solution of potassium-dichromate ($K_2Cr_2O_7$) to oxidise the carbon in the soil sample. The solution was acidified with sulphuric acid. The surplus of potassium-dichromate was then titrated against a ferro-ammonium sulphate solution (Mohr's salt). Since we also used boiling, we used a modified version of the method described by Walkley & Black in 1934. The formulas for the two reactions are as follows:

$$2\ K_2Cr_2O_7 + 8\ H_2SO_4 + 3\ C \rightarrow 2\ K_2SO_4 + 2\ Cr_2(SO_4)_3 + 8\ H_2O + 3\ CO_2 \qquad (1)$$

$$Cr_2O_7^{2-} + 6\ Fe^{2+} + 14\ H^+ \rightarrow 2\ Cr^{3+} + 6\ Fe^{3+} + 7\ H_2O \qquad (2)$$

The efficiency of the former reaction depends on the temperature. After adding 10 ml of dichromate solution to 1 g soil, each sample was boiled for exactly 5 minutes. The reaction has an efficiency of 87 % with this treatment, which means that the carbon content values should be multiplied by 1.15. The concentration in the two solutions was 0.067 M and 0.4 M respectively. Since the Fe-ammonium-solution was 6 times stronger than the dichromate-solution, the volumes at the change-point should be equal in a carbon-free control-sample (reaction 2).

From reaction 1 and 2 above we can deduce the following formula for the carbon content (g/g):

$((V_{Cr}C_{Cr} - (V_{Fe}C_{Fe}/6)) * 1.5 * 12.011*1.15)/ x$ g soil which can be rearranged to (% by weight):

$$((6\, V_{Cr}C_{Cr} - V_{Fe}C_{Fe}) * 3.45/ x \text{ g}) * 100 \qquad (3)$$

The control samples of the first solutions did indeed have the same volumes, which gives a C_{Cr} of 0.07 M. Later solutions might have had a different concentration, but some representative samples from almost all series were re-made, and the values were adjusted according to the new measurements.

Particle size distribution

We used sieving and sedimentation to determine the different particle sizes. The hydrometer method was used for the sedimentation part. After crushing the soil, we took 40.0 g of soil (including gravel and pebbles), added 100 ml of a sodium hexametaphosphate solution (5 %), some water and mixed it in a soil mixer for 5 minutes. The >2 mm fraction and 0.25 - 2 mm fraction were sieved and dried. Carbonates were not removed prior to dispersion and sedimentation (according to Israeli standard). One problem with the sedimentation was the fluctuating temperature (19°C - 29°C). The formulas used to calculate the particle percentage and particle diameter are:

1) $p = (R - R_L)/sed * 100$

   p= cumulative percentage

   R= reading on hydrometer

   R_L= the density of the blank solution

   sed= total sedimenting particles (40 g - (gravel + sand))

2) $d = \theta/t^{0.5}$

   d= particle diameter (micrometer)

   θ= sedimentation parameter (temp. dependent)

   t= time of sedimentation (minutes)

RESULTS

The results from the investigation will be presented in graphs, usually showing the mean values from the three different groups: in rows, between rows and outside. The individual values for each sample, means and standard deviations are presented in Appendices 1 to 5.

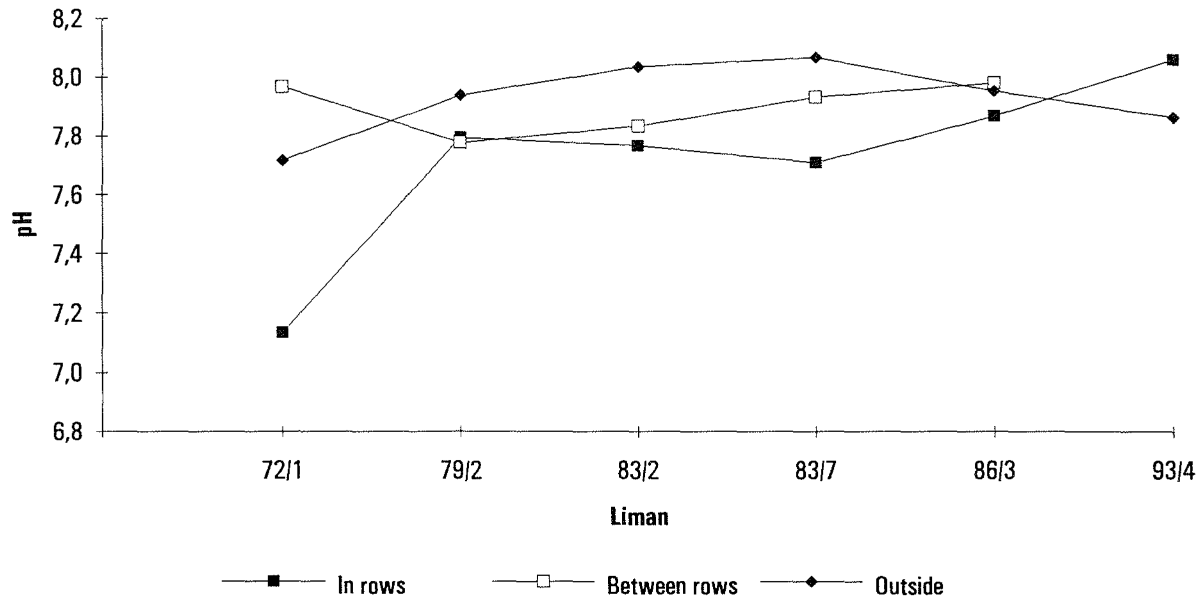

Figure 14. The pH in the upper layer (0 - 20 cm).

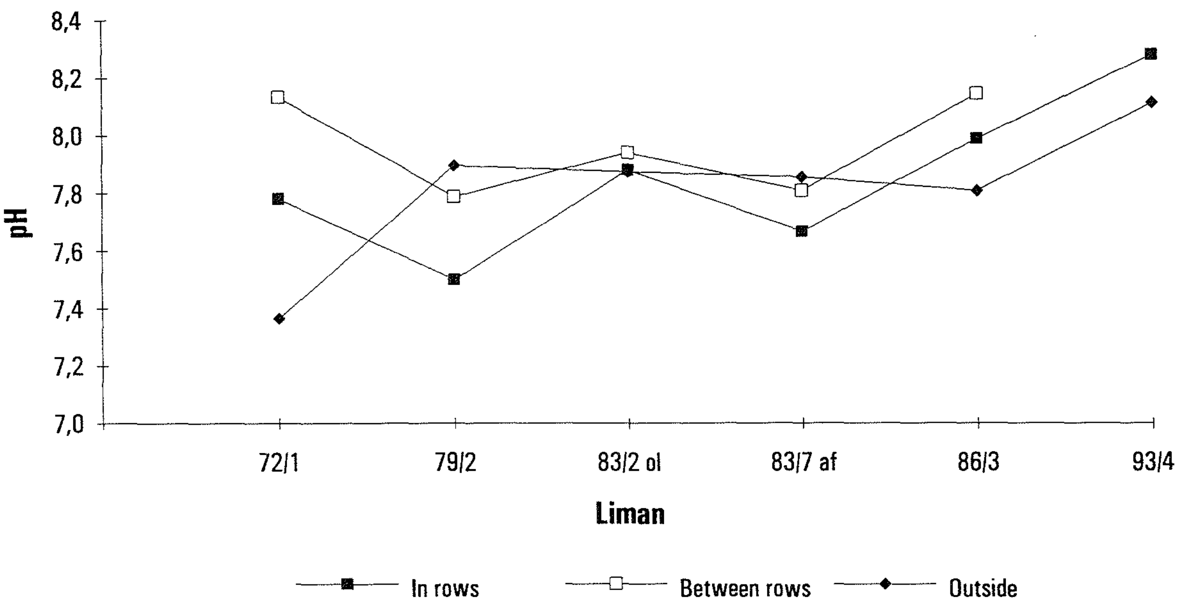

Figure 15. The pH in the lower layer (20 - 40 cm).

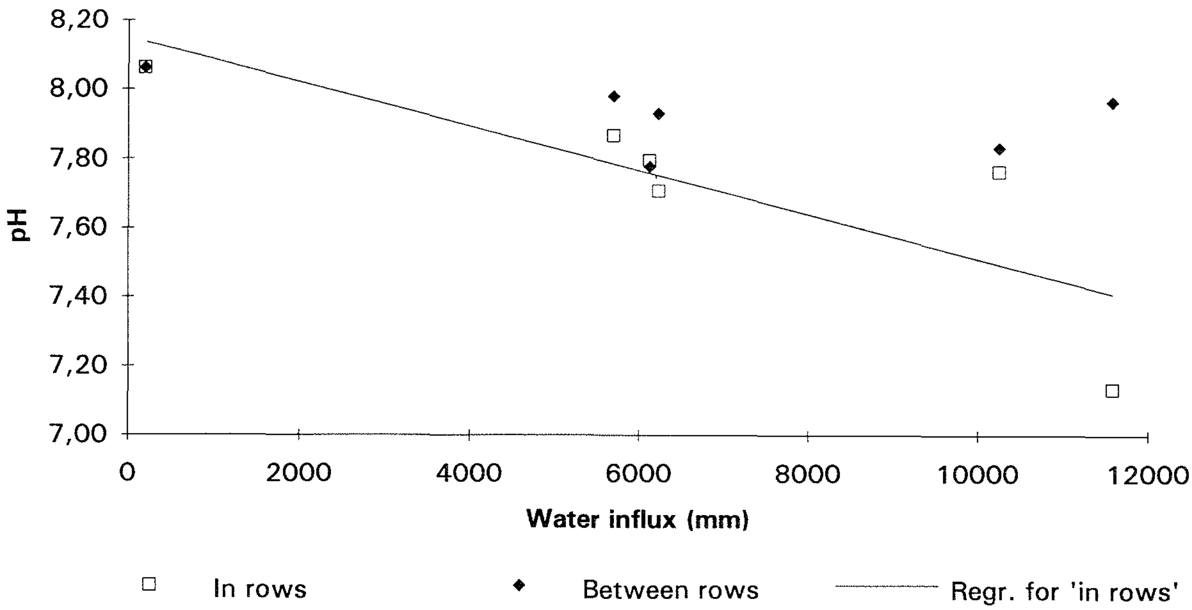

Figure 16. The pH in the upper layer inside the limans vs. total water influx.

Figure 14 and 16 show that only one of the averages really differs from the others. The p-value for differences in rows in the upper layer is less than 0.0001. Liman 72/1 is the exception here, with its almost neutral pH-value. The spread between individual samples is not extreme in this liman. Between rows in the same layer, no significant difference ($p \geq 0.001$) was found. In the lower layer the p-value in rows is also very low: 0.0004. Here it seems to be the 93/4 liman which is an outlier. Samples taken outside the liman also show no difference ($p = 0.244$), even though the shape of the line is similar to the line of "in rows" in the upper layer. The lines in the graphs should represent the trend of the pH with time (and water influx), but as seen in Fig. 16 it may only hold for the values in rows. A regression line in "between rows" is possibly as good as "in rows", but show no trend.

Figure 17 and 18 shows the EC of the upper and lower layer. As can be seen, the control values have a very large variation, and it is in reality even larger. Almost all of the limans with a high mean usually have only one sample with a really high salinity. This makes any statistical difference between the avereges impossible to detect. It is hardly possible to see any trend within the limans in terms of a decrease of salinity, since all of them have similarly low values. In the control samples of liman 72/1, the salts have only been washed down to the lower layer (20-40 cm)

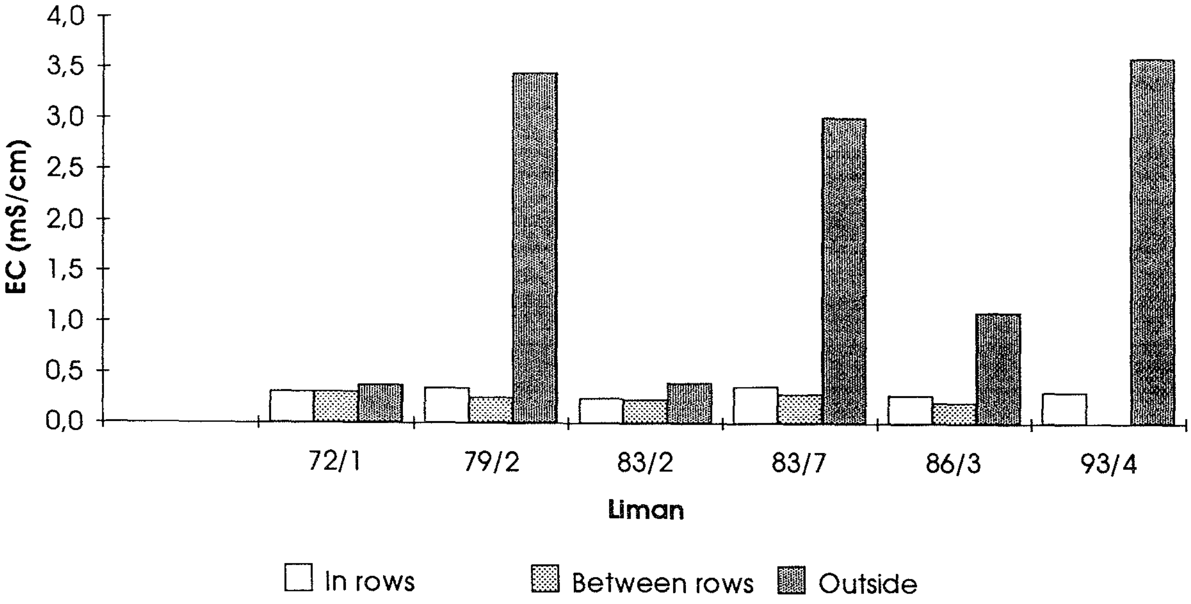

Figure 17. The electrical conductivity in the upper layer (0 - 20 cm).

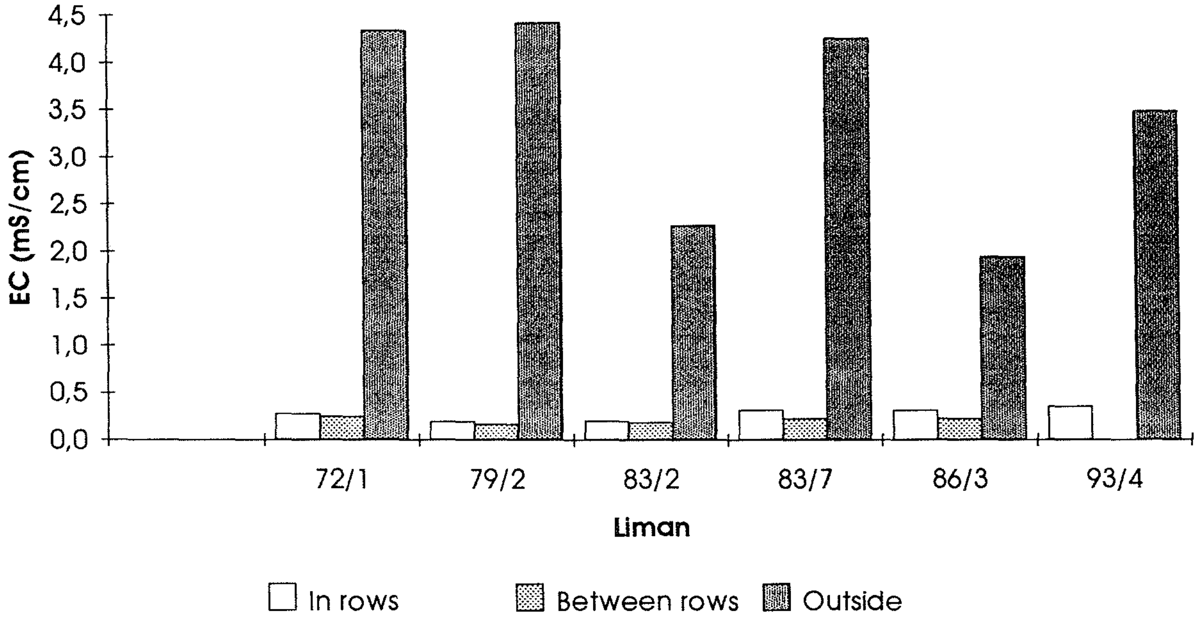

Figure 18. The electrical conductivity in the lower layer (20 - 40 cm).

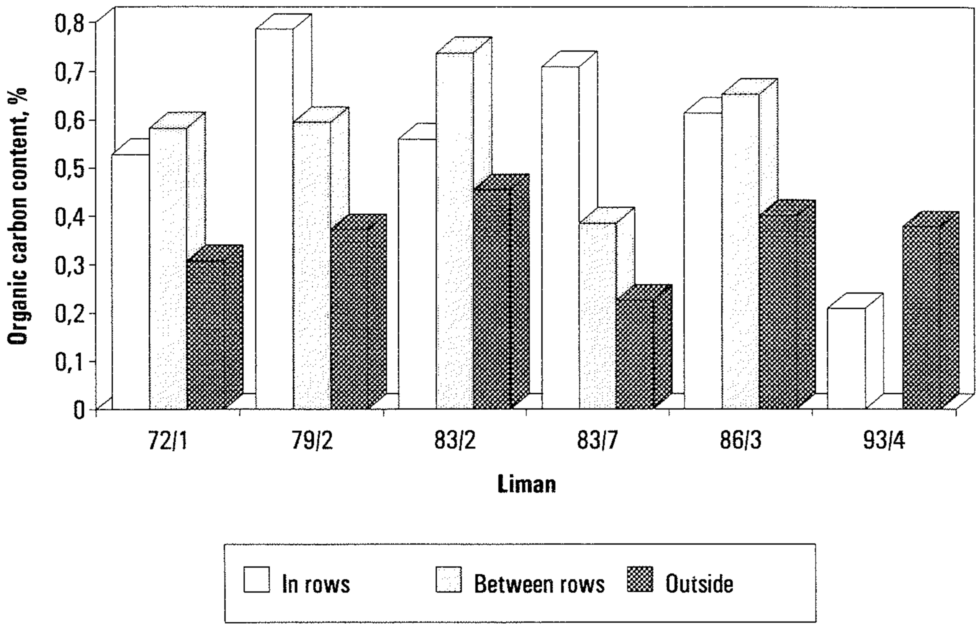

Figure 19. Organic carbon content in the limans.

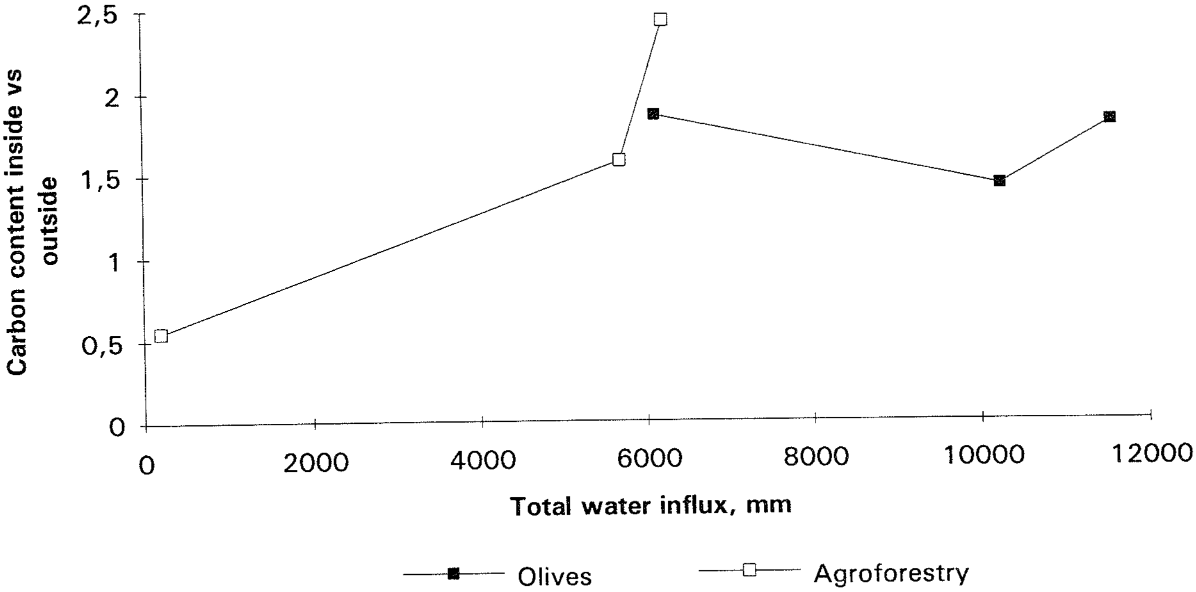

Figure 20. Ratio of inside to outside. Carbon content in limans as a funcion of total water influx.

The organic carbon and the particle size distribution are only from the upper layer. Figure 19 shows that it is difficult to see any trend over time in the organic carbon content, but that there is a clear difference between outside and inside limans. The mean of all control samples, which represents the natural content, is 0.35 %. The average of all limans except 93/4 is 0.6 %. A significant difference can be found ($p<0.0001$). Figure 20 seems to indicate that there is trend of increasing organic matter among the agroforestry limans, but that it hardly can be seen in the olives.

Figures 21 to 26 show the textural diagram for each liman. It appears that the interesting differences should be in the finer particle sizes (clay and silt), and therefore figure 27 is included. Liman 71/2 and 83/2 show hardly any difference between outside and inside in the finer particles, while limans 79/2 has 12.3 %, liman 83/7 14.2 % and liman 86/3 18.7% higher percentage inside the liman for these particle sizes. Liman 93/4 has slightly less of finer particles compared with the outside. As can be seen in appendix 4 and 5, the particle size range for silt reaches from 2 µm to 20 µm, which is the definition used both in Sweden and Israel.

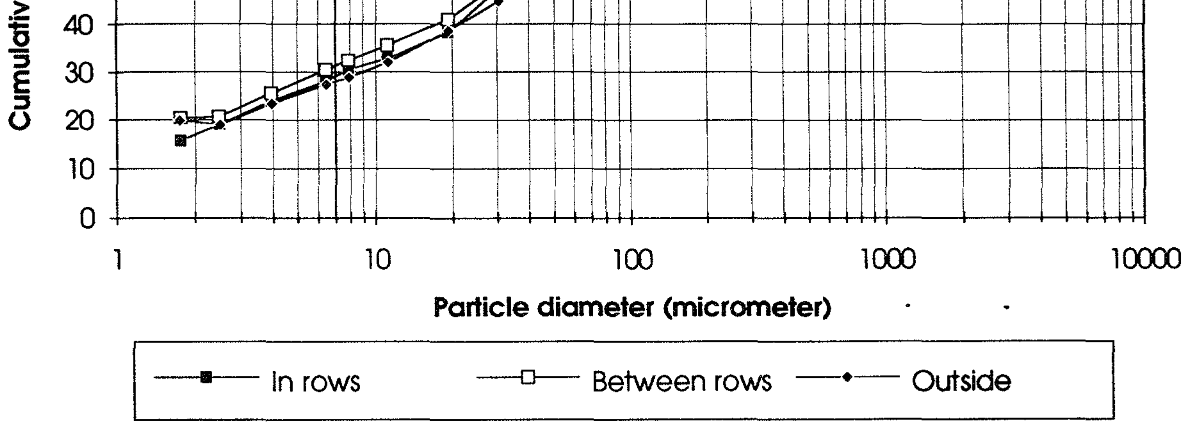

Figure 21. Textural diagram for liman 72/1.

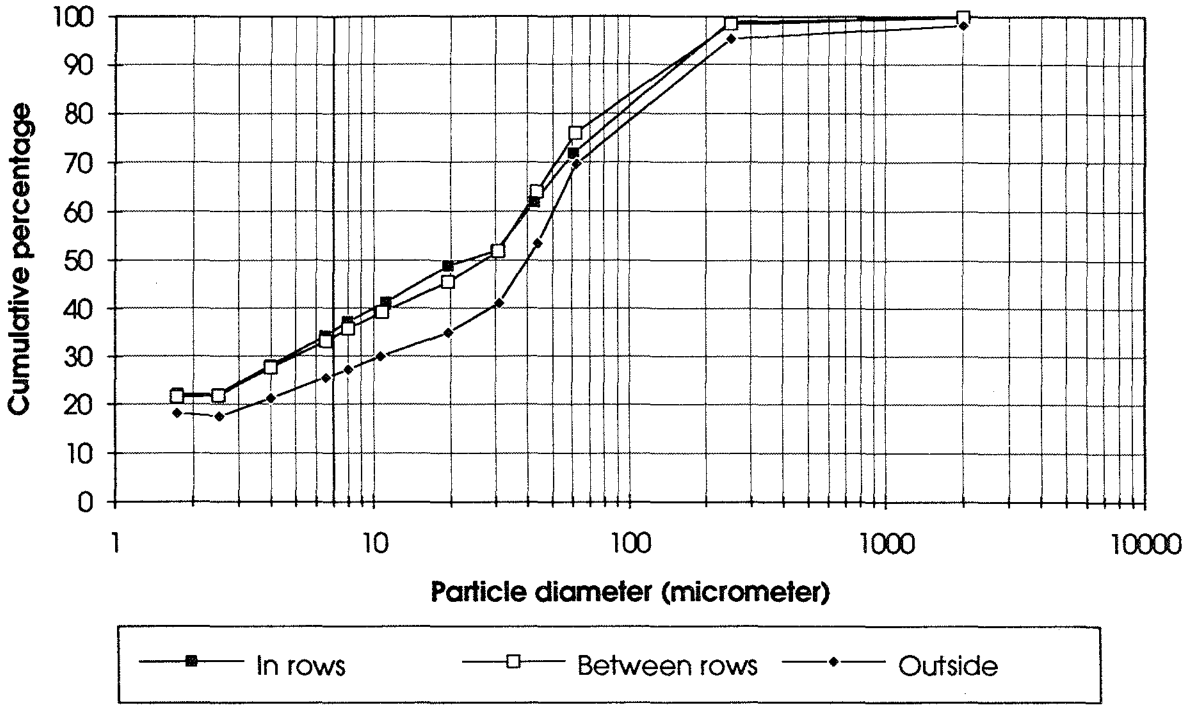

Figure 22. Textural diagram for liman 79/2.

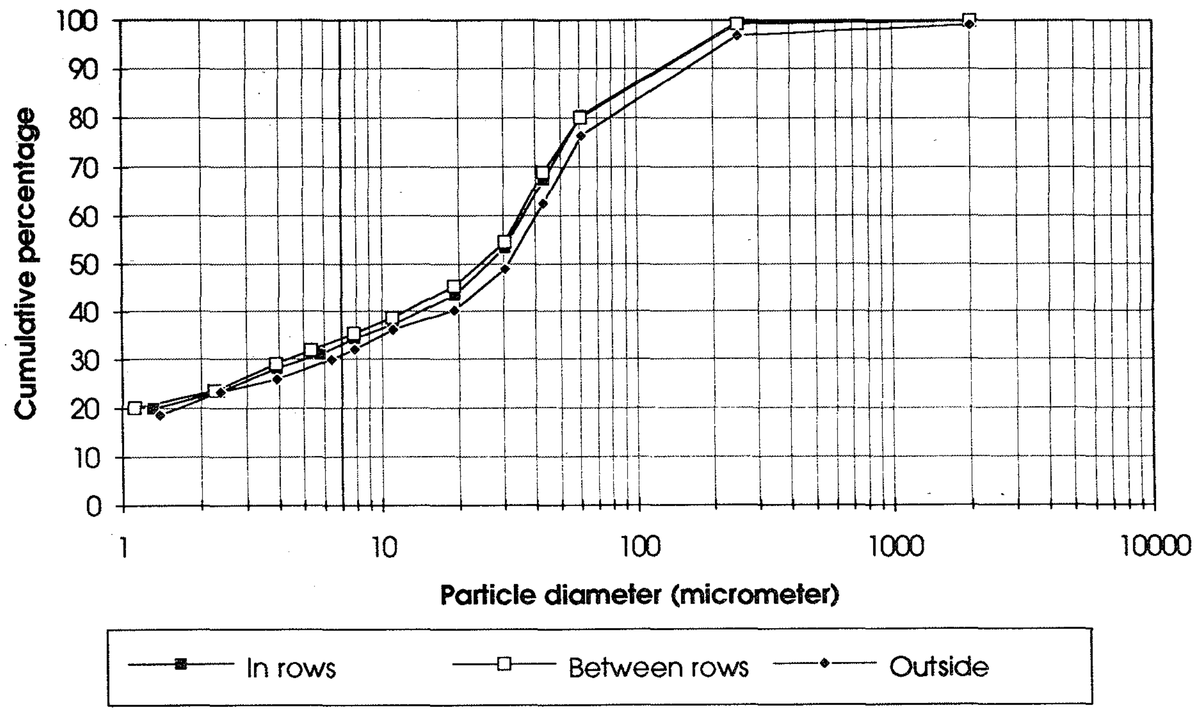

Figure 23. Textural diagram for liman 83/2

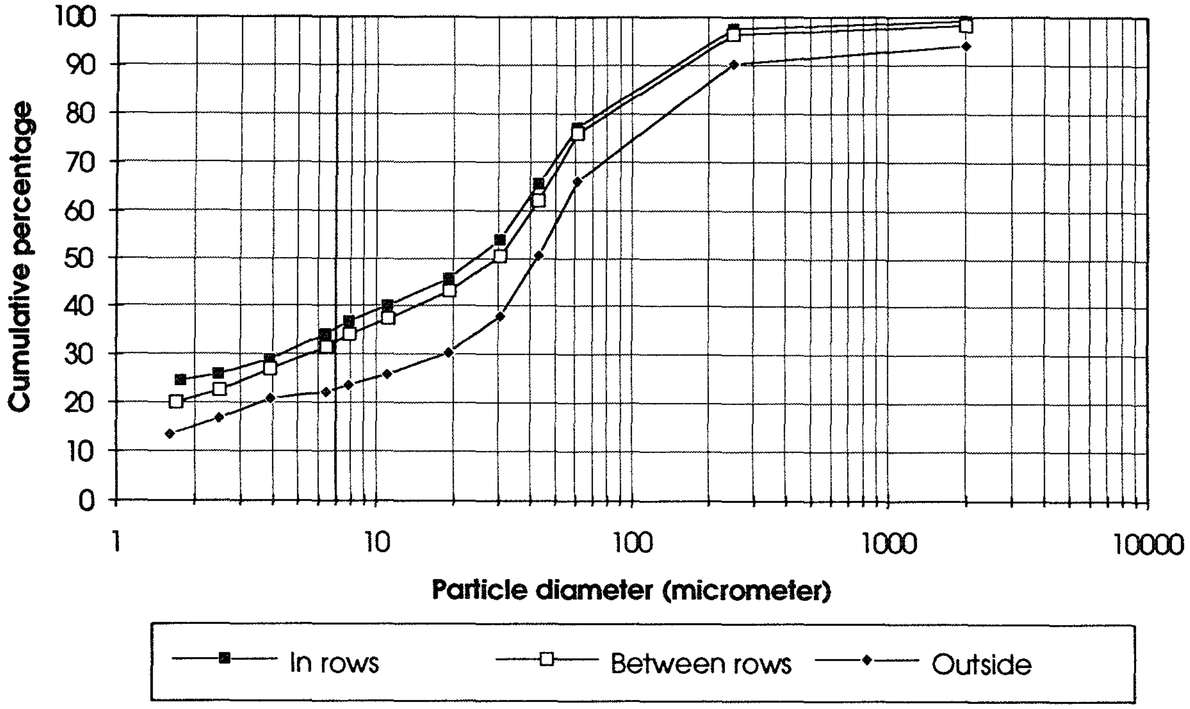

Figure 24. Textural diagram for liman 83/7.

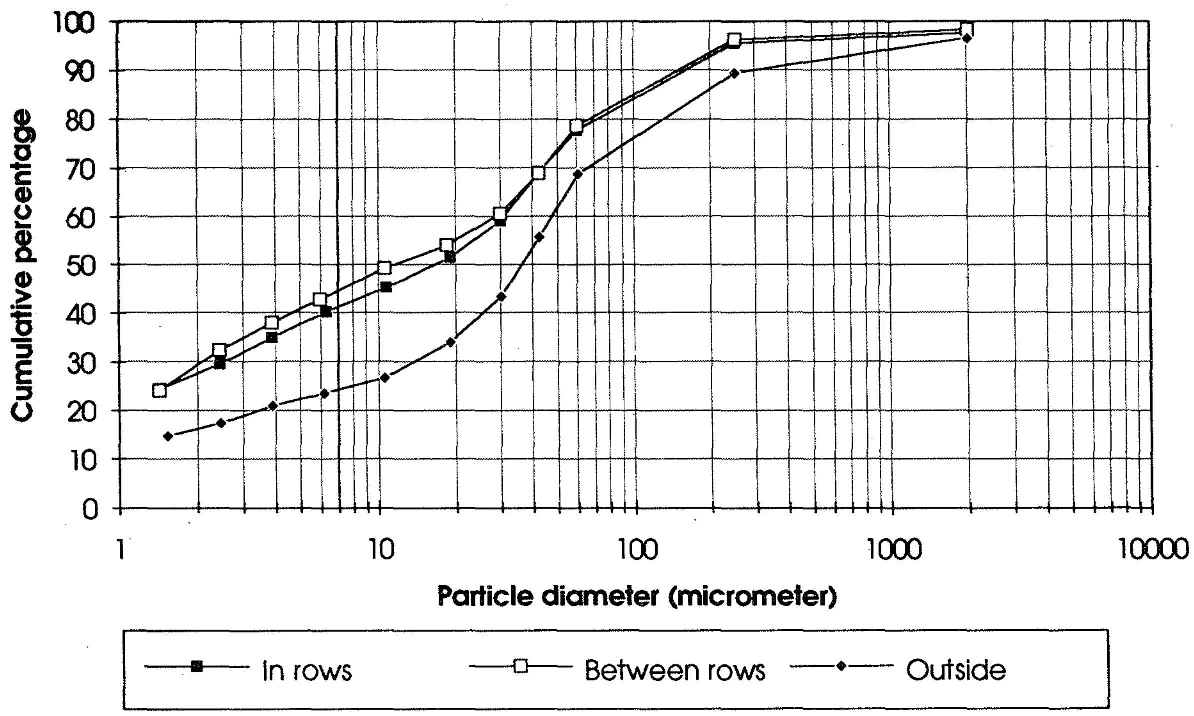

Figure 25. Textural diagram of liman 86/3.

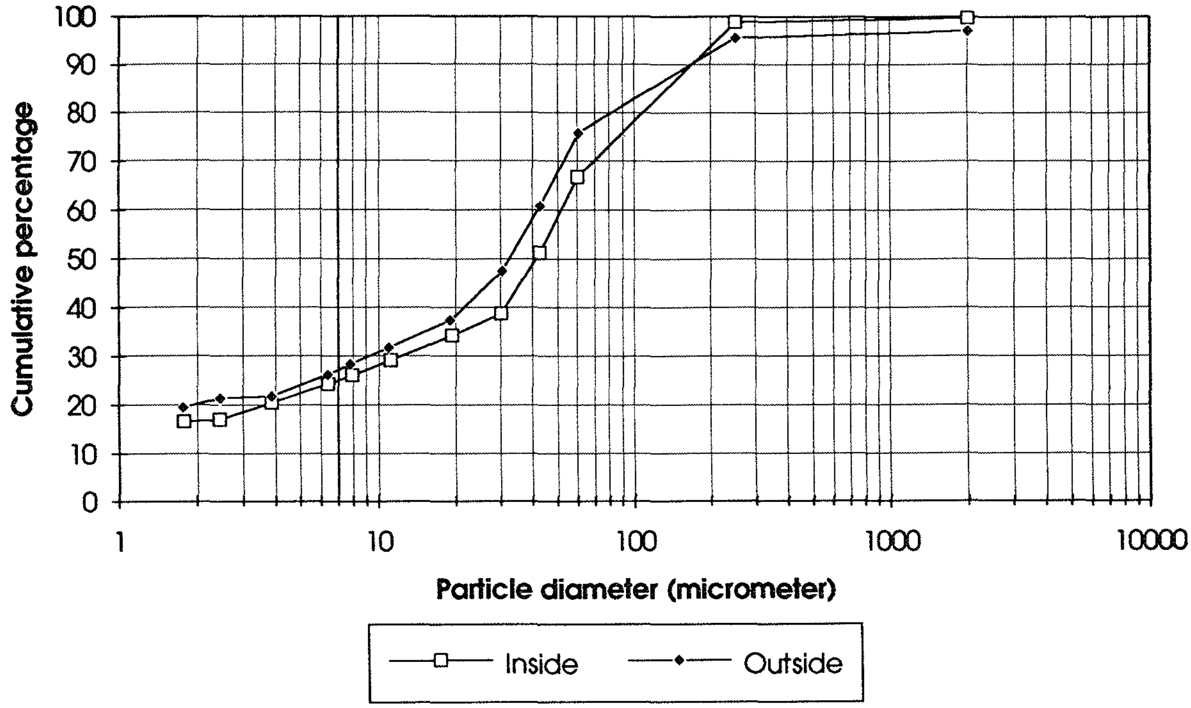

Figure 26. Textural diagram of liman 93/4.

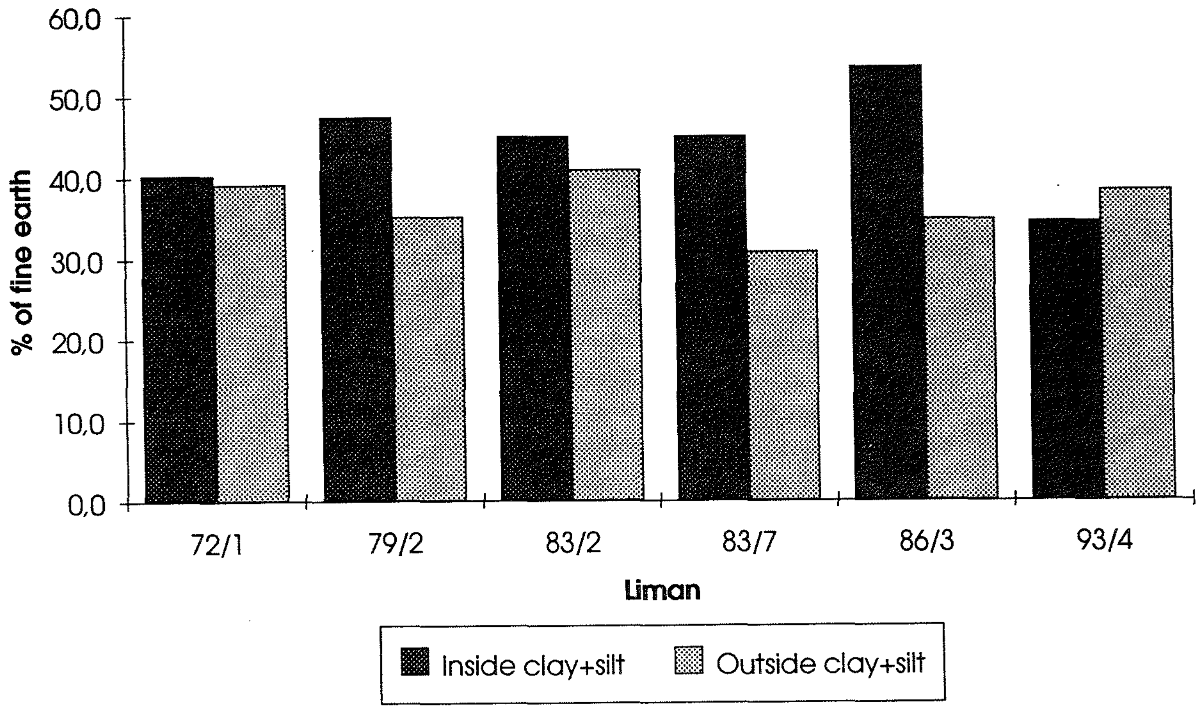

Figure 27. Clay and silt content inside the limans vs. outside.

DISCUSSION

pH

The natural pH is high, and the soil is rich in calcium carbonate. The youngest liman has the highest values (Fig. 14 and 15). It is difficult to imagine any process that could really increase the pH from this high natural state, but one could expect the opposite. There is however at least one process which buffers any acidification. The soil in both the catchment area and the limans are a loessial deposit, and aeolian transport is still going on (Yaalon and Dan, 1974). Carbonates from other deserts are continuously laid down in the Negev, and some of them should end up in the limans of Wadi Mashash, transported by the runoff water. This might explain why there is only one mean value in the upper layer which is significantly lower than the rest.

Two processes are mainly responsible for a lowering of the pH: organic acids released from the organic matter during build up, and leaching of the slightly soluble calcium carbonate by the percolating water. The oldest liman has a clearly lower pH value close to the trees in the upper layer, but not between the tree-rows, and not in the lower layer. That the low value is only a reflection of natural variability is thus a bit unlikely. The measurments "In rows" were done after each other, but they were done in the middle of many others. Why the difference in pH is not accompanied by a difference in organic matter is not clear. Which process is most important is also not clear, even if the release of acids ought to have the strongest influence. The vegetation in the limans is different, but which litterfall is most acid has not yet been shown. The olive is an evergreen with a rather limited litterfall, but in all limans except 93/4 there is a ground cover of grass. This is positive for the build up of humus in the limans, and thus also for a release of organic acids.

According to Eidt (1985), smaller changes in the soil pH occur during the season according to the soil moisture and temperature. The temperature during the sampling time was more or less constant, but that the moisture content was different was obvious. Some limans didn't receive any flood during the last rainy season. Whether this had any effect on the present data is unclear.

Plotted against the total water influx, there seems to be a trend in the upper layer, in rows. The highest value is found in the youngest liman, and the lowest in the oldest. Between the rows, and in the lower layer, the only clear difference is the highest value in the youngest liman. Why some means are lower in the lower layer than in the upper layer is not easily explained, but the interaction of the three processes indicated above must be part of the answer. That the limans have different catchment areas and hence the quality of the incoming water may differ must also be considered. Anyway a lowering of the pH, which has not reached further than at present, is not detrimental for the vegetation. On the contrary, it is beneficial, since phosphorus is more available at the neutral pH than in the natural state of the soil.

Electrical Conductivity

A gradient over time of decreasing EC values inside the limans was what I expected, but I got a slightly different picture. High EC-values are only found outside the limans, and seem to be more or less randomly distributed (Fig. 17 and 18). Many of the control samples have at the same time low salinity. Micro-topography may be the major reason for this: In the depressions the salts are washed away, while on local high points they are accumulated by capillary rise and evaporation. Inside the limans, only low values of EC are found. Notable is liman 93/4, which only received one flood. Unpublished data of Natalia Startsev show that before this flood, several salty areas existed inside the liman. How deep the salts were transported by this first flood is not known. The eastern half of the liman had slightly higher EC-values even after the flood, and this is maybe the reason why the Sudan grass grew very poorly here.

Careful study of both the EC-values and the pH-values show that there is a correlation. High EC-values are associated with low pH-values. This is not strange, since there is a competition between H^+ and other cations. The more salts, the more H^+ is forced into solution, which is seen by the lower pH-values (McLean, 1982). This is of course not the only reason for low pH-values.

That rain water has a low salinity is well known, but could the runoff water bring any salts from the catchment areas? The sediment transported with the water can undoubtedly contain some, but there is little danger of the water itself to pick up any harmful amount of ions. In runoff experiments carried out by Frasier et al. (1987), 1120 g m^{-2} of sodium chloride was applied on the catchment areas. This is a way to reduce the infiltration, and was quite successful. Nevertheless, the EC in the water from salt-treated areas was not significantly higher than from untreated areas, and the maximum rise in EC in distilled water was from 0.04 to 0.14 mS/cm. Furthermore, nothing in the limans indicates that salinization is occuring, rather the contrary. That this is ameliorating the growing conditions inside the liman is clear.

Organic matter

Organic matter, or humus, has tremendous influence on the structure and the fertility of a soil. The mineralization of nutrients, a higher cation exchange capacity, a better water retention and a more stable structure are some of the positive effects of a higher humus content (Goudie, 1990). In natural soils, the amount present is governed by the classical five soil-forming factors. It is true also in this case, if one adopts the view of Yaalon & Yaron that man is only setting a new zero time. Most important for the build up or maintenance of organic matter is the climate, followed by the vegetation. Other studies have shown that organic matter levels increase rather rapidly during the first few years of soil formation, subsequently slow down, and finally attain an equilibrium level (Stevenson, 1986). Stevenson (1986) combined two figures made by Senstius (1958) into figure 28 to show when humus is accumulated. It was originally made for a humid climate, but since no values are indicated on the y-axis, it can be used for a semi-arid climate as well. In the limans, the environment changes between an aerobic and anaerobic state, so a build-up is not completely unlikely. The decomposition rate is however rapid at higher temperatures. Since this is in the subtropical zone, there are marked winters with low temperatures also, which probably influences the build up in a positive way.

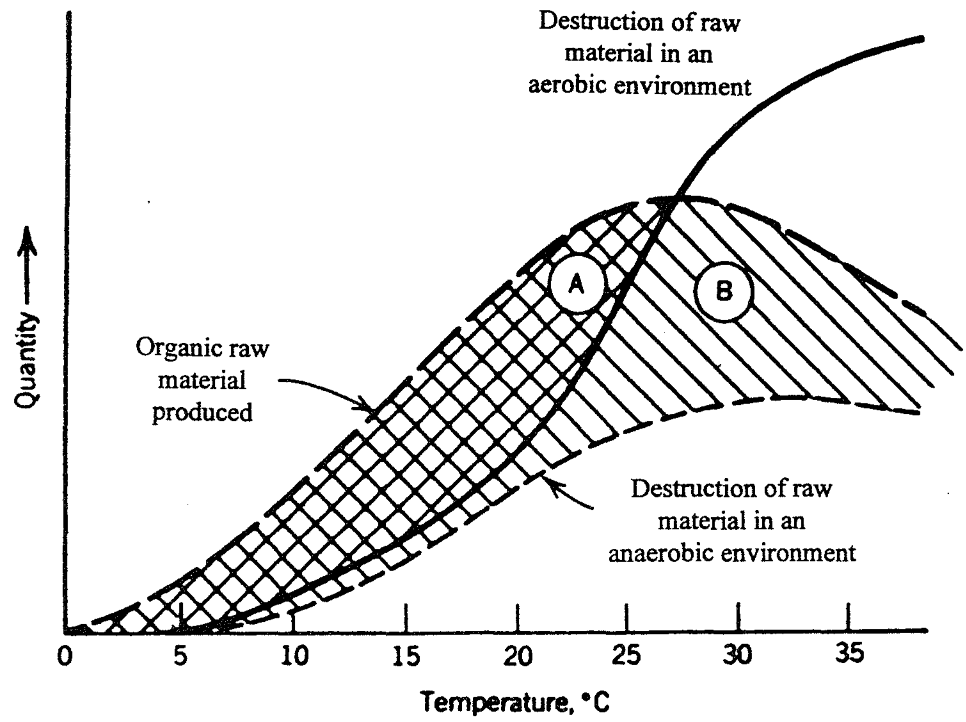

Figure 28. Influence of temperature on organic raw material production through photosynthesis and organic matter destruction by micro-organisms. Accumulation of humus under aerobic conditions is confined to zone A; accumulations under anaerobic conditions occur over the entire temperature range (A+B) (from Stevensson, 1986).

Since the micro-climate in the runoff farming system is quite altered, it can be difficult to tell how far to the semiarid or subhumid it has gone, regarding the soil. Young (1989, 105-128) presented a general table showing the amount of biomass required for maintenance of the organic matter level. It was done for tropical climatic zones, but gives an idea of what is needed. Oxidation loss assumes a decomposition constant of 0.04, but in normal years the erosion loss ought to be minimal from the limans. No data are yet available for the amount of litter in Wadi Mashash, or for the decomposition constant.

Table 4. Indicative plant biomass requirements for maintenance of soil organic matter (from Young, 1989)

Climatic zone	Initial topsoil carbon (kgC/ha)	Topsoil carbon (%)	Loss of carbon by oxidation (kg/ha and year)	Loss of carbon by erosion (kg/ha and year)	Required addition of carbon to soil humus (kg/ha and year)	Required plant residues added to soil (dry mass) (kg /ha and year) above ground	roots
Humid	30 000	2.0	1200	400	1600	8400	5800
Subhumid	15 000	1.0	600	200	800	4200	2900
Semi-arid	7 500	0.5	300	100	400	2100	1400

Another factor which strongly influences the carbon content is the grass vegetation in the limans. During and after the rainy season there is a lush and green ground cover in the limans, which disappears quite soon as the topsoil dries. Grassland soils are however substantially higher in C-content than forest soils (Stevenson, 1986). The carbon originating from the grass is then probably greater than that originating from the tree litter, and is masking the differences between the different tree crops. This might also explain why the increase in organic matter is quite rapid. The trees have on the other hand a larger influence on the micro-climate, and it is not impossible that the combination of trees and grass is the most beneficial.

It is perhaps too early to say whether the oldest liman has already reached a state of equilibrium, even if the present results indicate that this is the case (Fig. 19 and 20). That the organic carbon content is higher inside the limans (except the youngest) than outside is undoubtedly true. The earthworms found in some samples thrive in soils with a high carbon content, but may in turn influence the carbon content themselves. To actively spread these beneficial creatures should therefore have positive effects.

Particle size distribution

In the analysis of the distribution of the different particle sizes one needs to be especially careful. If, for example, there is more clay inside than outside, it can either mean that there has been a transport of clay to the liman, or a transport of silt and sand away from the outside. If no difference at all is found between outside and inside, it does not necessarily mean that nothing has happened. If the sediment transported to the liman contained all particle sizes, and in the same distribution as found on the outside, the actual transport to the liman would not be detected. On the other hand, if the area outside is also flooded, and receives sediments, no difference between outside and inside would be found. It must also be added that the limans hardly start from a level equal to the non-flooded surroundings. Many of them lie in areas which were flooded even before any liman was established.

Soil texture is normally a property which is quite stable and difficult to change. If material is added long enough and in large quantities there might, however, be a modification (Eidt, 1987). Is the time and sediment deposited in the limans enough to be detected? Unfortunately no measurement of the amount of incoming sediments has been made. Yair (1974) investigated a hill-slope of a first-order drainage basin near Sede Boker. Using his data, it is possible to arrive at an average content of sediments in the runoff water of 0.55 % by weight. How relevant this is for Wadi Mashash is difficult to say, since the transport pathway is many times longer. It can perhaps be balanced if the hill slopes around Wadi Mashash are richer in erodible particles. If one assumes a sediment content of 0.5 %, and a dry bulk density of 1.3 g/cm^3 for the suspended particles, liman 72/1 should have received the following: 11 600 mm runoff water =>
11 600 m^3/dunam * 6 dunams = 69 600 m^3 of water. This would then have contained 0.005 * 69 600 tons of sediments = 348 tons, which would equal 268 m^3. Spread over the whole liman, the layer would be 268 m^3/6000 m^2 = 0.045 m or 4.5 cm thick. In the upper layer a difference would then certainly be noticed, but in the 72/1 liman no difference can be seen.

The changes in the finer particle sizes are found in limans 79/2, 83/7 and 86/3 (Fig. 22, 24, 25 and 27). They have all received more or less the same amount of runoff water, 6000 mm, but they do not have the same catchment area. Why the two limans with the highest water income, 72/1 and 83/2, have the smallest difference in texture (Figs. 21 and 23) is not obvious, unless the processes outlined previously are going on. Liman 93/4 has slightly less of the finer particles inside (Figs. 26 and 27). Since it was recently constructed, the soil surface inside the liman is in fact a lower soil layer than the surface of the outside, and a difference like this is expected. Two limans, 79/2 and 86/3, have the inlet and outlet at opposite ends of the liman. The direction of the waterflow should therefore be clear. However, only 86/3 shows any gradient with the highest clay content near the inlet and the lowest at the other end (Appendix 4). A higher percentage of finer particles should be beneficial in the altered environment of the limans, as the water holding capacity and nutrient status will increase.

Reij et al (1988) discussed the danger of erosion combined with runoff farming. In the case described by Sandor et al (1986) this was the reality (see "Earlier related studies"). That erosion takes place in the Negev is also clear, but with the calculations above in mind one ought to consider the following. Much of the eroded material is trapped in the runoff fields and is probably doing more good there than on the hill slopes. It would in any case have been eroded from the catchment area, even without the limans. That the Negev is also in some respects "refilled" with wind-transported material moderates the negative effect of erosion.

CONCLUSIONS

It is difficult to point out any clear and unambiguous trends from the data of the present study. There are certainly changes in all of the measured properties in at least some limans. All changes are so far of the positive kind. That the pH should reach too low values does not seem likely. The EC is likely to stay at the low values it has now reached. The organic carbon might increase further, and will hardly start to decrease. The soil texture and the incoming material is perhaps the most uncertain. As was pointed out in the section on the diversion system, silting up has always been a problem with runoff farming. If the calculations from the previous sections are correct, a liman would fill up with sediments in around 150 years (30 cm * 22 years/ 4.5 cm). To counteract this one could either build on the walls and the spillway from the outside, or clear up the inside. This would then include tree cutting and breaking up of stumps, rather heavy work. Once in 150 years it might not, however, be too much. On the other hand, the soil inside the liman would probably be more valuable than the one outside. The *metapedogenesis* brought about by this type of runoff farming seems thus to have very few drawbacks, but mainly advantages.

SAMMANFATTNING

Avrinningsvatten som en jordmånsbildande faktor i arida områden

Att människan kan framkalla markförändringar som går avsevärt mycket snabbare än de naturliga processerna har länge varit känt. 1966 myntade de israeliska markforskarna Yaalon och Yaron termen *metapedogenes* för sådana förändringar. Detta examensarbete behandlar ett klart fall av metapedogenes. Avrinningsvatten, innehållande eroderat material, leds in i invallade fält, s k limaner, och får där infiltrera. Studien har gjorts i Negev-öknen, Israel.

"Avrinningsjordbruk" (vedertagen term saknas på svenska) har definierats av Bruins et al (1986) på följande sätt: "Rainwater harvesting agriculture är odling i torra områden med hjälp av avrinnings-regnvatten från vilken typ av avrinningsområde eller efemär flod som helst." Sådant jordbruk har en lång tradition i Negev-öknen, och nådde sin mest förfinade nivå under 400-talet e Kr. De som bäst behärskade denna teknik var de tidigare tämligen okända Nabateerna. I modern tid återupplivades "Runoff farming" i Negev genom professor M. Evenari och hans kollegor, N. Tadmor och L. Shanan. De etablerade också försöksgården Wadi Mashash 1971, vari tekniken med limaner har utvecklats. Jag studerade här 6 limaner av olika ålder: 72/1, 79/2, 83/2, 83/7, 86/3 och 93/4. I de första tre limanerna växer det olivträd, i 83/7 och 86/3 eucalyptus och akacia, och i den yngsta sudangräs. 4 olika viktiga markegenskaper undersöktes: pH, elektrisk ledningsförmåga (=salinitet, förkortat EC), organisk kolhalt och kornstorleksfördelning. Jordmånen är en lössavlagring utan några direkta horisonter.

Omkring 30 prover togs från varje liman från två djup: 0 - 20 cm och 20 - 40 cm. Proverna kan indelas i tre grupper: a) I rader (nära träden, obearbetat) b) Mellan rader (kultiverad mark) och c) Utanför limanen (kontroll). pH och EC mättes i alla prover, medan organiskt kol och textur-analys utfördes på proverna från det övre skiktet. pH- och EC-värdena kommer från 1:1-extrakt, organiska kolet analyserades med hjälp av en modifierad Walkley & Black - metod (jord + $K_2Cr_2O_7$ kokades i exakt fem minuter) och texturen beräknades med hjälp av hydrometermetoden i sedimentationscylindrar.

Markens naturliga pH är mycket högt, framför allt på grund av ett högt kalciumkarbonat-innehåll. I det övre skiktet ligger alla medelvärden utom ett mellan 7,7 och 8. Undantaget är 72/1, i rader, som har 7,1. I det undre skiktet finns inte på samma sätt någon avvikare, men spännvidden ligger mellan 7,4 och 8,2. I både övre och undre skiktet finns statistiskt säkerställda skillnader , men någon entydig tendens finns inte. Att den äldsta limanen ändå har det lägsta värdet i övre skiktet pekar dock åt ett visst håll. Den viktigaste processen för att sänka pH:t torde vara frigörandet av organiska syror medan humusen byggs upp. Försurningen har trots allt hittills endast varit gynnsam.

Ledningstalen (EC) från kontrollproverna uppvisar en mycket stor variation, från 0,2 till 17 mS/cm. Saltfläckar och punkter med låg salinitet verkar finnas mer eller mindre slumpmässigt utanför limanerna. Mikrotopografin förklarar detta. Två limaner, 83/2 och 86/3, verkar ha ett lägre medelvärde än de övriga, men eftersom variationen är så stor kan inget visas statistiskt. Alla EC inifrån limanerna har låga värden, mellan 0,2 och 0,4 mS/cm. Ingen tendens kan påvisas. Noterbart är att liman 93/4, vilken endast varit översvämmad en gång, ligger i nivå med de övriga. Opublicerade data från Natalia

Startsev bekräftar att denna enda infiltration har sköljt ur större delen av salterna. Ingen försaltning kan alltså observeras, endast motsatsen, vilket drastiskt förbättrar jorden som växtplats.

Halten av organiskt kol i marken är naturligt mycket låg. Genomsnittet för alla kontrollprover ligger på 0,35 %. Den viktigaste källan till organiskt kol är vegetationen, och eftersom den är mycket sparsam i denna region, är siffran inte förvånande. Att öka humushalten i marken är inte lätt, särskilt inte i varma klimat. Negev har dock markerade vintrar. Växlingen mellan aerobiskt och anaerobiskt tillstånd är säkert också gynnsam för uppbyggnad. Efter en relativt kort tid brukar ett jämviktstillstånd uppnås. Medelvärdet för insidan hos alla limaner, utom 93/4 som ännu inte burit någon gröda, var 0,6%. Skillnaden mot utsidan är statistiskt belagd, men ingen specifik trend kan uppvisas. I proverna med de högsta individuella värdena, 1,0 % och 1,2 %, hittades daggmaskar. En ökning av kolhalten är otvivelaktigt gynnsam för näringstatus och jordstruktur.

Vid tolkningen av kornstorleksfördelningen krävs vaksamhet. Fördelningen på de olika storleksklasserna är beroende av varandra till en totalsumma på 100 %. Om inte någon vall brister bör dock den enda transportriktningen vara till limanen. Om det som transporteras till limanen har samma fördelning som marken utanför kan ingen skillnad påvisas. Det bör dock vara de mindre partiklarna som kan öka. Två limaner, 72/1 och 83/2, uppvisar knappast någon skillnad mellan utsida och insida. Samtidigt är det dessa två som har mottagit de största vattenmängderna. Översvämning även utanför limanen kan vara en orsak. 79/2, 83/7 och 86/3 har tämligen klara ökningar i de minsta storlekarna. De största skillnaderna är: a) i lerfraktionen: liman 86/3 med 12 % högre lerhalt och b) i mjälafraktionen: liman 79/2 med 8,3 % högre halt än utanför. Summan av lera och mjäla är kanske det mest intressanta att jämföra. Liman 79/2 har då 12,3 %, liman 83/7 14,2 % och liman 86/3 18,7 % högre halt av de finare partiklarna på insidan jämfört med utsidan. Liman 93/4 har något lägre halt av finare partiklar inne i jämfört med utanför. Även här är alltså någon trend svår att spåra. Föreställningen att limanernas utgångsläge är lika med omgivande mark är mycket diskutabel, eftersom flera av dem ligger i områden som redan tidigare svämmades över. En ökning av de finare partiklarna torde i alla händelser vara positiv för jordens näringsförråd och vattenhållande förmåga.

Att material transporteras till limanerna är uppenbart, även om omfattningen av detta ännu inte är klarlagt. Grundat på mätningar gjorda nära Sede Boker kan man anta att det tillförda vattnet innehåller 0,5 viktsprocent sediment. I liman 72/1 skulle detta i så fall ha lett till ett lager på 4,5 cm sedan anläggandet. Limanen skulle fyllas upp på i runda tal 150 år.

Slutsatsen av detta examensarbete blir att inga entydiga tendenser kan påvisas, men att där det finns förändringar, har denna metapedogenes hittills alltid varit av det gynnsamma slaget. Vegetationen påverkar också mikroklimatet gynnsamt, vilket ytterligare förhöjer de positiva influenserna.

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APPENDIX 1. pH in the upper layer, 0 - 20 cm, of some limans at Wadi Mashash experimental farm. See Figure 9 and 10 for sample locations

Sample	Liman 72/1	Liman 79/2	Liman 83/2	Liman 83/7	Liman 86/3	Liman 93/4
I1	7.31	8.07	7.24	-	7.47	8.29
I2	7.08	8.02	7.89	7.70	7.97	8.71
I3	6.68	7.90	7.86	7.48	7.90	7.78
I4	7.33	8.10	7.89	7.89	7.84	7.76
I5	7.27	8.04	7.95	7.87	8.02	8.05
I6		7.99		7.60		7.73
7 (H1)		7.36			8.10	7.90
8 (H2)		7.53			7.78	8.08
9 (H3)		7.47				8.26
(H4)		7.47				
Average	7.13	7.80	7.77	7.71	7.87	8.06
Standard deviation	0.24	0.28	0.26	0.16	0.19	0.30
B1	8.05	8.06	7.25	8.00	8.18	
B2	7.96	8.02	7.93	7.80	7.87	
B3	7.90	7.54	8.01	8.00	-	
B4	7.96	7.74	8.00	7.97	7.90	
B5	7.97	7.56	7.98	7.96	7.98	
B6		7.75		7.99		
B7				7.80		
Average	7.97	7.78	7.83	7.93	7.98	
Standard deviation	0.05	0.20	0.29	0.08	0.12	
C1	7.23	7.20	8.14	8.25	7.70	8.35
C2	8.12	8.55	7.64	8.24	7.60	7.18
C3	7.50	8.14	8.18	8.24	8.11	8.70
C4	7.71	7.89	8.07	8.04	8.25	7.59
C5	8.02	7.91	8.15	7.58	8.11	7.50
Average	7.72	7.94	8.04	8.07	7.95	7.86
Standard deviation	0.33	0.44	0.20	0.26	0.26	0.57

Appendix 1 (cont.) pH in the lower layer, 20 - 40 cm, of some limans at Wadi Mashash experimental farm

Sample	Liman 72/1	Liman 79/2	Liman 83/2	Liman 83/7	Liman 86/3	Liman 93/4
I1	7.20	7.23	7.08	7.58	8.01	8.95
I2	7.93	7.42	8.05	7.75	8.11	8.81
I3	7.99	7.20	8.02	7.53	8.11	8.24
I4	8.06	7.48	8.11	7.61	7.75	7.50
I5	7.70	7.46	8.13	7.70	8.22	7.97
I6		7.42		7.83		7.95
7 (H1)		7.62			7.94	-
8 (H2)		7.75			7.77	8.29
9 (H3)		7.53				8.52
(H4)		7.90				
Average	7.78	7.50	7.88	7.67	7.99	8.28
Standard deviation	0.31	0.20	0.40	0.10	0.16	0.45
B1	8.23	8.13	7.29	7.85	8.27	
B2	8.12	7.40	8.08	7.73	8.09	
B3	8.07	7.60	8.05	7.75	8.09	
B4	8.16	7.60	8.08	7.65	8.07	
B5	8.08	7.95	8.20	7.84	8.20	
B6		8.04		7.85		
B7				7.98		
Average	8.13	7.79	7.94	7.81	8.14	
Standard deviation	0.06	0.27	0.33	0.10	0.08	
C1	7.00	7.01	7.25	8.05	7.34	8.60
C2	7.54	8.46	8.03	7.81	7.93	7.35
C3	7.15	7.88	8.25	8.15	8.06	8.32
C4	7.88	7.37	7.75	7.37	7.85	8.52
C5	7.25	8.75	8.08	7.89	7.86	7.77
Average	7.36	7.89	7.87	7.85	7.81	8.11
Standard deviation	0.31	0.65	0.35	0.27	0.25	0.48

APPENDIX 2. EC (mS/cm) in the upper layer, 0 - 20 cm, of some limans at Wadi Mashash experimental farm. See Figure 9 and 10 for sample locations

Sample	Liman 72/1	Liman 79/2	Liman 83/2	Liman 83/7	Liman 86/3	Liman 93/4
I1	0.27	0.40	0.24	-	0.41	0.41
I2	0.36	0.36	0.25	0.50	0.21	0.39
I3	0.32	0.46	0.23	0.27	0.23	0.25
I4	0.37	0.31	0.32	0.48	0.42	0.23
I5	0.22	0.33	0.21	0.22	0.24	0.27
I6		0.38		0.38		0.22
7 (H1)		0.41			0.21	0.25
8 (H2)		0.26			0.22	0.45
9 (H3)		0.27				0.34
(H4)		0.29				
Average	0.31	0.35	0.25	0.37	0.28	0.31
Standard deviation	0.06	0.06	0.04	0.11	0.09	0.08
B1	0.23	0.30	0.24	0.24	0.20	
B2	0.29	0.35	0.22	0.24	0.21	
B3	0.38	0.20	0.22	0.23	-	
B4	0.30	0.22	0.23	0.26	0.26	
B5	0.34	0.25	0.27	0.28	0.17	
B6		0.19		0.25		
B7				0.55		
Average	0.31	0.25	0.24	0.29	0.21	
Standard deviation	0.05	0.06	0.02	0.11	0.03	
C1	0.27	14.20	0.98	1.16	2.08	0.18
C2	0.27	0.50	0.23	0.51	2.63	17.12
C3	0.60	0.23	0.20	0.25	0.35	0.25
C4	0.26	2.03	0.36	0.26	0.24	0.21
C5	0.49	0.30	0.24	12.90	0.23	0.27
Average	0.38	3.45	0.40	3.02	1.11	3.61
Standard deviation	0.14	5.41	0.29	4.95	1.04	6.76

Appendix 2(cont.) **EC (mS/cm) in the lower layer, 20 - 40 cm, of some limans at Wadi Mashash experimental farm**

Sample	Liman 72/1	Liman 79/2	Liman 83/2	Liman 83/7	Liman 86/3	Liman 93/4
I1	0.31	0.20	0.23	0.24	0.25	0.44
I2	0.31	0.22	0.22	0.32	0.20	0.40
I3	0.29	0.17	0.20	0.36	0.18	0.35
I4	0.27	0.18	0.17	0.37	0.73	0.24
I5	0.21	0.19	0.18	0.32	0.20	0.21
I6		0.19		0.29	0.32	0.18
7 (H1)		0.22			0.33	-
8 (H2)		0.18				0.59
9 (H3)		0.19				0.43
(H4)		0.17				
Average	0.28	0.19	0.20	0.32	0.32	0.35
Standard deviation	0.04	0.02	0.02	0.04	0.18	0.13
B1	0.27	0.16	0.20	0.19	0.25	
B2	0.25	0.18	0.19	0.20	0.19	
B3	0.26	0.17	0.19	0.20	0.21	
B4	0.20	0.18	0.19	0.26	0.24	
B5	0.25	0.15	0.17	0.29	0.24	
B6		0.15		0.24		
B7				0.20		
Average	0.25	0.17	0.19	0.23	0.23	
Standard deviation	0.02	0.01	0.00	0.04	0.02	
C1	2.25	11.60	9.26	1.89	5.01	0.23
C2	4.70	4.47	0.81	3.56	1.75	13.94
C3	11.80	1.20	0.28	1.19	0.65	0.79
C4	0.44	4.55	0.79	13.89	0.61	0.24
C5	2.53	0.32	0.24	0.79	1.70	2.20
Average	4.34	4.43	2.28	4.26	1.94	3.48
Standard deviation	3.97	3.97	3.50	4.91	1.61	5.28

APPENDIX 3. Organic Carbon (%) in the upper layer, 0 - 20 cm, of some limans at Wadi Mashash experimental farm. See Figure 9 and 10 for sample locations

Sample	Liman 72/1	Liman 79/2	Liman 83/2	Liman 83/7	Liman 86/3	Liman 93/4
I1	0.322	0.796	0.647	0.492	0.456	0.138
I2	0.581	1.086	0.478	0.387	0.550	0.180
I3	0.632	0.666	0.510	0.572	0.518	0.220
I4	0.621	0.531	0.687	0.543	0.652	0.325
I5	0.484	1.006	0.478	1.043	0.333	0.281
I6		0.554		1.213		0.190
7 (H1)		0.884			0.744	0.214
8 (H2)		0.999			1.044	0.157
9 (H3)		0.543				0.171
(H4)		0.789				
Average	0.528	0.785	0.560	0.708	0.614	0.208
Standard deviation	0.12	0.20	0.09	0.31	0.21	0.06
B1	0.383	0.684	0.795	0.336	0.402	
B2	0.676	0.846	0.795	0.293	0.540	
B3	0.596	0.579	0.752	0.369	-	
B4	0.572	0.456	0.672	0.362	0.865	
B5	0.687	0.579	0.673	0.467	0.803	
B6		0.420		0.499		
B7				0.369		
Average	0.583	0.594	0.737	0.385	0.653	
Standard deviation	0.11	0.14	0.06	0.07	0.19	
C1	0.325	0.478	0.329	0.460	0.374	0.367
C2	0.264	0.318	0.578	0.214	0.385	0.413
C3	0.274	0.409	0.39	0.224	0.496	0.311
C4	0.424	0.402	0.412	0.094	0.414	0.391
C5	0.249	0.253	0.564	0.134	0.336	0.413
Average	0.307	0.372	0.455	0.225	0.401	0.379
Standard deviation	0.06	0.08	0.10	0.13	0.05	0.04

APPENDIX 4. Texture, including gravel, in some limans of Wadi Mashash experimental farm. Upper layer, 0 - 20 cm. See Figure 9 and 10 for sample locations

			Percentage by weight of the fractions, mm				
			Clay	Silt	F. Sand	C. Sand	Gravel
Liman	Pit		<0.002	0.002 - 0.02	0.02 - 0.2	0.2 - 2	> 2
72	I1		10.1	10.7	68.2	11.0	0.0
72	I2		16.2	24.4	52.6	6.8	0.0
72	I3		16.8	28.0	48.7	6.6	0.0
72	I4		20.6	22.9	49.3	7.0	0.2
72	I5		20.3	24.3	49.0	6.3	0.0
		Average	16.8	22.1	53.6	7.5	0.0
		Std. dev	3.8	5.9	7.5	1.7	0.0
72	B1		12.6	11.9	61.5	13.5	0.4
72	B2		17.9	20.6	52.2	9.3	0.0
72	B3		24.4	24.1	44.5	7.0	0.0
72	B4		22.8	22.0	47.7	7.1	0.3
72	B5		25.0	26.3	42.5	6.2	0.0
		Average	20.5	21.0	49.7	8.6	0.2
		Std. dev	4.7	4.9	6.7	2.7	0.2
72	C1		13.7	13.2	60.7	9.8	2.6
72	C2		16.9	19.0	55.6	8.5	0.0
72	C3		20.8	19.0	47.3	12.6	0.3
72	C4		19.6	20.3	51.8	7.6	0.5
72	C5		26.8	25.9	40.9	5.5	0.9
		Average	19.6	19.5	51.3	8.8	0.9
		Std. dev	4.4	4.1	6.8	2.4	0.9
79	I1		23.8	30.6	39.0	6.5	0.1
79	I2		22.3	35.9	35.6	6.0	0.1
79	I3		21.9	24.0	44.6	9.4	0.1
79	I4		19.0	19.2	48.5	12.8	0.5
79	I5		25.1	34.2	33.3	6.9	0.5
79	I6		16.5	20.3	51.5	11.4	0.3
79	H1		25.1	29.7	38.8	6.2	0.3
79	H2		21.8	22.5	49.5	6.0	0.1
79	H3		21.0	24.4	45.8	8.7	0.2
79	H4		25.0	27.9	40.6	6.4	0.0
		Average	22.1	26.9	42.7	8.0	0.2
		Std. dev	2.7	5.4	5.9	2.3	0.2

Appendix 4 (cont.)

Liman	Pit		Clay <0.002	Silt 0.002 - 0.02	F. Sand 0.02 - 0.2	C. Sand 0.2 - 2	Gravel > 2
			Percentage by weight of the fractions, mm				
79	B1		24.3	26.6	42.5	6.3	0.2
79	B2		24.1	29.1	40.7	6.1	0.0
79	B3		19.8	21.8	51.8	6.6	0.0
79	B4		19.8	20.6	49.7	9.6	0.3
79	B5		24.1	27.0	40.9	7.9	0.0
79	B6		17.5	20.1	54.3	8.0	0.0
		Average	21.6	24.2	46.7	7.4	0.1
		Std. dev	2.7	3.5	5.5	1.2	0.1
79	C1		25.0	24.9	40.4	8.1	1.6
79	C2		19.0	15.9	50.8	10.7	3.7
79	C3		14.7	17.9	58.7	8.5	0.2
79	C4		15.1	15.1	57.1	9.3	3.4
79	C5		15.8	12.2	60.0	11.5	0.4
		Average	17.9	17.2	53.4	9.6	1.9
		Std. dev	3.9	4.3	7.2	1.3	1.5
oli83	I1		24.1	24.8	45.4	5.7	0.0
oli83	I2		18.9	16.8	58.1	6.2	0.0
oli83	I3		23.5	25.2	46.8	4.4	0.0
oli83	I4		22.0	21.4	50.3	6.2	0.0
oli83	I5		21.8	21.7	51.0	5.4	0.0
		Average	22.1	22.0	50.3	5.6	0.0
		Std. dev	1.8	3.0	4.4	0.7	0.0
oli83	B1		22.0	21.5	50.4	6.1	0.0
oli83	B2		24.9	23.5	47.5	4.1	0.0
oli83	B3		20.9	19.7	52.3	7.0	0.0
oli83	B4		21.7	23.1	49.0	6.1	0.0
oli83	B5		24.1	28.3	41.8	5.5	0.3
		Average	22.7	23.2	48.2	5.8	0.0
		Std. dev	1.5	2.8	3.6	1.0	0.1
oli83	C1		24.9	25.0	39.0	6.7	4.4
oli83	C2		22.0	19.2	52.2	6.6	0.0
oli83	C3		19.6	14.9	58.5	7.0	0.0
oli83	C4		18.6	18.7	55.9	6.8	0.0
oli83	C5		22.0	19.8	46.4	11.6	0.1
		Average	21.4	19.5	50.4	7.8	0.9
		Std. dev	2.2	3.2	7.0	1.9	1.7

Appendix 4 (cont.)

			Percentage by weight of the fractions, mm				
			Clay	Silt	F. Sand	C. Sand	Gravel
Liman	Pit		<0.002	0.002 - 0.02	0.02 - 0.2	0.2 - 2	> 2
af83	I1		19.6	15.0	58.7	6.8	0.0
af83	I2		21.3	14.7	57.2	6.8	0.0
af83	I3		27.1	17.1	47.8	7.9	0.2
af83	I4		24.6	23.4	43.1	8.4	0.4
af83	I5		29.0	27.2	33.2	6.5	4.0
af83	I6		28.3	31.3	34.6	5.7	0.1
		Average	25.0	21.4	45.8	7.0	0.8
		Std. dev	3.5	6.3	9.9	0.9	1.4
af83	B1		17.3	17.7	53.6	8.2	3.2
af83	B2		16.9	16.2	58.1	8.7	0.0
af83	B3		22.3	21.2	46.4	8.1	2.0
af83	B4		21.6	20.7	49.8	7.5	0.4
af83	B5		24.9	26.6	36.8	5.1	6.6
af83	B6		22.6	26.2	44.9	6.2	0.0
af83	B7		22.7	28.4	42.2	6.4	0.3
		Average	21.2	22.4	47.4	7.2	1.8
		Std. dev	2.8	4.4	6.6	1.2	2.2
af83	C1		17.6	18.0	50.7	9.9	3.7
af83	C2		14.4	13.8	54.6	11.1	6.1
af83	C3		15.7	13.3	42.8	8.5	19.7
af83	C4		12.8	17.5	56.6	13.1	0.0
af83	C5		14.2	16.8	61.0	7.9	0.1
		Average	14.9	15.9	53.1	10.1	5.9
		Std. dev	1.6	1.9	6.1	1.9	7.2
86	I1		36.3	27.3	16.1	7.2	13.1
86	I2		23.2	23.6	44.0	8.0	1.1
86	I3		30.7	25.2	37.1	6.0	0.9
86	I4		16.6	18.6	58.1	6.8	0.0
86	I5		21.2	19.9	51.2	7.7	0.0
86	H1		35.3	31.5	26.5	5.1	1.5
86	H2		26.0	30.3	37.1	5.9	0.7
		Average	27.1	25.2	38.6	6.7	3.0
		Std. dev	6.8	3.2	14.4	0.7	5.1
86	B1		37.0	27.9	23.6	7.4	4.2
86	B2		23.1	23.5	41.9	9.0	2.5

Appendix 4 (cont.)

			Percentage by weight of the fractions, mm				
			Clay	Silt	F. Sand	C. Sand	Gravel
Liman	Pit		<0.002	0.002 - 0.02	0.02 - 0.2	0.2 - 2	>2
86	B3		-	-	-	-	-
86	B4		26.7	26.8	41.6	4.9	0.0
86	B5		27.9	26.3	40.6	5.2	0.0
		Average	28.7	26.1	36.9	6.6	1.7
		Std. dev	5.1	1.6	7.7	1.7	1.8
86	C1		14.0	12.5	37.9	21.2	14.4
86	C2		12.3	10.3	55.3	21.7	0.4
86	C3		20.0	24.1	49.1	6.6	0.0
86	C4		16.0	24.9	51.0	6.0	2.1
86	C5		16.6	23.4	52.4	7.3	0.3
		Average	15.8	19.0	49.1	12.6	3.5
		Std. dev	2.6	6.3	6.0	7.2	5.5
93	1		19.1	19.4	51.8	9.3	0.4
93	2		14.1	14.5	56.5	14.3	0.7
93	3		17.6	19.2	54.1	8.9	0.3
93	4		12.5	18.8	58.9	9.4	0.4
93	5		15.6	19.9	54.7	9.6	0.3
93	6		15.7	18.5	56.2	9.5	0.1
93	7		15.0	21.7	55.3	7.9	0.1
93	8		20.8	14.2	57.1	7.9	0.0
93	9		20.4	14.5	57.1	7.8	0.1
		Average	16.7	17.8	55.7	9.4	0.3
		Std. dev	2.7	2.6	2.0	1.9	0.2
93	C1		15.6	15.7	60.3	8.4	0.0
93	C2		28.0	17.7	35.8	3.7	14.8
93	C3		20.2	17.1	55.5	7.2	0.0
93	C4		20.3	21.8	51.4	6.4	0.0
93	C5		16.6	18.5	57.6	7.3	0.1
		Average	20.1	18.2	52.1	6.6	3.0
		Std. dev	4.4	2.0	8.6	1.6	5.9

APPENDIX 5. Texture of *fine earth* of some limans at Wadi Mashash experimental farm. Upper layer, 0 - 20 cm. See Figure 9 and 10 for sample locations

			Percentage by weight of the fraction, mm			
			Clay	Silt	F. Sand	C. Sand
Liman	Pit		<0.002	0.002 - 0.02	0.02 -0.2	0.2 - 2
72	I1		10.1	10.7	68.2	11.0
72	I2		16.2	24.4	52.6	6.8
72	I3		16.8	28.0	48.7	6.6
72	I4		20.7	22.9	49.4	7.0
72	I5		20.3	24.3	49.1	6.3
		Average	16.8	22.1	53.6	7.5
		Std. dev	3.8	5.9	7.5	1.7
72	B1		12.7	12.0	61.8	13.6
72	B2		17.9	20.6	52.2	9.3
72	B3		24.4	24.1	44.5	7.0
72	B4		22.9	22.1	47.9	7.1
72	B5		25.0	26.3	42.6	6.2
		Average	20.6	21.0	49.8	8.6
		Std. dev	4.7	4.9	6.8	2.7
72	C1		14.1	13.5	62.3	10.1
72	C2		16.9	19.0	55.7	8.5
72	C3		20.9	19.1	47.4	12.6
72	C4		19.7	20.5	52.1	7.7
72	C5		27.1	26.1	41.3	5.5
		Average	19.7	19.6	51.8	8.9
		Std. dev	4.4	4.0	7.2	2.4
79	I1		23.8	30.6	39.0	6.5
79	I2		22.3	36.0	35.6	6.1
79	I3		21.9	24.0	44.6	9.4
79	I4		19.1	19.3	48.7	12.9
79	I5		25.3	34.3	33.5	6.9
79	I6		16.5	20.4	51.7	11.4
79	H1		25.1	29.8	38.9	6.2
79	H2		21.9	22.5	49.6	6.0
79	H3		21.0	24.5	45.9	8.7
79	H4		25.0	27.9	40.6	6.4
		Average	22.2	26.9	42.8	8.1
		Std. dev	2.7	5.4	5.9	2.3

Appendix 5 (cont.)

			Percentage by weight of the fraction, mm			
			Clay	Silt	F. Sand	C. Sand
Liman	Pit		<0.002	0.002 - 0.02	0.02 -0.2	0.2 - 2
79	B1		24.4	26.7	42.6	6.3
79	B2		24.1	29.1	40.7	6.1
79	B3		19.8	21.9	51.8	6.6
79	B4		19.8	20.7	49.9	9.6
79	B5		24.1	27.0	40.9	7.9
79	B6		17.5	20.1	54.3	8.0
		Average	21.6	24.2	46.7	7.4
		Std. dev	2.7	3.5	5.5	1.2
79	C1		25.4	25.3	41.0	8.2
79	C2		19.7	16.5	52.7	11.1
79	C3		14.7	17.9	58.8	8.5
79	C4		15.7	15.6	59.1	9.6
79	C5		15.9	12.3	60.3	11.5
		Average	18.3	17.5	54.4	9.8
		Std. dev	4.0	4.3	7.2	1.3
oli83	I1		24.1	24.8	45.4	5.7
oli83	I2		18.9	16.8	58.1	6.2
oli83	I3		23.5	25.2	46.8	4.4
oli83	I4		22.0	21.4	50.3	6.2
oli83	I5		21.8	21.7	51.0	5.4
		Average	22.1	22.0	50.3	5.6
		Std. dev	1.8	3.0	4.4	0.7
oli83	B1		22.0	21.5	50.4	6.1
oli83	B2		24.9	23.5	47.5	4.1
oli83	B3		20.9	19.7	52.4	7.0
oli83	B4		21.7	23.2	49.0	6.1
oli83	B5		24.2	28.3	41.9	5.5
		Average	22.7	23.2	48.3	5.8
		Std. dev	1.5	2.9	3.5	1.0
oli83	C1		26.1	26.2	40.8	7.0
oli83	C2		22.0	19.2	52.2	6.6
oli83	C3		19.6	14.9	58.5	7.0
oli83	C4		18.6	18.7	55.9	6.8
oli83	C5		22.0	19.8	46.5	11.7
		Average	21.7	19.8	50.8	7.8
		Std. dev	2.6	3.6	6.4	1.9

Appendix 5 (cont.)

Liman	Pit		Clay <0.002	Silt 0.002 - 0.02	F. Sand 0.02 -0.2	C. Sand 0.2 - 2
			Percentage by weight of the fraction, mm			
af83	I1		19.6	15.0	58.7	6.8
af83	I2		21.3	14.7	57.3	6.8
af83	I3		27.1	17.1	47.8	7.9
af83	I4		24.7	23.5	43.3	8.5
af83	I5		30.2	28.4	34.6	6.8
af83	I6		28.4	31.3	34.6	5.7
		Average	25.2	21.7	46.1	7.1
		Std. dev	3.8	6.5	9.6	0.9
af83	B1		17.8	18.3	55.4	8.5
af83	B2		16.9	16.3	58.1	8.7
af83	B3		22.7	21.7	47.3	8.2
af83	B4		21.7	20.8	50.0	7.5
af83	B5		26.7	28.5	39.4	5.5
af83	B6		22.6	26.2	45.0	6.2
af83	B7		22.8	28.5	42.3	6.4
		Average	21.6	22.9	48.2	7.3
		Std. dev	3.1	4.6	6.3	1.2
af83	C1		18.3	18.7	52.7	10.3
af83	C2		15.3	14.7	58.1	11.8
af83	C3		19.5	16.5	53.3	10.6
af83	C4		12.8	17.5	56.6	13.1
af83	C5		14.2	16.8	61.0	8.0
		Average	16.0	16.8	56.4	10.8
		Std. dev	2.5	1.3	3.1	1.7
86	I1		41.8	31.4	18.5	8.3
86	I2		23.5	23.9	44.5	8.1
86	I3		31.0	25.4	37.5	6.1
86	I4		16.6	18.6	58.1	6.8
86	I5		21.2	19.9	51.2	7.7
86	H1		35.9	32.0	27.0	5.2
86	H2		26.1	30.5	37.4	6.0
		Average	28.0	26.0	39.2	6.9
		Std. dev	8.1	5.1	12.6	1.1
86	B1		38.6	29.1	24.6	7.7
86	B2		23.7	24.1	43.0	9.2

Appendix 5 (cont.)

			Percentage by weight of the fraction, mm			
			Clay	Silt	F. Sand	C. Sand
Liman	Pit		<0.002	0.002 - 0.02	0.02 -0.2	0.2 - 2
86	B3		-	-	-	-
86	B4		26.7	26.8	41.7	4.9
86	B5		27.9	26.3	40.6	5.2
		Average	29.2	26.6	37.5	6.7
		Std. dev	5.6	1.8	7.5	1.8
86	C1		16.4	14.6	44.3	24.7
86	C2		12.4	10.3	55.5	21.8
86	C3		20.0	24.2	49.2	6.6
86	C4		16.3	25.4	52.1	6.2
86	C5		16.6	23.5	52.6	7.4
		Average	16.3	19.6	50.7	13.3
		Std. dev	2.4	6.0	3.8	8.2
93	1		19.1	19.5	52.0	9.4
93	2		14.2	14.6	56.9	14.4
93	3		17.6	19.2	54.2	8.9
93	4		12.6	18.8	59.1	9.4
93	5		15.6	20.0	54.8	9.6
93	6		15.7	18.5	56.3	9.5
93	7		15.1	21.7	55.4	7.9
93	8		20.8	14.2	57.1	7.9
93	9		20.4	14.6	57.2	7.8
		Average	16.8	17.9	55.9	9.4
		std. dev	2.7	2.6	2.0	1.9
93	C1		15.6	15.7	60.3	8.4
93	C2		32.8	20.8	42.0	4.4
93	C3		20.2	17.1	55.5	7.2
93	C4		20.3	21.8	51.4	6.4
93	C5		16.6	18.5	57.6	7.3
		Average	21.1	18.8	53.4	6.7
		Std. dev	6.2	2.3	6.4	1.3

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