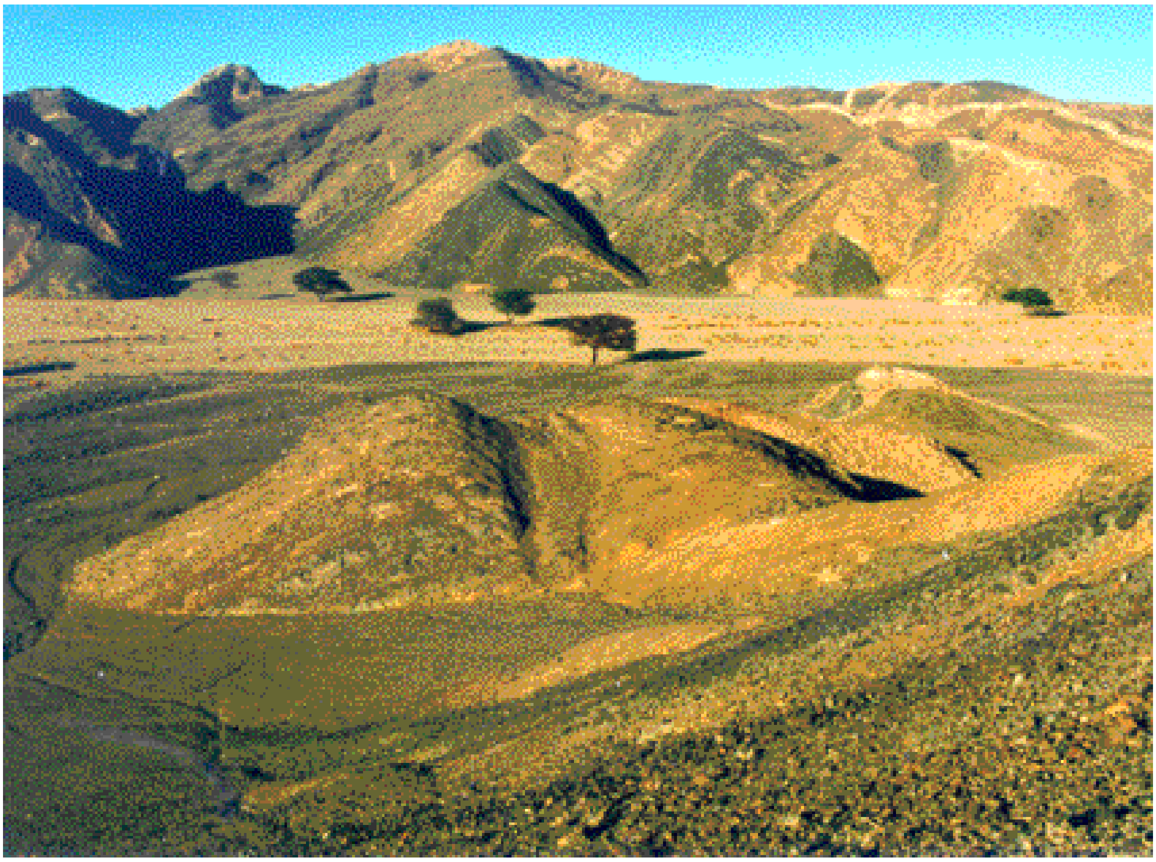
CHANGE AND VARIATION IN A HYPER-ARID CULTURAL LANDSCAPE:

A METHODOLOGICAL APPROACH USING REMOTE SENSING TIMESERIES

(LANDSAT MSS AND TM, 1973-1996)

FROM THE WADI VEGETATION OF THE EASTERN DESERT OF EGYPT



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Thesis candidatus scientiarum
1999

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The relationship man-tree must have religious dimensions again.
Only if you love the tree like yourself you will survive.

Hundertwasser, April 1991

Preface

This study constitutes part of the project “Cultural landscape development in the Nile valley borderlands”, initiated by Knut Krzywinski, University of Bergen, and funded by the Norwegian Research Council. The working hypothesis of the project is that hyper-arid drylands and deserts are cultural landscapes and their present condition and environmental problems are the results of processes involving both human and natural factors. History, archaeology, Egyptology and botany are the main disciplines in the project. Knut Krzywinski introduced to the project of which this study is a part important elements of the theoretical foundation that this study builds upon as presented in the first chapter.

The thesis is submitted to the University of Bergen in partial fulfilment of the requirements for the degree *Cand. scient.* in botany, vegetation history. My supervisor has been Knut Krzywinski, associate professor at the Botanical Institute, University of Bergen.

Acknowledgements

First of all I would like to thank Knut Krzywinski for introducing me to the Desert and to remote sensing, and for letting me join the project. I would also like to thank him for his patient supervision, inspiration and for always keeping his door open.

Together with Knut Krzywinski, Richard H. Pierce and Jonatan Krzywinski I spent four weeks in the Eastern Desert collecting data for my study. Thanks to all of them for practical help, valuable discussions and not least for a stay so rich in memories. I will always remember those weeks.

A special mention of thanks is extended to Sekina Ayyad and her family for being so hospitable during my stay in Cairo and Mansoura. I am also grateful to her and her student Mohammed for helping me to identify the botanical material collected. Thanks also to M. Kassas who let me use his library at the University of Giza.

Thanks to the members of Skrivegruppen: Knut Fægri, Knut Krzywinski, Anne Bjune, Erik Vie and Annette Overland, who initiated the writing process. A special mention of thanks to Knut Fægri who has also made comments and has been helpful in correcting the language in the final stage of the work. I would also like to express my gratitude to Richard H. Pierce for making valuable comments and for scrutinising the language.

Several persons have been very helpful in general computing problems: thanks to all of you, and a special thanks to the system operators at the Nansen Center and to Finn Thorkildsen and Torill Hamre for writing two programs.

A special thanks to Anne Christensen and Mohamed Babiker at the Nansen Center for valuable discussions about the Desert. I would also like to thank Mohamed for practical help with all sorts of problems we have discovered and for listening to all my frustrations.

Most of this work has been done at the Nansen Environmental and Remote Sensing Center and I would like to thank the administration for providing the necessary facilities. Thanks also to Ola M. Johannessen for his interest in my research.

Even though I have not spent much time at the Botanical Institute lately, that is my “home” institute, and I would like to thank both fellow students and employees for providing a good working environment and for several enjoyable years together with them.

I would like to express my gratitude to the Faculty of Mathematics and Natural Sciences at the University of Bergen for funding my fieldwork in Egypt.

Last but not least I would like to thanks my parents for always giving support and encouragement.

The University of Bergen, Norway

June 1999

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Tables of Contents

Table of Figures

Table of Tables

ABSTRACT

Nine wadi localities in a hyper-arid environment have been registered in the field and studied using earth observation data. Branch height, crown – and trunk – diameter, and indicators of land-use such as present traces of browsing, lopping and charcoal production were registered for arboreal vegetation, mostly *Acacia tortilis* and *Balanites aegyptiaca*. A point mapping (GPS) was selected to optimise subsequent integration with raster data and to facilitate a detailed interpretation of change images. Field data and change images are interpreted according to two gradients, one cultural and one hydrological.

Derived tree maps are overlaid referenced TM data in order to detect differences between pixels with and without vegetation. The Red band is the most consistent spectral band in its content of vegetation information. Nevertheless it is apparent that several methodological and technical factors constrain the possibilities to register vegetation in this environment of very scarce vegetation cover. Similar problems are also recognised in the change analysis which is based on the difference between Red bands of the years compared. Four different datasets are part of the analysis: 1973, 1979, 1984 (all Landsat MSS images) and 1996 (TM).

Field data indicate that changes are taking place in the cultural landscape of the Eastern Desert, and the change is primarily due to processes that both in causes and consequences is associated with ‘deforestation’. Although several sources of errors introduce variations in the change images, the images do reflect the field observations.

INTRODUCTION

Temporal changes in dryland vegetation have been discussed in several studies (*e.g.* Banjaw *et al.* 1991, Cole 1989, Helldén 1991, Lamprey 1988, Olsson 1993, Thomas and Middleton 1994). The majority of these have been a response to the severe droughts in the Sahel zone, in particular those of 1968-1973 and 1979-1984. Parallel to these droughts the concept of desertification increased in importance and soon became an issue of global concern (Thomas and Middleton 1994). Both causes and consequences have been extensively discussed, in political, public and scientific media. Today, however, there is a scientific debate about the concept itself (Helldén 1991, Olsson 1993, Thomas and Middleton 1994). Rather than there being one process in drylands, there are several different processes that may result in a changed environment there that is often perceived ‘desert-like’ (Thomas and Middleton 1994). One of the main processes causing change in dryland vegetation has proved to be deforestation (*op. cit.*, Christensen 1998, Cole 1989, Hammer Digernes, T. 1979, Olsson 1985) *i.e.* it is the arboreal vegetation that is subject to change. Not only increasing fuel-wood demand but also commercialisation of resources is a driving force of this process (Christensen 1998).

The seventies and eighties were decades in which satellite data became an important source for monitoring the environment. In particular dryland vegetation and changes in it have been a major theme of satellite monitoring (Chavez and MacKinnon 1994, Dregne and Tucker 1988, Franklin and Hiernaux 1991, Franklin *et al.* 1991, Matheson and Ringrose 1994, Otterman *et al.* 1974, Pickup *et al.* 1993, Prince *et al.* 1990, Ringrose *et al.* 1990, Tucker 1986, Tucker *et al.* 1991). Data of high spatial resolution, *e.g.* SPOT HRV XS and Landsat TM and MSS, have been applied in studies focusing on local areas; and results have confirmed field observations and therefore the potential of the data as well (Christensen 1998, Krzywinski 1993b).

Because of the great international interest of the Sahel in the seventies and eighties most temporal studies have focused on this zone. The central and northeastern parts of the Sudan are among the areas where studies involving several different disciplines; and as part of them satellite monitoring was performed, *e.g.* Christensen (1998) and Krzywinski (1993a, 1993b) as part of the RESAP project, and by Helldén (1984, 1988), Larsson (1993) and Olsson (1985). The current study is to be considered as an extension of the satellite monitoring of vegetation change conducted in the Sinkat area, the Sudan (Christensen 1998, Krzywinski 1993a, 1993b). In this study, however, the focus is shifted northwards to the Eastern Desert of Egypt. This is an area that has several similarities to the Sinkat district, both in cultural identity and in natural environment. The main difference in natural factors is aridity. Ayyad and Ghabbour (1985) classify this area as hyper-arid, and it has been classified as one of the most extreme deserts of the world. Nevertheless, perennial vegetation grows in wadis and in other landforms where run-on water conditions prevail. On the other hand, arboreal vegetation, which is subject to change, is very sparse.

This sparse arboreal vegetation cover introduces new challenges to monitoring vegetation and its changes with remote sensing data. Both radiometric and spatial resolution are limited for these data, and information content relating to vegetation will therefore decrease towards a theoretical limit below which the detection of vegetation cover is severely reduced or impossible. Field registrations in monitored areas too have to be carried out, but methods have to be reconsidered, because an optimal integration with raster data is required in order to interpret change in as much detail as possible. Problems have also been reported from other, less arid areas. Notwithstanding, relationships between vegetation cover and spectral reflectance that allow an absolute interpretation of digital data have been derived (Larsson 1993, Olsson 1985).

Objectives

The general objective is to study changes in wadi vegetation in the Eastern Desert of Egypt in the period between 1973 and 1996, using Landsat MSS and TM images. Two different questions are raised:

- Have there been temporal changes in the arboreal vegetation cover there; and if so, to what factors can they be attributed?
- At what level is it possible to extract vegetation information from optical satellite images so as to interpret temporal changes in a hyper-arid area?

THE CONCEPTUAL FRAMEWORK AND THEORETICAL BACKGROUND

Vegetation changes in the African drylands

Changes in land cover in African drylands have been observed for several decades. Environmental change was reported already from the thirties. Climate, *i.e.* drought, was held by many to be a main cause of these changes though native misuse of land was also blamed (as referred in Thomas and Middleton 1994, and by Bovill (1921) and Stebbing (1935) in Banjaw *et al.* 1991). However, it was the Sahelian[1] drought between 1968 and 1974 that attracted worldwide attention to dryland changes, *i.e.* to desertification; and drought again came into focus as a main cause. Human suffering and famine were brought to the attention of the general public through the powerful new mass media, in particular TV, and the scientific and political interest of the seventies reached a maximum at the 1977 **UN C**onference **o**n **D**esertification, UNCOD. Thomas and Middleton (1994) described the new aspect of the dryland change issue generated by UNCOD as being 'the conceptualisation of desertification as a serious problem of global rather than local interest, and as something important for the political agenda'.

The word *desertification* was already introduced in 1949 by Aubreville[2] (Thomas and Middleton 1994). Since then more than one hundred definitions of the term have been presented in the literature (Glantz and Orlovsky 1983, as referred in Thomas and Middleton 1994). As this number suggests, the concept of desertification is a subject of on-going discussion. However, the various definitions have many points in common, and these can be summarised as 'long lasting changes' resulting in 'desert-like conditions', usually meaning some kind of 'decrease in productivity' (Helldén 1991). The three definitions below are all UN definitions and show the differences of opinions even within this organisation.

[1] In Groom (1958) Sahel is translated as "The shore of a sea or a great river".
[2] His definition is as referred in Banjaw, *et al.* (1991) "the increase of deserts, dry areas with few plants, into semi-arid lands".

1. The most cited definition is the one adopted by the UNCOD (as referred in Thomas and Middleton 1994); "- the diminution or destruction of the biological potential of the land that can lead ultimately to desert like conditions. It is an aspect of the widespread deterioration of ecosystems and has diminished or destroyed the biological potential, *i.e.* the plant and animal production, for multiple use purpose at a time when increased productivity is needed to support growing populations in quest of development."

2. Before the UNCED in 1992 (Rio de Janeiro), UNEP adopted a new definition; "Desertification is land degradation in arid, semiarid and dry sub-humid areas resulting mainly from adverse human impact"

3. In the United Nations Convention to Combat Desertification in Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa (1994) the definition is, however, different; "desertification means land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities".

So defining desertification has been a problem, and today the debate is about the concept itself and what it was all about (Helldén 1991, Olsson 1993, Thomas and Middleton 1994). Even so, most people have a rather clear perception of desertification and the end state, *viz.* the desert. Perhaps the strongest visualisation of desertification was the 'marching desert'. It was the conclusion of Lamprey's report from 1975 (Lamprey 1988) that spread this image of the desert invading fertile land south of the former desert boundary. As reported in Hammer Digernes (1979), active sand dune systems became one proof of this advancing desert; "Just to the north and west of Bara a number of dunes are on the move again, burying villages, farming land, and grazing areas." Helldén (1991) presents several similar examples reflecting the same perception of desertification.

However, Lamprey's (1988) conclusion that the desert had moved 5,5 km annually between 1958 and 1975 was the result of a methodological mistake. He compared the vegetation boundary of 1975 as seen from aerial reconnaissance with the vegetation boundary of the map of Harrison from 1958 and concluded that it had moved 90 km southward. However, the 1958 map based the vegetation boundary on the 75 mm isohyet that was interpolated from a scanty network of rainfall stations, and Harrison had neither visited this area nor inspected its vegetation in detail (pers. com. K. Krzywinski). Moreover, the fifties was a period of favourable rainfall, while 1975 was a year after a severe dry period. Thus his sources of information were not comparable. But more important:

Despite little agreement upon a definition of *desertification* Lamprey's (1988) observation and conclusion already breaks with the first point requiring 'long lasting change'. In the concept of vegetation change it is important to distinguish between groups of plants with different life strategies. These strategies are discussed in detail below; but, in brief, plants are either drought-enduring or -escaping. After rain the drought escaping plants contribute significantly to the vegetation cover. Thus vegetation coverage and extent differs between a dry and wet period. Several satellite studies have confirmed the great variability of biomass in the Sahel zone (Dregne and Tucker 1988, Malingreau *et al.* 1996, Tucker 1986, Tucker *et al.* 1991). Hence the 'change' Lamprey found was not long-lasting, but most likely an artefact of an inappropriate methodology and the natural variability of drylands.

In retrospect the most prevalent conception of the desertification may refer to conditions that never occurred. Were there, then, no changes; was desertification only a myth? This is a question raised by some authors (Helldén 1991, Thomas and Middleton 1994). In accordance with parts of the later UN definitions desertification is recognised today to be land degradation; more specifically five different processes are described by Thomas and Middleton (1994). These are overgrazing, overcultivation, deforestation, salinisation of irrigated land, and industrial activities. None of these processes are restricted to drylands alone, and it is hard to distinguish what links them to deserts except that the desert is in their vicinity. Especially the deforestation process challenges the meaning of the concept of desertification, for deforestation too is an ongoing process in the desert itself. To say that a desert becomes desertified is, however, tautology. Some of this confusion is perhaps linked to the perception of deserts. One such example is from the UNEP Calendar 'Stop deserts growing. Save soils.' (1991, Nairobi, as referred in Helldén 1991 and Olsson 1993); "Desertification results in deserts, which are not just less productive lands, they are non-productive lands unsuitable for human life".

Another example is from Schlesinger *et al.* (1990, as referred in Kassas 1992); "Although desertification is often assumed to result in a reduced level of plant growth, net primary productivity is similar in the native grasslands and the invasive shrub communities .. However, changes in the quality of net primary production with shrub invasion lower the economic potential of the landscape, especially as rangeland. Thus, total net primary production may not always be the best measure of desertification processes.”

These examples are very different, even contradictory, but illustrate the misuse and misunderstanding of the terms applied. The first statement builds upon the conception that deserts are less productive than most other environments; but in its exaggeration it is exceptional. People possessing a lifestyle adapted to the desert environment have been living there for millennia and still are. The second quote is more generous when it comes to recognising deserts in terms of productivity, implying that a desert can be even more productive than the original environment; however, the economic value or potential of a desert is less than that of the original environment. Common to the statements is that the end-situation is ‘worse’, in terms either of productivity or of economic potential, than the original situation. And this change is measured on the scale of desertification where the lowest rank apparently is *desert*. Ranking is an important part of the notion of land degradation. As recognised by Blakie and Brookfield (1987) the Latin derivative of *degradation* implies ‘reduction to a lower rank’. Ranking requires a scale, and the process of degradation moves the land considered from ‘better’ to ‘worse’ on this scale. Defining such a scale is, therefore, dependent upon people’s perception of ‘better’ and ‘worse’ and thus their valuation of nature and land-use. However, perceptions vary between and within cultures and among persons and are therefore not suitable for defining a rank. Hence the suitability of the term ‘land degradation’ may also be questioned. The term ‘change’ is at least neutral and therefore perhaps more appropriate.

Summing up, there are two main problems with the term ‘desertification’, one related to perceptions, the other to the concept itself;

1. Most people understood desertification as the advancing desert. This never happened. Admittedly, there are activated dunes, but they are not a part of the desert front, to the extent that such a front exists. These dunes are old; and, as Evenari (1985b, and one of his references Tricart 1969) has pointed out, they are relatively stable. Last, but not least: “Only about one-third to one-quarter of the world’s deserts are covered by aeolian sand, so its role in deserts should not be exaggerated” Goudie and Wilkinson (1977).

1. There is, therefore, a conceptual confusion about the term ‘desertification’, and it seems impossible to define it. Actually it implies different forms of land-use change. These

> processes are global and by no means limited to deserts. However, due to the spatial vicinity of deserts to drylands, the end-state is usually perceived as desert-like. This brings up the question about the perception of deserts and whether the desert concept itself is well defined.

It is evident that a better understanding of the desert ecosystem is needed before one can discuss what actually constitutes a change.

Deserts - seeking a definition

Most people have some idea about what a desert[3] is, as is clearly seen in quotes from the desertification debate. The most important aspect is aridity, *i.e.* the water deficit. Looking up 'desert' in a dictionary adds other commonly perceived characteristics to the term (Hornby *et al.* 1987); "barren land, waterless and treeless, often sand-covered, -barren; uncultivated, -uninhabited". Some of these are not just perceptions of our time, similar terms are found already in biblical times: " when you followed me in the wilderness, through a land unsown", Jeremiah (2:2)[4]. This statement can be understood as the point of view of an outsider who considered agriculture as important. Actually, the other terms too have to be interpreted in relation to more humid conditions. However, these terms, or rather perceptions of an outsider, do not contribute to an understanding of the desert ecosystem. Describing or defining an ecosystem requires knowledge about it as it is, not as seen from or compared with a moist environment. To make a useful definition of desert has, however, proved to be difficult (Evenari 1985b, Louw and Seely 1982, McGinnies *et al.* 1968); and this difficulty in defining *desert* makes a discussion of change and creation of deserts equally difficult.

Water is a prerequisite for life; and characteristics of deserts are, as seen in both the examples above, often conceptually opposed to water. Agriculture, trees and humans, all kinds of life, require water to exist. And most definitions suggested are meteorological, and focus exactly on the water regime; "water controlled ecosystems with infrequent, discrete, and largely unpredictable water inputs" (Noy-Meir 1973). This definition highlights why water is particularly important in deserts.

[3] From Latin *desertum* – fundamentally absence of human inhabitants

[4] Translations may, however, differ " when you followed me in the wilderness, in a land that was not sown". In one Norwegian translation 'wilderness' is interpreted as 'desert', "da du fulgte meg i ørkenen, i et land der ingen kan så." (Bibelen 1985).

Another aspect of defining deserts is to delimit them geographically. However, there is a problem in devising ways to express dryness/aridity (Goudie and Wilkinson 1977). Some attempts, shown in table 1, visualise the diversity of borders defined and concepts applied. Primarily two different measures have been used to define desert borders, *i.e.* precipitation values and the aridity index. However, both concepts are problematic in use. The use of isohyets constitutes a problem since the amount of precipitation *per se* is not of primary interest, what is essential is the availability of water, and the two are not necessarily connected. The aridity index is an empirical expression that combines water-supply and -need. Evenari (1985b) recognises a system developed by Meigs (1953) who treats one of the aridity indices as "the most appropriate" to delimit the hot desert environments of the world. However, the aridity concept itself is also problematic in application (Reitan, and Green 1968). This is due to the theoretical and practical problems inherent in the term 'potential evapotranspiration'[5] which expresses the water need.

Table 1 Attempts to define desert-boundaries and -types according to the amount of precipitation and aridity indices.

Concept	**Category**	**Definition; mm of annual precipitation**	**Author**
Desert	-	< 100	Le Houérou (1970)
Desert; *sensu stricto*	-	< 250	Evenari, *et al.* (1985)
Hot deserts	-	0-600	Evenari *et al.* (1985)
-	Extremely arid environment	< 60-100	Meigs (1953)
Extreme desert	Arid ecosystem	< 70	Shmida *et al.* (1985)
True desert	Arid ecosystem	< 120	Shmida *et al.* (1985)
-	Arid environment	60-100 – 150-250	Meigs (1953)
Semi-desert	Semi-arid ecosystem	mean 150 - 300-400	Shmida *et al.* (1985)
-	Semi-arid areas	> 400	Le Houérou (1970)
-	Semi-arid environment	150-250 - 250-500	Meigs (1953)
Index type	**Category**	**Definition; scaled on an index**	
Moisture index	Sub-humid	0 - -20	McGinnies *et al.* (1968)
Moisture index	Semi-arid	-20 - -40	McGinnies *et al.* (1968)
Moisture index	Arid	< -40	McGinnies *et al.* (1968)
Aridity index	Semi-arid	< 0.03	UNESCO, 1979[6]
Aridity index	Arid	0.03 - 0.20	UNESCO, 1979
Aridity index	Hyper-arid	0.20 -0.50	UNESCO, 1979

However, many factors other than water are also common to the hot deserts of the world (Evenari 1985b). Even without taking into consideration cold deserts and chemical deserts, a global definition of deserts is difficult mainly due to the variable nature of criteria and the

[5] The equations devised to quantify potential evapotranspiration by Thorntwaite (1948) are described as "the best known, most widely used and least understood equations" Reitan, and Green (1968).
[6] As referred in Ayyad and Ghabbour (1985)

presence of transition zones in the actual areas. Instead of selecting a strict definition of desert that attempts to catch the totality, it may be advisable to consider a desert syndrome. Factors such as climate, weather, geomorphology, hydrology, soils, vegetation and animal life have to be considered. Some keywords are given in table 2, the main emphasis in the following is, however, placed on plants and their adaptations to desert conditions.

Table 2 Factors and variables in a desert syndrome.

Factors	Variables
Climate and weather	Temperature, wind, precipitation; variability & unpredictability, evaporation, dew, fog, relative humidity
Geomorphology	Landforms, catchment, slope
Hydrology	Run-off/run-on, evaporation, transpiration, subsurface water
Soils	Nutrients, composition, depth, texture, moisture
Vegetation	Life-forms and –strategies
Animal life	Life-forms and –strategies

Adaptations of hot desert plants

Living organisms adapt to their environment and to each other[7]. Thus different environments can be defined by the organisms living there, and it should be possible to describe deserts by the inventory of their desert plants. The basic life process of plants is photosynthesis and understanding adaptations of plants requires understanding of this process. Requirements for photosynthesis and hence plant growth are: optimal temperatures, minerals, light, water and carbon dioxide. Plant production is also limited by these inputs, and productivity can never exceed the restrictions set by the most limiting factor. In deserts, water is (generally) the limiting factor; hence the description of deserts as ‘water controlled ecosystems’ is, on the whole, well founded.

The water available for photosynthesis in an ecosystem has, however, to be differentiated from the total water input to that ecosystem. The latter is, in the final analysis, given by the precipitation received in the area. Water available to plants is not only soil water but also water available for direct uptake. The latter can be fog and dew, both of which have been shown to be important for the water economy of desert plants (Louw and Seely 1982). However, water uptake from soil by roots is the primary strategy for plants; and as Noy-Meir (1973) put it, “Soil water in deserts is far from being a single homogenous resource; it is highly diversified in several dimensions”. Precipitation is redistributed under the influence of factors like run-off/run-on, evaporation,

[7] Noy-Meir (1979/80) discuss to what extent competition among organisms is prevalent in deserts or whether only the physical factors of the environment can describe the adaptations of the organisms.

transpiration, soil drainage and texture (*op. cit.*). This redistribution of water is especially important in deserts. One good example is from Egypt, near Cairo, where annual rainfall is only 25 mm but where the run-on is high and the effective water availability is 500 mm (Walter 1973, as referred in Furley and Newey 1983). Redistribution and run-on depend upon topography; therefore, lower lying areas receive more water than higher ones. After hitting the ground precipitation percolates under the influence of gravity. This causes a depth time lag gradient, lower lying areas and deeper soil layers receiving later and retaining more water than higher areas or upper soil layers. Also, different depths are subject to different evaporation pressures. Final water storage is also influenced by soil texture, and in arid and semiarid areas an 'inverse texture effect' is recognised (Noy-Meir 1973). In contrast to conditions in humid climates sandy and rocky soils support taller and denser perennial vegetation than finer soils do (*op. cit.*). Water-holding capacity is low in the upper layers of such sandy and rocky soil as water will percolate to deeper layers. Finer soils (clayey, silty and loamy soils) have greater water retaining capacity, but usually desert rains cannot penetrate deeper than 30 cm (Noy-Meir 1973). Thus, these are the water-uptake conditions desert plants have to adapt to.

Several authors have classified desert plants into different groups (Evenari 1985a, Goudie and Wilkinson 1977, Kassas 1966, Kassas and Batanouny 1984, Noy-Meir 1973); and these systems are usually related to the water strategies of such plants. The following classification is based on the one described by Noy-Meir (1973), see table 3. His classification is based on length of, and coincidence between photosynthetical period and water availability.

Table 3 Groups of desert plants reflecting water strategy (according to Noy-Meir 1973).

<table>
<tr><th rowspan="3">Poikilohydric</th><th colspan="2">Ephemerals</th><th colspan="3">Drought persistent</th></tr>
<tr><td rowspan="2">Annuals</td><td rowspan="2">Perennial ephemerals</td><td rowspan="2">Fluctuating</td><td colspan="2">Stationary</td></tr>
<tr><td>Evergreen</td><td>Succulent</td></tr>
</table>

Poikilohydric species

These plants maintain all their structures independent of water availability, but they are only photosynthetically active when water is available. Transition between active and inactive states involves only reversible biochemical changes in the presence or absence of moisture. This group includes lichens and algae, and a few ferns and higher plants.

Ephemerals

These plants use only water from the upper soil layers. In their photosynthetically active form they are thus temporally related to rainfall. They germinate only after heavy rainfall or a sequence of rain events; while between moist events they are photosynthetically inactive, surviving either as seeds or as dormant plants. Another common term for this group is 'drought evaders' or 'drought escaping' plants, and the majority of desert species fall within this group. Two groups of ephemerals are recognised.

Annuals

The members of this group complete their life cycle from seed to seed within a few weeks of rainfall. During dry periods the only surviving organ is the seed. They are small herbs and both summer and winter annuals are recognised according to the rainfall regime of the area in which they occur. Their water resources are usually restricted to the upper 30 cm of the soil.

Perennials

These species are able to survive in a dormant state beyond the first weeks after rainfall. This is possible due to special organs that store water and energy. Hence this group can complete its lifecycle in another season than it began. These ephemerals extract water from deeper layers than the annuals (30-60/120 cm).

Drought persistent species

This group includes all perennial species that maintain some photosynthesis also during longer dry periods. This not only requires a stable water uptake but also a good internal water economy. These species have developed several features which tend to restrict water loss either permanently or temporarily.

Water uptake

A primary way to secure long-term water input is to extract soil water from deep layers that exhibit less temporal variation in water availability. Root depths of up to ten meters are common; even fifty meters were reported when the Suez channel was constructed (as referred in Kassas and El-Abyad 1962)[8]). During fieldwork a huge *Acacia tortilis spp.* was

[8] The roots of *Tamarix sp.* "could be followed during the building of Suez Canal in places to a depth of 50 meters" (Rubner, 1948, quoted by Polunin, 1960, p. 541.)

observed growing next to a 55 meter deep (Murray 1925)[9] and periodically dry well[10] (indicating the considerable depths that may be required to reach permanent soil moisture). Several species develop specialised root systems: there are horizontal rain-roots in the upper layers to increase short-term water uptake after rainfall. Higher osmotic pressure also increases the ability to take up water from the dry desert soil. Water absorption through the leaf epidermis is also reported to contribute significantly to plants' water uptake (Louw and Seely 1982), but less is known about the total influence of this source of water. Several species have crusts of salts upon their leaves, *e.g. Tamarix*, and this feature probably enables them to condense the moisture of the air (Hassib 1950).

Reducing water loss

The main cause of water loss is due to the gas exchange needed for photosynthesis and respiration when stomata are opened to release oxygen and take up carbon dioxide. In general, at least ninety-five percent, perhaps even more, of the water absorbed by roots is lost through transpiration (Kassas and Batanouny 1984). Only about ten percent is lost through the cuticle (Louw and Seely 1982). Adaptations to reduce water loss can be physiological, morphological or anatomical.

Physiologically, it is possible to reduce transpiration by restricting gas exchange to periods of lower transpiration pressure. Two different strategies have been observed, both binding carbon dioxide in intermediate compounds. This is opposed to the normal C3 pathway where carbon dioxide is used directly. Intermediate carbon dioxide compounds allow photosynthesis without gas exchange. In the **C**rassalucean **A**cid **M**etabolism (CAM) pathway carbon dioxide uptake is restricted to the night, thus avoiding both high temperatures and strong light. The C4 pathway reduces uptake to shorter periods during the day.

Morphologically, adaptations to water loss can be seen in both leaf and shoot characteristics. Usually, the parts above ground constitute only a small part of the total plant. Low shoot to root ratio is a typical feature for drought-enduring desert plants. A further reduction of the transpiring surface is an effective means of limiting transpiration. This is possible either by shedding leaves in dry periods or by dwarfing. Features such as

[9] According to Murray this well was 55 m deep after it was dug in 1906. However, during a visit at the station a guard told us that it had been cleaned recently and consequently is somewhat deeper today.
[10] El-Kanais, on the Idfu – Marsa-al Alam road, see fig. 20.

thorns[11] and succulence are other effective means frequently seen. Another way to meet high transpiration is to deal effectively with the high temperatures. It is mainly IR-radiation that causes the high leaf temperatures. Usually the leaf temperature is more than 10°C higher than the surrounding air. In general plants are unable to withstand temperatures above 55°C (Strasbourger's textbook 1976)[12]. Transpiration has a cooling potential of 2400 J/g (Louw and Seely 1982) and is therefore an effective way to reduce high temperatures. However, this entails too much water loss. Different protection strategies exist. These strategies can be having small and/or narrow leaflets that increase dissipation of heat by convection. Nyctinastic movements of leaves in the presence of high light intensities, *e.g.* daytime sleep movements, are seen in *Acacia*. Increasing reflection by growing white hairs is another strategy.

Anatomically, leaves[13] of plants in extremely sunny and relatively dry places often exhibit some special features. They may be equi-facial and have little or no distinction between palisade and spongy mesophyll (1976). The mesophyll of xerophytes is small-celled and thick-walled, and it is often reinforced by special sclerenchymous elements (sclereids). The intercellular spaces are often few in number. Some special structures involve a thickening of the epidermis (more layers, thicker outer wall), a thickening of the cuticle, and a sinking of stomata.

In this variety of adaptations and strategies to increase the efficacy of their water economy some different subgroups of drought-persistent plants are recognised. The main difference is whether a constant or reduced photosynthetically active biomass is seen during drought.

The fluctuating persistent species, mainly shrubs, reduce their photosynthetically active biomass and transpiring surface during dry periods. They do this by shedding leaves or stems or by replacing them with smaller, denser leaves with lower gas exchange rates (as referred in Noy-Meir 1973). Roots in the dry upper soil layers can also be shed. Photosynthetic activity is maintained, but water and energy losses are reduced and therefore small water reserves are needed.

The stationary persistent species are the true drought-enduring species. They attempt to keep green biomass constant throughout the year. Although stationary persistent species

[11]Thorns reduce incident radiation and heat loads on desert plants. A boundary layer of air is created that protects the plant and disperses heat.
[12] Exceptions of 80°C are also mentioned (*op. cit.*)

meet the same challenges, the two subgroups, the evergreens and the succulents, respond to them differently. While the succulents accumulate internal water reserves to cope with drought, the evergreens seek the deep and permanent water resources.

Change in desert vegetation

Understanding the water conditions desert plants deal with and how they have adapted to them sets the background for discussing change. The following discussion will lay its main emphasis on the ephemeral species and the arboreal perennial species because they are the chief concern of this study.

One possible definition of change in an ecosystem could be `‘a process, induced and/or controlled by disturbances, that permanently moves an ecosystem away from a stable (equilibrium) state’`. In this case a disturbance is thought of as a phenomenon that the system is not naturally adapted to.

Understanding what constitutes a change depends upon the interpretation of the stable state. Clearly, stability has to be considered on a temporal scale. All ecosystems exhibit variation in time. One obvious example is the seasonal variations seen in humid climates. However, this is not considered to be a change since, after one year, the circle is completed; once again a new cycle starts. Thus, variability can be, and often is, an aspect of stability. However, the time scale of the cycle of variation can differ among ecosystems.

An ecosystem constituted by ephemeral desert species exhibits a stability based on a recurring life-cycle, but in this case it has neither a constant time-period nor a temporally predictable start, unlike the temporal regularity that constitutes a basic factor in the area where the factors determining life-cycle are seasonal in origin. In terms of water availability the temporally irregular life-cycle is perfectly stable.

This may also be visualised by the ‘pulse-reserve’ paradigm, see Fig. 1. The photosynthetically active part of ephemeral life is considered as the pulse and is triggered by rainfall. The pulse ends in the production of seeds, the reserve form, from which a new pulse can be triggered by the next rainfall event. The time-scale does not regulate this process. In terms of this paradigm `“Stability will be endangered only by mechanisms causing overexploitation of the reserves or consistent prevention of backflow to reserves”` (as referred in Noy-Meir 1973).

[13] A general description of leaf anatomy is given in the section about vegetation monitoring.

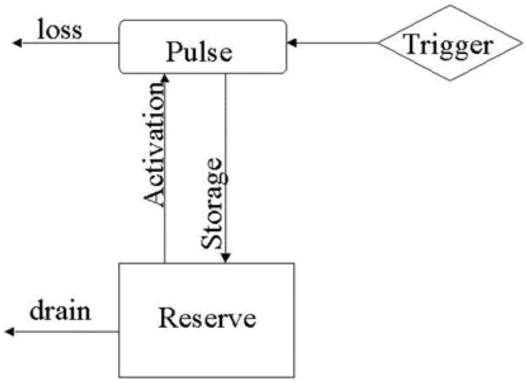


Figure 1 The pulse-reserve paradigm (after Noy-Meir 1973).

A stable system can react to a disturbance in different ways. It might be able to withstand the disturbance, *i.e.* the system is resistant[14]. On the other hand, it might only temporarily move away from its stable state before returning to it, *i.e.* it has a high resilience. In neither of these two cases a change has occurred. If, however, the system cannot withstand or recover from a disturbance and hence is permanently moved away from its stable state, a change has occurred.

Clearly, re-growth and, more importantly, regeneration are main factors in a process that can produce changes. The pulse of the ephemeral life-cycle is temporally restricted, but spatially it is widespread. Both these characteristics reduce the effect of potential disturbances and reduce the probability of over-exploitation. The production of seeds is high, and their small size and light weight facilitate their dispersal. Hence back-flow, both locally and regionally, is good. Finally, a new pulse, with its resulting seed production, is easily triggered by optimal rainfall conditions[15]. Thus, the ephemeral life-cycle seems to be highly resistant to disturbances and/or to be very capable of dealing with them.

The case for arboreal, desert species is, however, different. They are spatially restricted to areas of deep, permanent soil moisture, while temporally there seem to be few natural restrictions to their growth. Hence they are valuable resources but are also more vulnerable to disturbances. Their seeds are fewer, bigger and heavier than those of ephemerals (Kassas 1953a), and are spread either by domestic animals or floods. Both these agents are by comparison more local, rare and restricted. Also their regeneration is different from that of

[14] Such systems are also said to be highly stable (Holling 1973, Walker and Noy-Meir 1982); however, I prefer to distinguish between the natural stability of a system and “stability” as a term related to how a system responds to a disturbance.
[15] According to Kassas (1966) germination is restricted by both too little and too heavy rainfall.

ephemerals. A single rain event is not sufficient for the regeneration of trees. Successive events are required to provide enough humidity for roots to penetrate deep soil water resources (Krzywinski 1990, Krzywinski 1993a). The highly variable rainfall pattern of deserts makes this a very rare, though not unlikely pattern. In each rain event there is a wasteage of seeds because they are either washed away or killed after germination. The latter occurs either when temporal moisture disappears or because permanent moisture does not exist at that spot. Mechanical destruction caused by floods following precipitation can also kill seedlings. Thus, only a very low percentage of seeds is successfully germinated, as has been shown experimentally by Seif El Din and Obeid (1971).

Although little is known about the natural regeneration, growth and age of arboreal desert species, present information as described above, indicates that this system is one that requires a long time to complete a life-cycle and hence to maintain its structure. Therefore, it also seems to be very vulnerable to disturbances of high intensity.

Against this background it is easy to discern a fundamental error in the desertification debate. Differences in rainfall regime, or prolonged lack of rainfall, are not a ‘disturbance’ but a constant in the natural regime that desert species are adapted to. The highly variable life-cycle of ephemeral species is also one of high stability. As a consequence, the natural variability of the stable drylands has been mistaken for change, and drylands have been referred to as “ extremely fragile ecosystems” (Lamprey 1988); whereas, in reality they are very stable. This highlights the importance of understanding the specific ecosystem under consideration and the concepts involved when discussing change.

However, understanding human life as a part of the ecosystem is equally important. People living in deserts usually have a strategy that includes migration or transhumance, adapted to the temporal and spatial variability of ephemeral resources and limited perennial resources. In longer dry periods, which is the rule in deserts, perennial species, mainly arboreal, are the only dependable resources. However, they constitute a dispersed resource; and utilisation of these resources must extend over huge areas if over-exploitation is to be avoided. Traditionally, trees are utilised both as fodder for domestic animals and as a source of energy. As long as these utilisations are spread over large areas and neither is allowed to become too intense, utilisation may be sustainable. During the last decades, however, there has been an intensified use of trees as a source of energy, particularly in extensive charcoal production Christensen (1998). Not only branches but also whole trees are used in the process. This is such an intense utilisation that over-exploitation of resources ensues. The system also becomes more vulnerable to the traditional landuse; especially browsing of seedlings will have a far more adverse effect in this combination with 'prevention of backflow of reserves'. Hence it is legitimate to talk about a process of 'deforestation' - and, as seen, that is a process which introduces a new factor in the equation of stability and change in the desert environment.

Once the concepts are defined and understood correctly, it becomes apparent that the perennial arboreal species, being subject to increased utilisation, are also subject to change in the desert environment. Consequently, they are the species considered in this study of vegetation change in the Eastern Desert of Egypt.

Vegetation description and mapping

Studying vegetation requires description and mapping. Parameters of interest are overtly set by the aims of the study, implicitly by the type of vegetation studied. However, to accomplish the process of description and mapping, certain assumptions and approximations are made since neither time nor techniques are available to draw the complete picture; *i.e.* a 1:1 description of nature.

Description and mapping of vegetation involves two different steps: first to select a representative sample area within a study area and then to select the measures and parameters to be described and mapped. In both of these steps the best approach possible under the circumstances has to be chosen in order representatively to reflect the vegetation. Hence it is obvious that methodology changes with the aims of a study and with vegetation type[16].

The sample area is either predefined by plot size or outlined during the description phase (plot-less techniques). When plots are used, the size should reflect the species studied and the vegetation type. There is a close relationship between diversity and area; the larger area the more species are included in the plot. The slope of such a species-area plot approaches zero when an area is reached that reflects the plot-size which catches most of the species

[16]One example is the differences between methods applied by continental European and North American ecologists (Mueller-Dombois and Ellenberg 1974). The latter have developed a set of methods reflecting the diverse set of trees. Either individuals within a plot are counted or a plot-less method is applied. In continental Europe, however, there are few indigenous species of trees; and in most forests the few species present are planted (*op. cit.*). Therefore undergrowth vegetation in forests presented a greater analytical challenge (*op. cit.*)

variation within the study area. The plot-size is not constant. It varies according to the vegetation layer and vegetation type studied. Studying herbs only requires small plots if vegetation is dense. A larger size has to be chosen in more scattered vegetation. Studying trees requires larger plots; therefore trees may be studied using plot-less techniques[17].

The next step is to define the parameters of interest. Some common parameters are frequency, cover, density, yield and performance. Parameters are often described by a rating scale, primarily to save time and because absolute measures often are impossible to obtain. The most common rating systems are the Domin and Braun-Blanquet scales. They are measures of frequency as a percentage of cover (Table 4).

Table 4 The Domin and Braun-Blanquet scales for vegetation description (after Kershaw and Looney 1985).

Cover frequency	Domin scale	Braun-Blanquet scale
Cover about 100%	10	5
Cover > 75%	9	5
Cover 50-75%	8	4
Cover 33-50%	7	3
Cover 25-33%	6	3
Abundant, cover about 20%	5	2
Abundant, cover about 5%	4	2
Scattered, cover small	3	1
Very scattered, cover small	2	1
Scarce, cover small	1	1
Isolated, cover small	+	+

These scales highlight the importance of the type of vegetation/area under study. Obviously these ratings are only applicable in areas of quite dense vegetation cover. Drylands, which are recognised partly by their scattered and low vegetation cover, were not taken into account when these scales were developed. However, the vegetation type has to be considered before applying such scales. Usually the perennial vegetation cover in arid and semi-arid regions is less than 25%, thus only using the bottom half of these scales. This is a recognised problem and the Log-series survey method[18] has been developed in response to this (McAuliffe 1990).

[17]Among plotless techniques that are available are the Bitterlich variable radius method and the Wisconsin distance methods including the wandering quarter method.
[18]This defines classes on a logarithmic scale, the midpoint of each interval being double that of the preceding one, and allows rapid estimates of density and cover.

Integrating dryland vegetation data with spatial raster data

Working in drylands makes it necessary to reconsider field methodology, in particular when the species of interest are perennial arboreal species. Further considerations have to be taken when integrating field- and remotely sensed- data. Remotely sensed data are spatial data of the raster type, the smallest unit is a square possessing a value that describes its reflective characteristics. It is this value that links vegetation and remotely sensed data. Two parameters are thus prerequisite when describing the vegetation; spatial distribution and a measure that relates to the reflective characteristics of the vegetation.

When the objective of the study is to monitor temporal changes in vegetation at the pixel level, the possible field options are further constrained. It is important to recognise the individual trees or stands at the pixel level on the satellite image. Using quadrates as the smallest mapping unit is unfortunate because the information within the limits of the quadrate is averaged, and thus valuable information is lost; "One of the most important descriptive parameters of desert vegetation is the absolute amount of perennial plant cover…" (McAuliffe 1990). The next step is integration of the two types of quadrates, the field and the raster quadrate. Integration requires optimal overlapping. This is problematic primarily when seeking information at the pixel level.

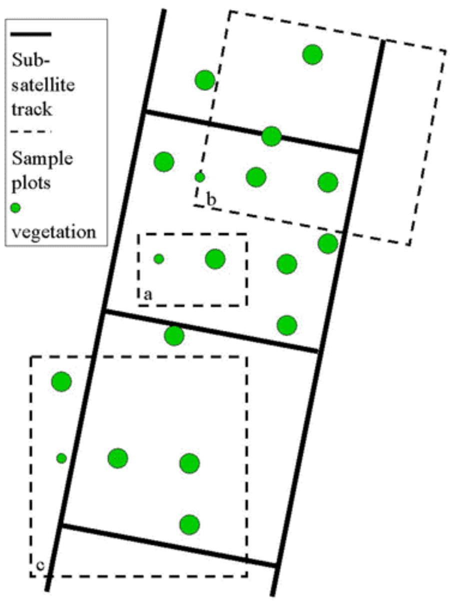


Figure 2 Quadrate mapping and satellite data, quadrates a, b, and c illustrating different problems

A big quadrate excludes extraction of information at the pixel level. A quadrate smaller than the pixel size, on the other hand, makes correlation between pixel value and vegetation variables difficult because the quadrate may not catch all the vegetation in the pixel, see Fig. 2, quadrate a. Olsson (1985) had problems integrating her field data, quadrates of 50 x 50 m or 2 x 25 x 25 m, and explains the bad correlation between cover and pixel value by the fact that "it was impossible to localise them (the quadrates) on the pixel level in the satellite images". A quadrate of equal size is thus optimal in size but exhibits another problem integrating quadrates, see Fig. 2, quadrate b and c. The sub-satellite track decides the spatial setting of the pixels, so the sides of the field quadrate should be aligned to this track to facilitate the comparison between satellite and field data. This is mentioned by Blomberg (1992), and selecting localities and gradients fitting the orbit might be one way to approach the problem, but only in one dimension; the quadrate will still have to be outlined and accordingly may overlap two or more pixels, see Fig. 2, quadrate b.

The way around the problem then seems to be to use point observations instead of quadrates. A point is easily integrated with raster data on the level of interest. Different plot-less mapping methods have been developed, *e.g.* those of the North American ecologists. The main idea is that number of trees per unit area can be calculated from the average distance between the trees. These methods are, however, developed for forestry, in regions of dense forest. In scattered vegetation their success is disputable[19] (Mueller-Dombois and Ellenberg 1974). A scattered perennial vegetation cover also raises doubts about the need for generalisation at all because a complete mapping of trees is possible. A complete point mapping, *i.e.* drawing a picture as complete as possible, is the best way to achieve the detailed level of information that is required for integration at the pixel level.

Point mapping and positioning methods

All observations have to be labelled in space when integration with spatial data is intended. However, the accuracy required for the positions is different for a quadrate and a point. The quadrate is a unit that supposedly represents the totality of a larger area. As long as the

[19] One of these well-accepted methods, the point centred quarter, has problems when dealing with widely spaced individuals. Applicability is also restricted to only random distribution. Some modifications to overcome this are implemented in the wandering quarter method Catana Jr (1963). These methods, however, encounter the same limitations as the quadrate methods, for in essence they only try to describe the frequency, cover or density, not the distribution within the area examined.

position puts the quadrate within this larger area, it is sufficient for further analysis. A point only represents itself; hence its precise location is very important.

The interrelation of selected points on earth's surface is part of geodetic science. Positioning is done in a selected reference system, or a datum. One of the elements that describes this datum is an ellipsoid, a mathematical expression of the geoid. The geoid reflects the earth's topography. Over the ellipsoid is laid a coordinate reference system. This system specifies locations on the surface of the earth, and they are based on the datum. The coordinate value can therefore change when their interpretation is based on another datum; *i.e.* the same position on the surface of the earth will have another coordinate value when it is based on a different datum. This difference is called the datum shift (Fig. 3) and it is described by seven parameters. Three translation parameters describe the positional difference between origos, three rotation parameters describe the direction of the axes and one parameter the scale. Except in cases where high precision is required the coordinate systems are assumed to be parallel (rotation parameters are zero) and the scale parameter is set to one.

Geodetic techniques of point positioning can be either direct or indirect. Different horizontal positioning methods are recognised. Of the older methods, four are described by Smith (1997): astronomical techniques, triangulation, trilateration and traversing. Especially the first three methods are very laborious and difficult although high accuracy is achievable.

The newer techniques are satellite based. The breakthrough came in 1957 with the launch of the first artificial satellites. The main idea is that if it is possible to position objects in predictable orbits around the earth then it is possible to calculate the position of an

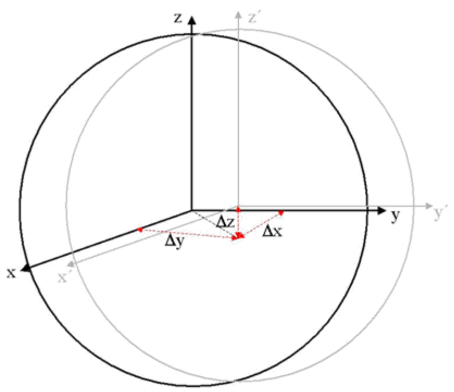


Figure 3 The datum shift.

observer on earth. The present approach to the use of satellites for positioning is the NAVSTAR, usually known as the global positioning system, GPS.

The Global Positioning System

The GPS is a military system (US Department of Defence) but provides civilian users with both navigation and surveying data. Compared to conventional positioning systems the GPS has some advantages because it is weather independent and is available 24 hours a day, because positions are given directly in a global reference system[20] and because it is relatively fast and cheap. This is a short presentation, which aims only at providing the understanding necessary for the purpose in this study. The information is retrieved mainly from Blankenburgh, Leick (1995) and Smith (1997).

The main method for positioning is to measure the distance between the observer and three or more satellites with known positions. Thus three factors have to be known to decide a position: the signal frequency, the time used by the signal to travel from the satellite to the observer, and the position of the satellites (described by the ephemerides) at the time of signal transmission. Both time and ephemerides information[21] are part of the signal transmitted.

Two different services are provided by the GPS. They are the Precise Positioning Service and the Standard Positioning Service. Originally these served military users (10-20 m accuracy) and civilians (20-30 m accuracy) respectively. The difference in accuracy is due to different codes modulated on the carrier frequencies of the signal. These codes are pseudo random noise (PRN) codes. They appear randomly, but actually follow a predictable sequence in which they weaken the precision of the receiver accuracy.

The positioning accuracy is further influenced and reduced by the effect of other elements. Five of these are: the satellite, the signal and the atmosphere, the receiver, selective availability (cf. below) and the datum[22] (Smith 1997).

The orbit of the satellite has to be known precisely but is influenced by such factors as the earth's gravitational attraction, ocean and earth tides. Such errors are tentatively predicted

[20]The global reference system of the GPS is the datum World Geodetic System of 1984 (Smith 1997).
[21] This information is part of the navigation message which is modulated on the carrier frequencies and also contains information on clock behaviour and system status.
[22] The datum mainly influences the height accuracy, hence it is not discussed here.

by global models, are broadcast by control stations, and are expected to decrease as the models get better.

Both the ionosphere and the troposphere can delay the signal, thus contributing to an error of several meters. Shading of antennae by mountains, buildings etc. also influences the transmission of the signal and reduces accuracy.

The receiver is subject to both clock errors and atmospheric effects. The time difference between receiver's clock and satellite's clock is the basis for estimating the distance between them. Any discrepancy between these two clocks will directly affect the range by an amount related to the velocity of the signal.

Selective Availability (SA) is an operator-introduced error that degrades the positioning accuracy of the Standard Positioning Service by manipulating the clock and the satellite ephemerides information. The SA has been operating permanently on some of the satellites since 25 March 1990. The SA can, however, be reduced if required by military operations.

In spite of all these sources of reduced accuracy, civilian users are supplied with an accuracy that is within 100 m 95% of the time.

New techniques are being developed to reduce the effect of these sources of error. Differential GPS is one such technique: two receivers are used together, ideally one of them operating at an accurately known position. Hence positional error sources, such as SA and PRN codes, can be quantified and subtracted to achieve very accurate positions. However, atmospheric or shadowing effects cannot be removed this way.

Satellite data as a historical information source

Remote sensing is a broad concept. One definition is "the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area or phenomenon under investigation" (Lillesand and Kiefer 1994). This definition catches a variety of processes; using both eyes and ears in an information gathering process will be remote sensing by this definition.

As distinguished from remote sensing by living organisms, the present, instrumental remote sensing technologies have a device/sensor that is physically separate from the interpreters of the data. Satellite remote sensing data are data collected by a sensor that measures radiometric energy and is located on a satellite. Satellite data can be processed in several ways, and can also usually be displayed as an image. The use of a radiometric sensor to create images has, however, a long history as compared to the short history of satellite data (Estes and Cosentino 1989). As the technology and its uses have developed, there has been a parallel shift in the platform, from balloons, to rockets, to aeroplanes, to today's satellite. The first civilian satellite carrying radiometric sensors, later known as the Landsat-1 satellite, was launched in 1972.

Dry-land degradation and satellite remote sensing

The launch of the Landsat-1 satellite took place in the first decade of the 'desertification' debate. At the time of this launch there was considerable optimism concerning the contribution of satellite data to environmental monitoring (Prince *et al.* 1990) and in particular to early warning of drought and famine (pers. com. K. Krzywinski). In 1981 another satellite was launched, *viz.* the NOAA with its sensor, the AVHRR. This satellite has contributed significantly to the monitoring of the Sahelian environment. Some characteristics of the satellites most commonly used to monitor drylands are shown in Table 5.

Table 5 Some characteristics for the most commonly used satellites monitoring drylands

Sensor	Satellite	Operating years	Coverage cycle[23]	Frame coverage	No. of Bands		Ground resolution
					Visible	Infrared[24]	
MSS	Landsat 1-5	1972-1992	18 or 16	180km^2	3	1	80m^2
TM	Landsat 4-	1982-	16	180km^2	3	3	30m^2
HRV-XS	SPOT	1986-	26	60km^2	2	1-2	20m^2
AVHRR	NOAA	1981-	12 hours	2400km^2	2	2-3	1.1 km^2

For those working with remote sensing, the choice of platform and instruments is a choice of price, coverage and resolution. Three types of resolution have to be considered; spatial, temporal and spectral resolution. The spatial resolution, or the pixel size, is defined by the **I**nstantaneous **F**ield **O**f **V**iew (IFOV, cf. p. 29) and the altitude of the sensor. Thus the pixel is the smallest element in the image, and any features smaller than this element can't be visually distinguished from their surroundings. The temporal resolution is set by the type of satellite orbit, and the spectral resolution is determined by the number and widths of the bands/channels selected.

[23] Combination of the cycles of different satellites and tilting of the sensors (not MSS and TM) can reduce the time between coverage of an area.
[24] The number varies for some sensors, as seen on HRV-XS and AVHRR.

Common to all satellite remote sensing is the large amount of spatial and temporal data supplied. This is of utmost importance when studying large-scale processes. Therefore, gathering satellite remote sensing data is recognised as the only satisfactory way both to obtain systematic regional observations and to undertake spatially comprehensive monitoring of the Sahelian environment (Prince *et al.* 1990). The satellites that have contributed to the Sahelian and dryland monitoring can be divided into two groups.

The first group consists of the NOAA AVHRR series. It has a high temporal but coarse spatial resolution, which gives a great coverage for each frame, *i.e.* an overview of a large region/area. It is possible to extract a full Sahelian coverage every tenth day and thus to monitor seasonal variations and to compare different years. Tucker *et al.* (1991) compared seasonal vegetation images based upon NDVI (see Table 9) between 1981 and 1989 and found that one of the most characteristic features of the Sahel is the large variation between years. Other studies too have reached similar conclusions (cf. p. 6).

These studies were made in a response to and as a contribution to the desertification debate. Although they contribute to large-scale information, their information content on change (cf. p.15) is minimal or at least difficult to assess. The great variability in vegetation shown by the AVHRR studies is due to natural fluctuations in annual herbs/ephemerals and is not connected to processes of change. Perennial vegetation is widely scattered in drylands, and within the one million square meters of the NOAA-AVHRR pixel it is almost impossible to detect changes in this vegetation. This very low and scattered vegetation cover will disappear in the other background pixel information. Although they are different from Lamprey's (1988) study; since comparable data sources are applied, they are equal in status when it comes to assessing change – both approaches are of little use.

The other group of satellites consists of MSS, TM and, to some extent, SPOT HRV-XS[25]. These sensors monitor smaller areas (180 x 180 km and 60 x 60 km) but have finer spatial (between 400 and 4000 square meters) and a poorer temporal resolution. A more detailed spatial impression of vegetation is given. Thus, in many cases local studies are more interesting; and a long-term aspect can be approached since time coverage extends back to 1972. This long-term view is an important aspect in studies of vegetation change. Thus, many of the studies based on these sensors have highlighted the occurrence of perennial

[25] Today also other satellite data, such as from IRC 1 and Nimbus, are of high spatial resolution and offer therefore a great potential for future studies of dryland vegetation and change.

arboreal species (Christensen 1998, Franklin and Hiernaux 1991, Franklin *et al.* 1991, Helldén 1984, 1988, Krzywinski 1993a, 1993b, Larsson 1993, Olsson 1985, and more studies are summarised in Prince *et al.* 1990). This type of research has highlighted the spectral characteristics of different species of trees and the correlation between different tree-size/ biomass measures and spectral indices as well as temporal changes and estimation of removed biomass.

The kind of study it is possible to complete is closely connected to the type of satellite data acquired. A detailed change study requires high spatial resolution but also data over a long time scale. The only data presently fulfilling both these requirements are Landsat data.

The Landsat Program

The following information has been retrieved mainly from Colwell (1983), Harris (1987) and Lillesand and Kiefer (1994).

From 1972 until today, 7 Landsat satellites have been launched (Table 6) under the Earth Resource Technology Satellite Program. At the outset the Earth Resource Technology Satellite Program was a part of the NASA satellite program. The program was developed as a response to the observations and deductions from the Mercury and Gemini orbital flights.

Table 6 The Landsat satellites

Satellite	Launched	Decommisioned
Landsat1	July 23, 1972	January 6, 1978
Landsat2	January 22, 1975	February 25, 1982
Landsat3	March 5, 1978	March 31, 1983
Landsat4	July 16, 1982	Standby mode since Dec. 14, 1993
Landsat5	March 1, 1984	-
Landsat6	October 5, 1993	Failure upon launch
Landsat 7	April 15, 1999	-

The technical characteristics, both of sensors and choice of orbit, were formed by the needs of two of the potential users, the United States Geological Survey and the United States Department of Agriculture. The orbit characteristics became a compromise between the geologists' need for long shadows and the maximum illumination required by the agricultural department. Finally, a mid-morning equatorial crossing time was selected to avoid the alternative mid-afternoon clouds. On the sensor issue, however, no agreement was reached; and this resulted in there being two sensors on the first generation, Landsat 1-3, satellites. The geologists got their **R**eturn **B**eam **V**idicon, the RBV, and the agricultural department its **M**ulti**S**pectral **S**canner, the MSS. On the second-generation satellites, Landsat 4 and onwards, the **T**hematic **M**apper, the TM, replaced the RBV. This is an improved version of the MSS, both spectrally and radiometrically and in its resolution. Landsat 7 has one sensor only, the **E**nhanced **T**hematic **M**apper Plus (ETM+)[26].

In the further description of the sensors only MSS and TM are highlighted because these are the ones applied in this study.

Landsat general characteristics

All of the Landsat sensors are passive; they register reflected sunlight. The sun-synchronous orbit (Fig. 4) secures equal sun conditions since the satellite observes the same area at the same time whenever it crosses it. The orbit is near-polar and repeating. A near polar orbit has its limitations, however, for observation north of a certain latitude is impossible. In the case of the Landsat satellites this limit is at about the 82^{nd} parallel of latitude.

After a certain time period the orbit repeats itself, giving new observations from exactly the same area as the satellite has registered before. The time period is slightly different between Landsat 1 - 3 and Landsat 4 - 5, and this is one of the reasons for the distinction between two Landsat generations. Other differences between the two generations of Landsat satellites are given in Table 7.

Table 7 Some differences between the two Landsat generations.

	Landsat 1-3	**Landsat 4-5 (7)**
Altitude	913 km[27]	705 km
Orbital cycle	18 days	16 days
Equatorial crossing time (40^o N)	9:30	10:30
Sensors	RBV & MSS	MSS &TM
MSS resolution	56m x 79m	56m x 81,5m

The lower orbit of the second-generation satellites makes them retrievable by the Space Shuttle and simplifies problems associated with achieving the higher resolution of the TM.

All Landsat images are catalogued according to the **W**orld **R**eference **S**ystem, the WRS, where each orbit within a cycle is designated as a path. The centre of each frame is designated as a row.

[26] According to the plans, ETM+ has a 15m-resolution, panchromatic band in addition to the other bands of the TM. However, some improvements have been made (Lillesand and Kiefer 1994).

[27] 913km is the height given in Colwell (1983), while 900 km is the height given in Lillesand and Kiefer (1994), specified to vary between 880 and 940 km.

The across-track scanning sensors

Both the MSS and TM are across-track or whiskbroom scanners. The basic principles of this sensor type is a moving scanning device, a rotating or oscilliating mirror that scans the terrain along scan lines that are at right angles to the flight line (Lillesand and Kiefer 1994), see Fig. 5.

The energy to be detected is seen within the system's IFOV, described by the dimensions of the detector's fiber optics (Lillesand and Kiefer 1994), see eq. 1.

Equation 1 The IFOV of the sensor.

$D = H\beta$

Where:
D = diameter of the circular ground area viewed
H = sensor height above the terrain
β = IFOV of the system, expressed in radians

The incoming energy is separated into different spectral bands. The spectral bands of the MSS and TM are described in Table 8. The bands on Landsat 1 - 3 were numbered from 4 to 7 since the band numbers 1 - 4 were applied to the RBV. In this study all MSS bands are referred to as MSS1 - MSS4.

Figure 4 The sun-synchronous orbit, retrieved from Lillesand and Kiefer (1994).

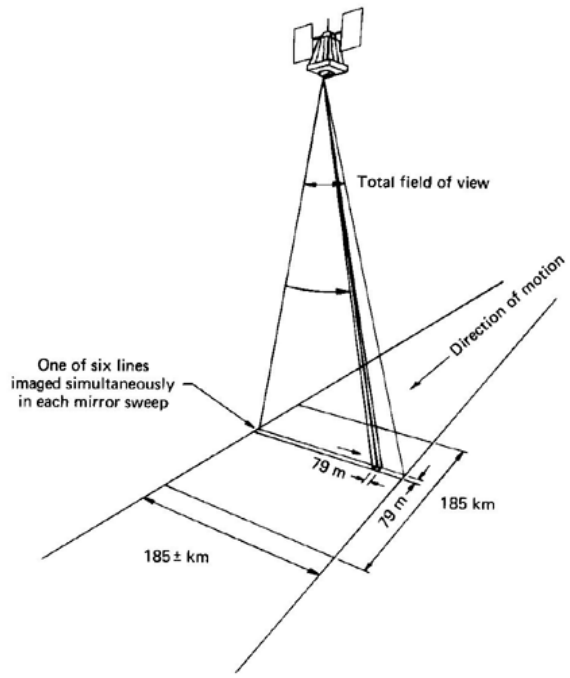


Figure 5 The across tracking scanner examplified by Landsat MSS, retrieved from Lillesand and Kiefer (1994).

Table 8 The spectral bands of MSS and TM

Instrument	Band1 (mm)	Band2 (mm)	Band3 (mm)	Band4 (mm)	Band 5 (mm)	Band6 (mm)	Band7 (mm)
TM 10	0.45-0.52	0.52-0.60	0.63-0.69	0.76-0.90	1.55-1.75	10.4-12.5	2.08-2.35
MSS	0.5-0.6	0.6-0.7	0.7-0.8	0.8-1.1			

In each band detectors register radiance values within a maximum and minimum radiance level (L_{max} and L_{min}). An **A**nalog-to-**D**igital (AD) converter calculates the digital numbers from the radiance values. The converter can have different bit-levels. While the AD-converter of the MSS is 6 bits, the TM converter is 8 bits. The analog to digital conversion is completed before data transmission to the ground receiving station. Connected to the detectors is a calibration device (Colwell 1983, Markham and Barker 1987), usually calibration lamps and a shutter. After scanning a line the detectors are exposed to the calibration lamps, and these data are saved and used in the ground processing of the data.

MSS

The scanning device of the MSS is an oscillating mirror that scans in the cross track direction with a swath of 185 km, see Fig. 5. Six lines are scanned simultaneously in each west-east mirror sweep. The mirror focuses the scanned ground cover in the focal plane. In this plane 24 light-pipes are arranged in a 6 x 4 array. Six light pipes are vertically arranged for each of the four bands. Each light pipe leads to a filter-detector arrangement that responds to the radiance focused on it. Each detector views an area two ground pixels to the west of the band immediately preceding on its line. The dimension of the fiber-ends provides the angular IFOV. In the case of the first generation sensors the IFOV is 0.086 mrad (11,56°) which gives an area of 79 square meters. However, there's a discrepancy between this IFOV and the actual pixel size of 56 x 79 square meter.

The oscillating mirror sweeps across the terrain at a speed of 5,612 m/µs. Every 9.958 µs an electrical output of each detector is sampled (Colwell 1983). Thus the detectors' focus moves only 56 m between each electrical sample. This gives an actual pixel size of 56 x 79 m^2, but the brightness value of the pixel is derived from the square of 79 x 79 m^2. In practice, this means there is an 11 m overlap between two pixels; the ground features of these 11 x 79 m^2 are sampled in both the neighbouring pixels, see Fig. 6. This over-sampling of pixels also occurs in the MSS of Landsat 4 and 5, but with a slightly different IFOV: (14,92°) 81.5 m x 81.5 m, giving a final pixel size of 56 x 81.5 m^2. This problem is, however, avoided in the TM which gives a pixel size of 30 m^2.

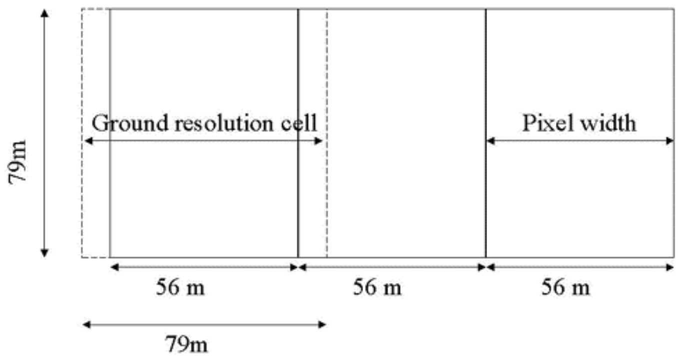


Figure 6 The discrepancy between ground resolution and pixel size, modified from Lillesand and Kiefer (1994).

The detectors of the MSS are of different types. Bands 4, 5 and 6 have **P**hoto **M**ultiplier **T**ubes (PMT) as detectors, while band 7 has silicon detectors. The noise level of the PMTs limits the system signal/noise performance at high light levels. At low light levels the limiting factor is quantization noise.

All MSS have an internal calibrator system consisting of a pair of lamp assemblies and a rotating shutter wheel (Markham and Barker 1987). The shutter blocks off light during scan retrace, and the lamps output a light pulse that rises rapidly. This pulse, also called the calibration wedge, saturates all the detectors for a short while; and it is samples from this calibration wedge that are used for the ground processing calibration. Similar samples were taken before the satellites were launched to calculate pre-launch gains and offsets; and if different, these new ones are also taken into consideration in the calibration process.

TM

The TM differs from MSS in a number of details. There are more bands, and equivalent bands are narrower giving an improved sensitivity. Also the resolution is improved to 30 m. Moreover, to attain higher resolution a number of improvements were made to the scanner. There is a second set of scanning mirrors, and scanning is performed in both directions. In each of the reflective bands there are sixteen detectors. In the thermal band, band number six, there are only four detectors, hence the 120 m resolution of this band. The optical bands (1-4) have silicon detectors and are focused onto a prime focal plane. The detectors of band 5 to7 are cooled ones, focused on the cooled focal plane to obtain the required sensitivity. Bands 5 and 7 have InSb[28] detectors, while band 6 has HgCdTe[29] detectors.

The internal radiometric calibration system for the TM reflective bands consists of three calibration lamps and a shutter. The calibration data is analysed to determine the actual gains and biases. Before applying these to all the detectors, all detectors are equalised such that each histogram has the same mean and standard deviation as the overall band histogram.

Vegetation monitoring

A general introduction -the green case

Vegetation interferes with sunlight in several ways. Especially in areas of high vegetation density the leaf is the most characteristic and influential component of this interference.

A plant leaf (see Fig. 7) is a highly specialised structure adapted to photosynthetic activity. It consists mainly of four different layers, an upper and lower epidermis, a layer of elongated parenchymatic cells and a layer of spongy mesophyllic cells. Especially in the latter layer large air filled volumes predominate between cells. The epidermis, with its stomatal cells, secures gas exchange (CO_2, O_2) and is largely transparent to incident **P**hotosynthetically **A**ctive **R**adiation (PAR; 0.4-0.7µm). The chloroplasts in the parenchyma cells do the solar energy absorption, while the hydrated mesophyll cells contribute water to photosynthesis.

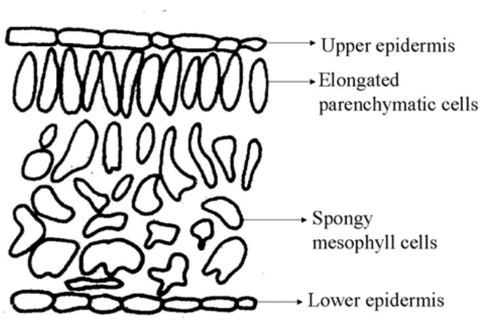


Figure 7 Schematic cross section of typical citrus leaf (after Harris 1987)

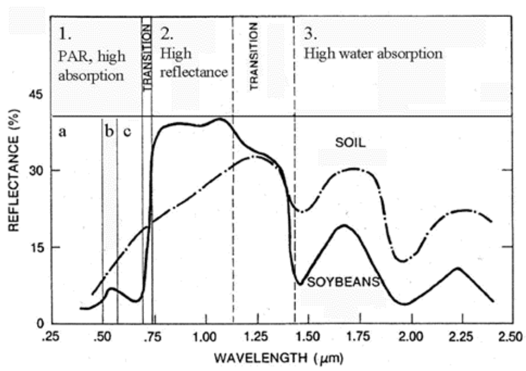


Figure 8 Leaf and soil hemispherical reflectance (after Tucker and Sellers 1986).

[28] Indium antimonide
[29] Mecury cadmium telluride

The function (photosynthesis) and structure of the leaf generate a special spectral signature, as illustrated in Fig. 8. From this figure it is possible to recognise three main regions of hemispherical reflectance.

1. In the region of PAR (sub-regions a-c) the leaf absorption is very high, due to the pigments of chlorophyll a and b, and the caretenoids in the chloroplasts. The Red wavelengths (0,62-0,70 μm) usually stand in the strongest contrast to soil reflection due to high chlorophyll absorption. Another factor increasing the pigment absorption is the high scatter[30] of the PAR, giving pigments multiple chances to absorb the active wavelengths.
2. Between 0,74-1,1μm, in the near-IR region, the reflectance is very high. Thus absorption is minimal, and scattering amplifies the spectral reflectance, especially for dense canopies. The sub-region from 0,79-0,90 μm is considered most appropriate for monitoring vegetation because it avoids atmospheric water vapour absorption. The reflectance can reach fifty per cent on the 'IR plateau', the level of which depends on the internal structure of the leaf. The level increases with the number of layers of cells, their size and the orientation of cell walls (Guyot and Riom 1988).
3. In the region of 1.3-2.5 μm, mid-IR there is high absorption due to the liquid water of the mesophyllic cells.

As seen from Fig. 8, soil reflectance increases steadily over visible and near-IR wavelengths; and in the mid-IR wavelengths it oscillates like, but above, reflectance from vegetation. Potentially the best regions to obtain vegetation information separately from background information are thus the Red and the near-IR (0,79-0,90 μm) which are closely connected to chlorophyll density and green leaf density respectively (Tucker and Sellers 1986). A multi-spectral, optical satellite image is usually displayed as a false colour composite of three layers: a blue, green and red layer. The IR channel is normally displayed in the red layer, and the Red channel in the green; and this combination of high values in the red layer and low values in the green layer gives vegetation a red colour.

The hemispherical reflectance of leaves is not, however, the only factor influencing the vegetation canopy reflectance. Colwell (1974) mentions several other parameters which

[30]High scatter is due mainly to differences in the refractive index between the air spaces (1.0), hydrated cells (1.4), and the irregular facets of the exteriors of cells.

can change vegetation canopy reflectance even if the leaf hemispherical reflectance remains constant, or vice versa. These parameters are important at different levels and to a varying extent:

1. Leaf hemispherical transmittance: This parameter is correlated to hemispherical reflectance of leaves but is different for Red and IR wavelengths. Red is positively correlated, while IR is negatively correlated. Changing leaf- condition or structure (*e.g.* stress, drought, or species composition), while all other canopy characteristics remain constant, may not change IR canopy reflectance because the change in reflectance is partially compensated for by the transmission change. The same case will, however, give a significant change in the Red canopy reflectance. This influence is mainly on the species and individual level.

2. Leaf area and orientation: A change (smaller leaves or more vertical orientation of the leaves) in one or both of the parameters might increase Red and decrease near-IR reflectance, making vegetation approach the soil reflectance curve. These parameters are important at the individual level.

3. Hemispherical reflectance and transmittance of supporting structures (stalk, trunks, limbs, petioles): Guyot and Riom (1988) have studied the reflectance of bark on spruce. The reflectance increases progressively from visible to mid-IR and resembles soil reflectance. When the density (of needles) is low, the effect of bark reflectance is particularly sensitive in the near-IR and mid-IR (Guyot and Riom 1988).

4. Effective background reflectance: Its importance increases as coverage becomes thinner, and its influence changes with different background types. The effect is local.

5. Angular effects: Three angles are important for the registered reflectance; solar zenith angle, look angle and azimuth angle; and their effects are inter-related. Solar zenith angle is the angle between the direction of incident sunlight and the vertical line from nadir to zenith. Look-angle is similar to zenith angle, but is defined by the sensor. Both of these angles can vary within their planes, and it is the angle between these planes that the azimuth angle describes. These angles are illustrated in Fig. 9. The solar zenith angle changes daily and yearly. When vegetation coverage rises beyond a certain threshold, the reflectance is saturated and thus insensitive to a further increase in coverage. This point of insensitivity to greater vegetation coverage varies with the solar

zenith- and look-angles. If the zenith angle increases while the look-angle is kept at 0° (nadir viewing), the point of insensitivity is at a lesser coverage (the same reflectance is registered for vegetation coverages that it was possible to distinguish with a smaller zenith angle). The same trend is seen if the solar zenith angle is kept constant and the look angle increases. The sensitivity of the IR band is greater than that of the Red band. Also, the effects of the azimuth and look-angles has to be considered together. If the azimuth is 90°, a change in look-angle gives a symmetrical spectral response around the nadir axis. However, the symmetry is different for visible and IR wavelengths. If the azimuth is 180°, looking up-sun, it gives a lower reflectance than when looking down-sun, *i.e.* when the azimuth is 0° (Colwell 1974, Guyot and Riom 1988).

6. A last factor influencing the final reflectance or digital number (DN) of the pixel is its size. High spatial resolution better reflects the diversity of the environment monitored, while increasing the pixel size better catches the homogeneity of the environment. Observed variability is reduced as the pixel size increases.

Most methods for monitoring vegetation are based upon the characteristic differences between the leaf hemispherical reflectance of the visible and IR region. Plotting the Red – IR data-space for a vegetated surface draws a characteristic feature, commonly known as the ‘tasseled cap’. This is illustrated in Fig. 10, and the outlined feature is explained by the high IR DNs accompanying the low Red DNs. Jasinski and Eagleson (1989) discuss the structure of the red-IR scatter-gram using a linear stochastic geometric canopy-soil reflectance model for semi-vegetated landscapes. They recognise two axes, the first, known as the soil line, is a result of the correlation of soil over different wavelengths. The second

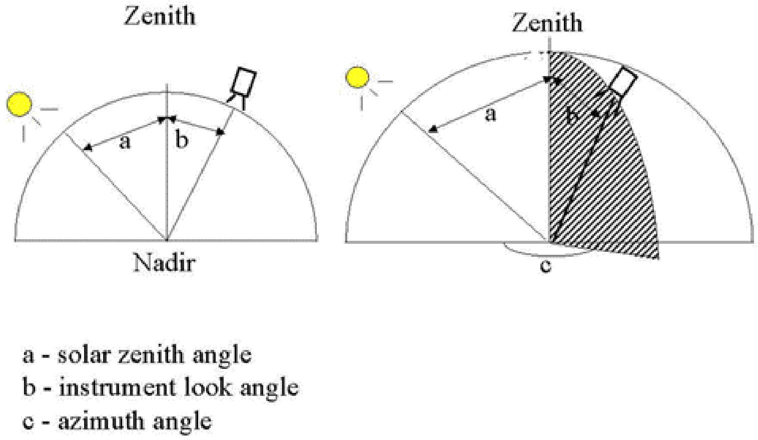


Figure 9 The three angles that influence registered reflectance.

axis, orthogonal to the first, indicates increasing vegetation coverage (see Fig. 11b). A third "canopy" line can sometimes be discernible as an envelope curve along the top, in which case it indicates differences in vegetation reflectance caused by parameters, such as those referred to by Colwell (1974). Some of these parameters are specific to the species registered.

The Red and IR wavelengths are combined into different indices to relate registered reflectance to vegetation parameters. Several authors sum up the different indices that are in use (Estes and Cosentino 1989, Olsson 1985, Perry Jr. and Lautenschlager 1984, Tucker 1979) and Perry Jr. and Lautenschlager (1984) mention 48 different versions of vegetation indices. Such indices are used to amplify the vegetation characteristics, by normalising data and thus reducing topographical effects; and also the amount of data is reduced to one dimension only. Broadly these indices can be grouped into three different types; difference indices, ratio indices and orthogonal indices.

The 'difference indices' calculate the difference between the IR and Red reflectance. A high positive difference is characteristic for vegetation cover.

The different 'ratio indices' are basically variations on the simple ratio between IR and red. The addition of constants, squaring or taking square roots are common operations performed to normalise output values (*e.g.* to give positive values only, or values only between 0 and 1). All of the indices do, however, produce lines radiating out from an origo in the data-space, see Fig. 11a. Pixels on one such line have similar vegetation indeces.

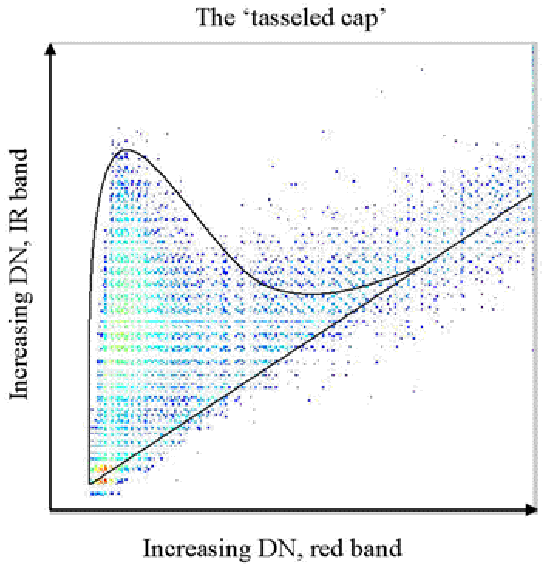


Figure 10 The tasseled cap of the IR-Red data-space (data are extracted from a mid-summer MSS data-set from Western Norway)

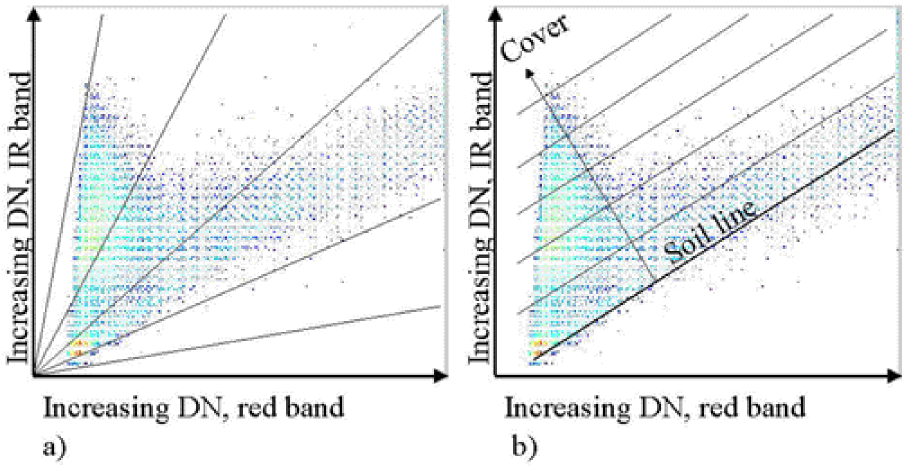


Figure 11 Basis for interpretation of different types of vegetation indices: a) ratio indices, b) orthogonal indices.

This type of index effectively normalises spectral variations both in soil background (Colwell 1974) and in irradiance conditions (Tucker 1979). However, they overestimate vegetation cover over dark soils and underestimate it over bright soils (Elvidge and Lyon 1985).

The ‘orthogonal indices’ are based upon the observation that soil or background plots on a single soil line and from this line vegetation emerges orthogonally (Richardson and Wiegand 1977). Thus variations in soil and vegetation are described by orthogonal axes. Both the two-dimensional red-IR data-space and a n-dimensional data-space of all channels from the sensor can be the starting-point for an analysis. Different methods, such as linear regression, principal component analysis (PCA) and Gram-Schmidt orthogonalisation[31], are used to find the axes of variation. The first axis coincides with the soil line and explains most of the variation in the data set. The second axis indicates increasing vegetation cover. The units of these vegetation indices are therefore parallel to the soil line, see Fig. 11 b.

These types of vegetation indices are therefore quite distinct when it comes to interpreting the Red – IR data-space. However, only small differences are seen between studies using one or the other vegetation index, regardless of whether a comparison is between or within the groups (Perry Jr. and Lautenschlager 1984). The same authors also point out the

[31] In a PCA the experimenter imposes no prior order physical interpretation on the principal directions. A Gram-Schmidt orthogonalisation does, however, allow the experimenter to influence the process by choosing the order in which the calculations are performed (Perry Jr. and Lautenschlager 1984).

functional equivalence of many of the indices used. Some of the most commonly applied indices are given in Table 9.

Table 9 Vegetation indices commonly used.

Name	Description
VI; (simple) **V**egetation **I**ndex	IR / Red (both IR channels have been applied; *i.e.* MSS3 and MSS4)
DVI: **D**ifference VI	(2.40MSS4) – MSS2
NDVI: **N**ormalised DVI	(IR-Red)/(IR+Red) (both IR channels have been applied)
TVI; **T**ransformed VI[32]	√(((IR-Red)/(IR+Red))+0.5) (both IR channels have been applied)
GVI; **G**reenness VI	-0.29xMSS1 - 0.56xMSS2 + 0.60xMSS3 + 0.49xMSS4
PVI; **P**erpendicular VI[33]	(IR-a(Red)-b)/√(1+a^2) (both IR channels have been applied)
SBI; **S**oil **B**rightness **I**ndex	0.433xMSS1 + 0.632xMSS2 + 0.506xMSS3 + 0.264xMSS4

Vegetation monitoring in dry environments

In dry regions the permanent vegetation cover is low and thinly scattered. The photosynthetical areas of plants can also be smaller (*e.g.* smaller or fewer leaves) and maybe have lower activity (cf. Adaptations of hot desert plants, p. 10). Consequently, branches and trunks constitute a greater part of the vegetation picture. The importance of such non-green parts is recognised by Colwell (1974) and Olsson (1985). The background too is highly visible, and the shadow cast by vegetation is more apparent. Therefore, two background components, colour and shadow, are of very great importance in dry regions and are further increased by the high transmission of tree canopies. Franklin *et al.* (1991), working in a Sahelian environment, registered that between 54 and 87.5 percent of incident radiation in Red and n-IR was transmitted to the ground.

Several authors have reported lower a sensitivity for near-IR reflectance and for vegetation indices including it when monitoring vegetation (Chavez and MacKinnon 1994, Matheson and Ringrose 1994, Olsson 1985, Otterman *et al.* 1974, Pickup *et al.* 1993). Olsson (1985) and Colwell (1974) even find a negative correlation, completely inconsistent with the theory of high near-IR scatter for green leaves. Larsson (1993), however, estimating canopy cover in *Acacia* woodlands, found NDVI to give the highest correlation in an area where field-measured canopy cover ranges up to 60%.

The Red band is reported to have good correlation, both with vegetation cover and biomass (Chavez and MacKinnon 1994, Olsson 1985, Pickup *et al.* 1993) but lacks its usual local minimum Olsson (1985) (see Fig. 8).

[32] An alternative formula is suggested by Perry Jr. and Lautenschlager (1984).
[33]PVI is defined as the perpendicular distance between the candidate vegetation point and the soil background line in the IR-Red data space; a and b are regression coefficients.

The IR and Red band characteristics over a tree and its sunlit and shadowed background have been studied by Franklin *et al.* (1991). Red reflectance of vegetation canopy has the lowest reflectance, whether sunlit or not, as compared to both sunlit and shadowed background. The Red correlation is well explained by a shadowing effect (Franklin *et al.* 1991). Since vegetation is dark in the Red spectrum, dark shadows amplify the vegetation signature.

However, IR reflectance does not behave that consistently. It is highest for sunlit canopy, while shadowed canopy is at about the same level as reflectance from a sunlit background, and shadowed background is slightly lower than for a sunlit background (*op. cit.*). The negative correlation that sometimes exists between IR reflectance and vegetation cover is also explained by the effect of shadow; it is found when increases in vegetation cover are accompanied by increases in the amount of shadow (Colwell 1974). The effect of shadow is, however, greater in the Red- than in the IR- spectral region, and artificial differences can therefore occur in band ratios (*op. cit.*).

Soil background reflectivity often exhibits great variability in semi-vegetated scenes, both on small and large scales. The interpretation of spectral vegetation data is facilitated by an equal background which is visualised by a constant soil line. A constant soil line exists only under two conditions (Jasinski and Eagleson 1989):

1. "there is only one dominant type of soil variability", or
2. "the scatter due to different types of soil variability act in the same direction"

In their study Elvidge and Lyon (1985) conclude that one orthogonal index, the PVI is the best available vegetation index to use in multi-spectral imagery of arid and semi-arid regions because it copes with the wide variation in rock and soil characteristics that occur there.

On the other hand, it is reported that there is no single soil line and that differences in soil background in partly vegetated areas will produce changes in index values, even though the amount and type of cover remain the same (Pickup *et al.* 1993). Also for the Red band equivalent cover is reported to have a different reflectance when measured over light or dark backgrounds (Colwell 1974). Colwell (1974) even finds the Red correlation to be restricted to light soils only. He measured grass cover over both light and dark soils, and for the latter the Red reflectance was insensitive/uncorrelated.

In the n-IR spectral region, however, a very bright background gives high reflectance whether vegetation is present or not; *i.e.* a change in vegetation cover gives only a minimal change in brightness in the IR band (Chavez and MacKinnon 1994). This is also affects derived vegetation indices, *e.g.* NDVI, which will not change much even if vegetation cover changes (*op. cit.*).

This difference in the sensitivity of the Red and IR spectral regions to variation in background characteristics can make spatial comparisons difficult unless the soil characteristics are known and included in the interpretations. A temporal comparison should, however, be possible if it is reasonable to assume that background reflectance is constant during the period considered.

Geometric correction of images; image rectification and resampling

There are both technical and practical reasons for performing a geometric correction of images. Some technical factors that distort image geometry (Lillesand and Kiefer 1994, Richards 1986) are given in Table 10. These factors can be either systematic or random. A systematic factor can easily be modelled and thus corrected separately. One example is the error caused by the rotation of the earth, where de-skewing (see Fig. 24) is the subsequent process of correction.

Table 10 Technical factors that distort image geometry

<table>
<tr><th colspan="3">Platform</th><th>Sensor</th><th>Object viewed</th></tr>
<tr><td colspan="3">Variations in stability:</td><td rowspan="2">Wide view
Finite scan rate
Non-idealities/linearities</td><td rowspan="2">Earth curvature & rotation
Relief displacement
Refraction caused by atmosphere</td></tr>
<tr><td>Altitude</td><td>Attitude</td><td>Velocity</td></tr>
</table>

Random factors, for example those caused by instability in a platform, have to be corrected by analysing well distributed **G**round **C**ontrol **P**oints, GCPs, in the image. The method of this correction overlaps with the practical part of correction in that both processes normally interpret GCPs in a well-known geographical framework. In practice a correction therefore puts the images into the same geographical framework as that of other data sources, a transformation essential for change analysis.

Geometric correction is done by a rectification and resampling of the image to the selected framework. The rectification is a regression process where GCPs are the link between image coordinates and coordinates of the selected framework. Residuals of the regression are reported as the **R**oot **M**ean **S**quare (RMS) error, interpreted as the distance between the input/correct postion and the retransformed/actual output position. The distance is calculated in pixel size.

After correction, a new pixel grid fitting the selected framework is generated. Usually, however, these two grids do not overlap spatially; *i.e.* the new pixel area covers more than that of one pixel – or parts of more than one - in the old grid. Resampling is the process of giving new pixel values. Different methods are available [34].

The nearest neighbour method takes the pixel value, the DN, of the nearest pixel, *i.e.* the input pixel that covers most of the output pixel position, and uses that value as the output value. Bilinear interpolation is a method that takes a distance weighted average of the four nearest pixels. The last resampling technique is cubic convolution. The block of sixteen pixels in the input grid that surrounds the output pixel is used to calculate the output pixel DN.

Calibration of images

One of the prerequisites for performing change analysis is that the data are comparable. While spatial comparison is facilitated by geometric correction, a radiometric correction is the measure which secures that the same ground conditions have equal radiance values or digital numbers. However, conditions at three main stages in the acquisition process make satellite data different from each other:

- Pre-satellite conditions
- At-satellite conditions
- Post-satellite conditions

Pre-satellite conditions

The atmosphere is the signal transmitter from the source, the sun, to the receiver, the satellite. In an ideal case, the satellite measured radiance would depend directly upon the ground properties (Tanré *et al.* 1990). However, both the energy source and the transmission media influence the signal received. The influence of the sun depends on different factors, *e.g.* the sun-earth distance, the sun angle, solar illumination and acquisition time.

During the signal transmission the atmosphere itself influences the signal through such processes as absorption and scattering. Due to these processes only a fraction of the photons that would be observed in the ideal case reaches the satellite sensor: 80% at 850 nm and 50% at 450 nm (Tanré *et al.* 1990). Absorption is caused mainly by molecules such as O_3, O_2, CO_2, H_2O and to a lesser extent by aerosols. Molecular absorption is mostly avoided by selecting channels in atmospheric windows. The viewing geometry of the satellite is another factor that influences absorption.

There are two main types of scattering: Mie scattering caused by aerosols and Rayleigh scattering caused by air-molecules. Both scattering processes are wavelength-dependent, but the Mie type to a lesser extent than the Rayleigh type. It is the shorter wavelengths that are most influenced. Scattering influences the signal either on the sun-surface path or the surface-satellite path, by strengthening or attenuating the signal. The actual influence of scattering along the surface-satellite path will depend on the surface properties. A homogeneous surface strengthens the signal, while a heterogeneous surface attenuates it.

At-satellite conditions

The received at-satellite radiance is then registered by the different band detectors of the sensor and converted into digital numbers. There are two factors that produce errors at this level in the process, the accuracy and stability of detectors and the internal calibration system. Detector performance is set already during the pre-launch calibrations. However, there are several factors that can degrade this process. In their review of radiometric calibration of Landsat MSS data, Markham and Barker (1987) estimate these factors to be an error source of between ±2 and ±5-10 per cent. However, also post launch variations in both vacuum-shift and temperature influence detector performance. The effect of ambient temperature on sensor gain is also mentioned by Tsuchiya *et al.* (1996). They also observed variations in gain over land, oceans and clouds, most prominently in the PMT detectors of Bands 4, 5 and 6. The internal calibration system which, in theory, corrects these changes is assumed by Markham and Barker (1987) to be the main cause of a long-term sensor drift, which they estimate to be 5-30 per cent over a three year period. Hence, a temporal drift in sensor performance cannot be satisfactorily detected and corrected. The effect seen between images (both from the same and from different sensors) is that equal ground

[34] If the pixel size is changed, new values are calculated by the same methods.

properties are registered with different DNs, also when atmospheric conditions are taken into consideration.

Post-satellite conditions

Ground processing procedures have varied, both over time (Elvidge *et al.* 1995, Markham and Barker 1987, Yuan and Elvidge 1996) and between agencies (Tsuchiya *et al.* 1996). Tsuchiya *et al.* (1996) report differences between NASA and NASDA both in the selection of a standard detector to eliminate striping and in making a conversion table based on calibration data transmitted from the satellite. Differences in ground processing between agencies supplying data in this study are also recognised.

Methods of calibration

Due to pre-, at- and post-satellite factors and their influence on the radiometric conditions within images, calibration is a prerequisite for change analysis. Two main types of calibration are possible: absolute calibration and relative radiometric calibration.

Absolute calibration converts digital numbers into the ground radiance or reflectance and then corrects for atmospheric effects. Two different approaches are possible: one using modelling, the other based on ground truth observation. The first method corrects the at-satellite radiance by modelling the atmospheric influences (Tanré *et al.* 1990). A correction for instrument and ground processing differences would, however, be necessary in advance of the absolute calibration when the input images come from different sensors and/or agencies. This would be very cumbersome if the image material were large and acquired under different atmospheric conditions, for correction would require information on sensor calibration and atmospheric properties that are not readily available (Pickup *et al.* 1993).

The ground truth approach uses ground reflectance measurements during the satellite overpass to establish a relation between ground reflectance and at-satellite radiance or image digital numbers. Usually change analysis is planned in the present using material from the past; hence a ground truth approach is impossible for all of the images.

A relative calibration, or **R**elative **R**adiometric **N**ormalization (RRN) (Elvidge *et al.* 1995, Yuan and Elvidge 1996) uses one image as a reference and adjusts slave images to the radiometric properties of the reference. This approach thus avoids any ground truth or supplementary information gathering on the pre-, at-, or post-satellite conditions. Different

RRN-algorithms have been developed and applied. Some of these are presented in Table 11.

Table 11 Some radiometric normalisation techniques applied by different authors.

Radiometric Normalisation	**Used by**
No Change Normalisation	Elvidge *et al.* (1995), Mas (1999), Yuan and Elvidge, (1996)
Selective PCA	Chavez and MacKinnon (1994)
Normalisation Targets	Eckhardt *et al.* (1990), Jensen *et al.* (1995)
Haze Correction	Lillesand and Kiefer (1994), Yuan and Elvidge (1996)
Minimum Maximum Normalisation	Yuan and Elvidge (1996)
Mean Standard Deviation Normalisation	Yuan and Elvidge (1996)
Simple Regression Normalisation	Colwell (1983), Yuan and Elvidge (1996)
Dark set – Bright set Normalisation	Hall *et al.* (1991), Yuan and Elvidge (1996)
Pseudo-Invariant Feature Normalisation	Yuan and Elvidge (1996)
Histogram Equalisation	Chavez and MacKinnon (1994), Yuan and Elvidge (1996)

AREA AND STUDY LOCALITIES

Deserts: Causality and geographical distribution

Despite difficulties in defining a desert, the main deserts of the world are recognised by most authors (*e.g.* Goodall *et al.* 1979, Louw and Seely 1982, McGinnies *et al.* 1968). Their geographical pattern may be explained by three main causes of aridity (Reitan and Green 1968) acting separately or in combination.

1. Separation of a region from sources of oceanic moisture by topography or by distance
2. Lack of storm systems, *i.e.* the mechanisms that cause convergence, create unstable environments, and provide the uplift necessary for precipitation
3. Formation of dry, stable air masses that resist convective currents. Stability can be caused by large scale atmospheric motions (a pressure and wind system), *i.e.* the subtropical high pressure cells (Hadley cells)

From these causes a broad classification of deserts is derived (Cloudsley-Thompson 1984). Four groups are mentioned: sub-tropical deserts, cool coastal deserts, rain-shadow deserts, and interior continental deserts. Of these only the sub-tropical is discussed further here.

Sub-tropical deserts are typically found in the western and central parts of the different continents. Winds are easterlies, and except in cases of high continentality or a shading effect, a certain distance from the sea is required before oceanic moisture is lost. A core of hot deserts is found between 20° and 25° North and South. Sub-tropical deserts are also found outside these limits but normally within 30° North and South. The fluctuating **I**nter-**T**ropical **C**onvergence **Z**one, ITCZ, is decisive for the geographical location.

The General Circulation of the Atmosphere, caused by the world pressure and wind systems, determines the position of the ITCZ. Hadley cells are cells of circulating air and constitute the main units of the world pressure and wind system. Trade winds gather moisture at the equator; and when winds rise, they cool adiabatically. Cooling of moist air results in condensation, *i.e.* moisture is lost. Thus high level winds, moving in the direction opposite to the trade winds, become relatively dry. Then these dry air masses descend over the sub-tropics and become compressed and heated. The position of the descending limb of the sub-tropical Hadley cell, determines the ITCZ.

Typically, hot deserts remain under this influence throughout the year. Other meteorological events (cyclones, monsoons, jet streams, convective storms, continentality and sea currents) and topographical factors modify or amplify the type of desert that is found.

Another global phenomenon influencing the atmosphere and thus the weather is ENSO: **E**l **N**iño – **S**ourthern **O**scilliation. It occurs in cycles of between 3-4 and 8 years (Grønås 1998). However, if El Niño persists long enough or becomes strong enough, weather conditions can be altered on a global scale. El Niño causes warm conditions and is sometimes followed by cold conditions, called La Niña. Their influences are observed primarily in the tropics and sub-tropics.

Sahara desert

The Sahara[35], which covers the northern part of the African continent (22-32°N), is the largest desert in the world. This region of extreme aridity, high temperatures and violent winds covers an area of 9.1 million square km. Such a huge area is due to a high degree of continentality in northern Africa. The Red Sea is too narrow and warm to cool and moisten the winds from the Sinai and more easterly deserts. Thus air masses are still dry when they reach the northern parts of Africa.

The Sahara extends by definition (cf. above) as far south as the 100 mm isohyet, although this has not been rigidly upheld (Cloudsley-Thompson 1984). The time of rainfall is one factor often used to differentiate between regions within the Sahara. Three regions are described:

1. In the northern part the climate is Mediterranean, receiving winter rain amounting to less than 100 mm annually.
2. In the south the scanty rain falls irregularly during summer. The climate is tropical with warm winters and hot summers.
3. In the central part there is no seasonal rainfall. Also, temperature and aridity are extreme. The mean annual temperature is above 30°C, and the average maximum temperature, more significant for plant growth, is around 40 – 45°C.

[35] An Arabic word meaning desert. Groom (1958) translates it as “A desert, a waste; a wide, flat plain”, cf. p. 8.

Although rainfall is variable all over the Sahara, the highest variability is seen in its central part. Generally, the inter-annual departure from the mean is above 40 percent; however, in the central Sahara it exceeds 80-100 % (150 % (Goudie and Wilkinson 1977), 250% in the northern Sudan (El-Tom 1975)). Variability of this magnitude makes the annual mean meaningless. Even so, it is often used to characterise the central Sahara and is reported to be less than 10 mm (Kassas and Batanouny 1984). No systematic trend in rainfall can be derived from more than hundred years of available weather records (Le Houérou 1970); thus irregularity is more important than rainfall means. It is worth considering if this irregularity is in some aspects regular and hence can be related to ENSO in one way or another.

According to Le Houérou (1970), the Sahara has four main types of landforms[36]. The first is hills and mountains. Together with the second type, the denuded rocky plateaux also called *hammadas*, they cover 10% of the land surface. Most of the land surface (60 %) is covered by the third landform, the *reg/serir*, *i.e.* are low land wind scoured plains with gravel or boulders. The fourth type is the *erg*, *i.e.* the sand dunes. Although commonly believed to dominate deserts, they cover only 22% of the surface of the Sahara.

About 1200 species contribute to the flora of the Sahara. The six largest families are *Compositae, Graminae, Cruciferae, Leguminosae, Chenopodiacae and Caryophyllacae* (Wickens 1984). Phytogeographically, the Sahara belongs to the Saharo-Arabian region with elements from both the Holarctic and the Paleotropic realms.

During short time-spans after rainfall, herbs and small shrubs predominate in the vegetation. Larger shrubs and trees, are for the most part, spatially restricted and appear where there is permanent sub-surface moisture or where ground water is found at shallow depths. Sub-surface moisture is found mainly in connection with mountains, wadis and their flood plains.

Eastern Desert; the area of interest

The Eastern Desert of Egypt is situated between the Nile and the Red Sea. It covers an area of approximately 223,000 km^2 (Hassib 1950). This huge area can be divided into smaller, more homogenous units. Usually one differentiates between the Red Sea coastal area including the Red Sea Mountains and the land to the east along the coast and, on the other

[36] A more complete list of landforms found in hot deserts is given by Evenari (1985b) and includes *regs*, *hammadas*, *wadis*, inselbergs, pediments, playas, piedmont plains, *bajadas* and alluvial fans.

hand, the inland desert west of the mountains. The coastal land is further divided into salt marshes, the coastal desert and the mountains, each found at increasing distance from the sea. The inland desert is also divided into smaller units, but along a north-south axis and mainly according to dominating geology.

The area that is the subject of this study is the southeastern part of the Egyptian Eastern Desert. The area in focus is mainly part of the coastal desert and mountains and the westernmost part of the inland desert. Geographically it is delimited by 24^{o} N to the south and by 25.18^{o} N to the north, see Fig. 12. The inland desert at these latitudes is classified as sandstone desert.

Figure 12 The study area in relation to selected meteorological stations. Study area is outlined. The square indicates coverage of satellite data.

The Etbai, the homeland of the ancestral Bejas and today's Ababda

The Eastern Desert and the study area are part of a land formerly known as Etbai. This is the name its Beja inhabitants[37], gave this land east of the Nile between Suez in the north and the mountains in Eritrea (Krzywinski 1998, Murray 1951). This people is related to other peoples, *e.g.* the Habab of Eritrea and the Danakil and Somali (Murray 1951).

The Etbai is a land of great historical importance, both because of its strategic position and of its rich resources in minerals and rocks. "Never since the dawn of history has the Eastern Desert been so little traversed as it is today." (Murray 1925)

[37] The Beja are the African Bedouins; bedouins, "a barbarous plural of Bedawy", Lane-pool (1854 - 1931), are men "of the desert".

Already in the Old Kingdoms of Egypt, in pyramid times, caravans went east of the Nile, to the land of Punt (Krzywinski 1998). Nobody knows exactly where Punt was; however, several authors report that part of the route to Punt passed through the Eastern Desert (Hobbs 1989, Krzywinski 1998, Murray 1951). Krzywinski (1998)[38] argues that Punt was actually located within the Etbai, in its southern part in the present Sudan.

Travels to Punt are known from Ptolemaic and Roman times as well. During these periods also "immensly important trade-routes from East to West, from India to Europe, passed through Egypt" (Murray 1925). The Romans traded for cinnamon, gums, tortoiseshell, and ivory from Arabia, northeast Africa and India: "some of the world's most important commodities crossed through the Eastern Desert" (Hobbs 1989). Later, in Islamic times, the pilgrimage route to Mecca through the Eastern Desert was important (Murray 1925).

However, the desert was not only of strategic importance for trade routes and caravans, it was also of importance in itself. The mountains are rich in gold, silver, copper, tin and emeralds and valuable stones such as porphyry, granite and *breccia verde antica* (Krzywinski 1998, Murray 1951). Quarries in the Etbai have supplied materials for Egyptian, Greek and Roman monumental constructions (Krzywinski 1998).

The routes of travel and trade have changed with the times. Both the starting point along the Nile and the principal point of disembarkation have varied. One of the main harbours used by both the Ptolemies (332 B.C.-32 B.C.) and the Romans (32 B.C.-A.D. 600) (Murray 1925), and perhaps also by the Egyptians going to Punt (Krzywinski 1998), was Berenice. The southern part of the trade routes to Berenice traverses the main study area (see Fig. 13). Between the routes there were also interconnections to mines and quarries (Murray 1925).

Until the Beja converted to Islam, about A.D. 600, they were known as Blemmyes. The Blemmyes had no written language; however, they are mentioned in some Greek, Roman and Christian sources. Many of the important ancient sources concerning the Blemmyes have recently been translated and commented upon in Eide et al. (1994) Registrations during fieldwork[39] also indicate their importance and influence (pers. com. R. H. Pierce, K.

[38] The main argument is connected to the distribution of the species giving antiu, the main product from Punt. It has recently been argued that antiu is the *Dracena ombet* which is found in the mist oasis in the mountains of Sudan.
[39] Both during field-work in 1996 and earlier, both in Egypt and Sudan, other participants of this and other projects have systematically registered sites that can be related to the Blemmyes.

Krzywinski and J. Krzywinski). Both ancient cities and burial monuments that cannot be related to outsiders' activities and therefore are thought to indicate Blemmy activity, are frequently seen in the Etbai. These cities are located close to emerald mines that were known possessions of the Blemmyes. The graves are mainly from the period between A.D: 1 and 400, and are thus partially contemporary with the period when Blemmyes are believed to have had their greatest influence and power, *i.e.* between A.D. 200 and 400. Murray (1951) refers to some later incidents illustrating that they still were of great influence[40].

Today there are different tribes of Beja. Although the actual number is open to discussion, Murray (1951) recognises five tribes: the Beni Amir, the Hadendawa, the Amar'ar, the Bisharin and the Ababda. The study area lies in the land of the Ababda. Some of the tribes still speak their own language Tu'Bedawie. However, the modern Ababda speak only

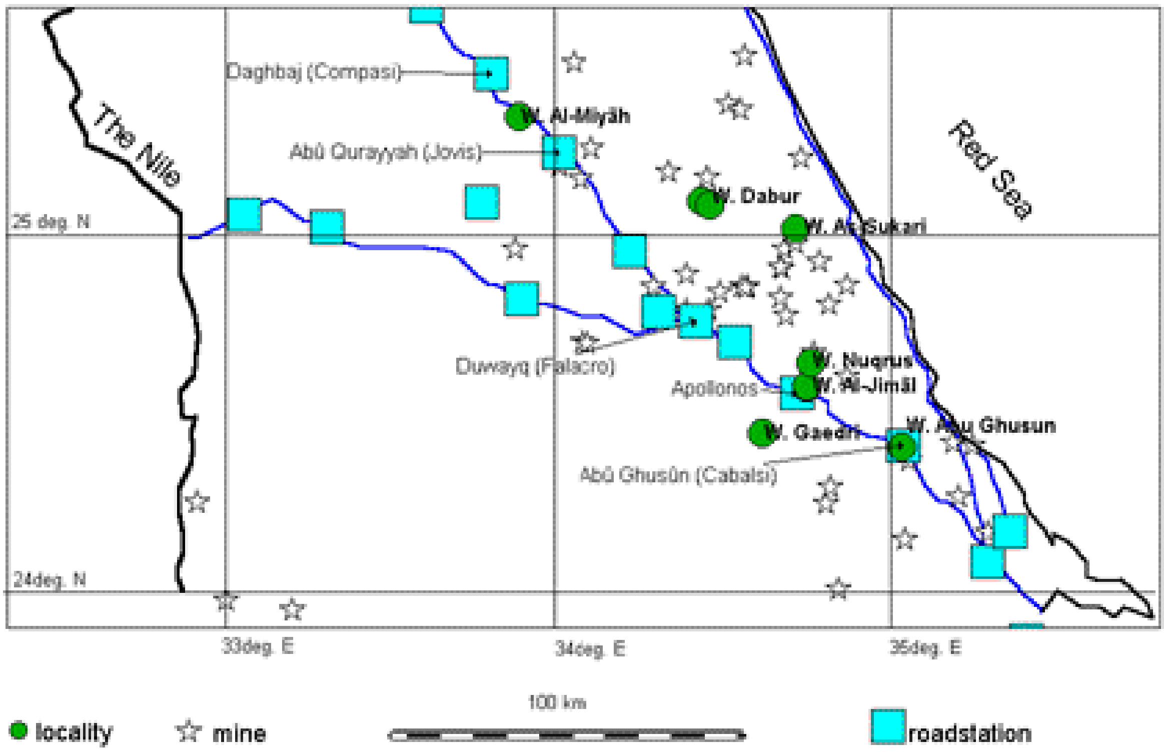


Figure 13 Localities, mines, roadstations and routes in the study area and vicinity

[40]However, both dating and references of these incidents are somewhat unclear.

Arabic as their mother tongue (Murray 1951). They broke away from the rule of their king, acquired an Arab chief and converted to Islam (*op. cit.*)[41].

During our own field-work we met people travelling in the wadis with their animals. Normally they have camels, goats and sheep. "The Ababdeh derive their livelihood from converting the products of their country into money, as well as from stock-rearing; in particular they supply excellent fuel in the shape of timber, brushwood, camels' dung, and excellent charcoal made by themselves from acacia-wood; they are therefore also charcoal burners." (Lane-pool 1854-1931) During severe droughts they might settle and work, for instance as miners, road builders or, more recently, in the oil industry. Some also settle for good and this is related to official Egyptian settlement policy. Villages are built close to modern infrastructure, and water is transported to people in the desert. These actions are two of the initiatives taken by the government to induce sedentarisation of nomadic people. Thus, fewer people today have a traditional lifestyle, and this weakens their relations to the desert and the resources they used to rely upon.

Climate

A belt of green and fertile land follows the Nile. However, this belt is narrow and in strong contrast to the huge deserts to the east and west. Travelling to the Eastern Desert you leave the green shores behind and enter one of the earth's most arid deserts.

Ayyad and Ghabbour (1985) divide Egyptian deserts into two aridity zones: hyper-arid and arid. They base their classification on an aridity index defined as precipitation divided by **p**otential **e**vapo**t**ranspiration (P/ETP), where ETP is calculated according to Penman's formula. The classification also takes into consideration the mean temperatures of the coldest and hottest month and the time of the rainy period relative to the temperature regime. Thus it is a classification-scheme slightly modified from that applied by UNESCO (1979, as referred to in Ayyad and Ghabbour 1985).

According to this scheme, the Eastern Desert belongs to the hyper-arid zone with mild winters and hot summers. The mean temperature of the hottest month is between 20 and 30°C. The rain is less than 30 mm per year, and occasional and unpredictable, while evaporation as well as potential evapotranspiration are both high. The difference between potential evapotranspiration and precipitation determines the balance of moisture, which in

[41] Dating of this event is not exact, but might be around the 13th century. However, the first time Ababda

the present case is negative throughout the year. The evaporation, as described by Ali (1984), varies between 5 and 15 mm per day in the study area. Also the (Piche) evaporation is higher in summer than in winter (Zahran and Willis 1992)[42].

There are only a few meteorological stations situated in or near our study area. Rainfall, relative humidity, and temperature data have been consulted for five of these stations. Their geographical locations relative to study area are shown in Fig. 12. The following presentation is based on an 18-year sequence of primary climatic measurements in the period between 1973 and 1990. This was the period it was originally planned to study. However, MSS data from the study area were not available for 1990, and the study was extended to 1996. At that point, it was too expensive also to include meteorological data from the period between 1990 and 1996. All primary data were acquired from the Egyptian Meteorological Authority.

Rainfall

Ayyad and Ghabbour (1985) recognise four rainfall regimes in the desert ecosystem of Egypt and Sudan. The Eastern Desert including the current study area falls within an almost rainless belt covering Upper Egypt and northern Sudan above 18°N. In the central parts of this belt, rain is not at all an annually recurring event. Rainfall increases both south- and north- wards. The Red Sea mountains influence rainfall orographically and cause the annual isohyets to bend northwards.

Fig. 14 shows the total yearly precipitation for the five stations in the period from 1973 until 1990. Both Aswan and Luxor are stations situated along the Nile. Aswan is the southernmost of these and here rain is not just a rare event but in fact extremely scarce. The mean for the period is 0.20 mm. The late seventies and all of the eighties, except for 1982 and 1986 were rainless years for Aswan. The eighties were also rainless in Luxor, except for 1980 and 1982. During the seventies several years gave rainfall; and three years gave amounts close to the mean, and 1977 and 1979 somewhat larger amounts.

At the coastal stations, the northernmost, Hurghada, receives rain more regularly, and in fact only few years have received no rain at all. The maximum rainfall was below 18 mm for the period, and the mean just above 4 mm. Further south along the coast a similar

appear in history is in 1673 (Murray 1951).

[42] The Piche evaporation for the Red Sea coastal land is reported to range between 13.7 and 21.5 mm/day during the summer and 5.2 and 10.4 mm/day in the winter.

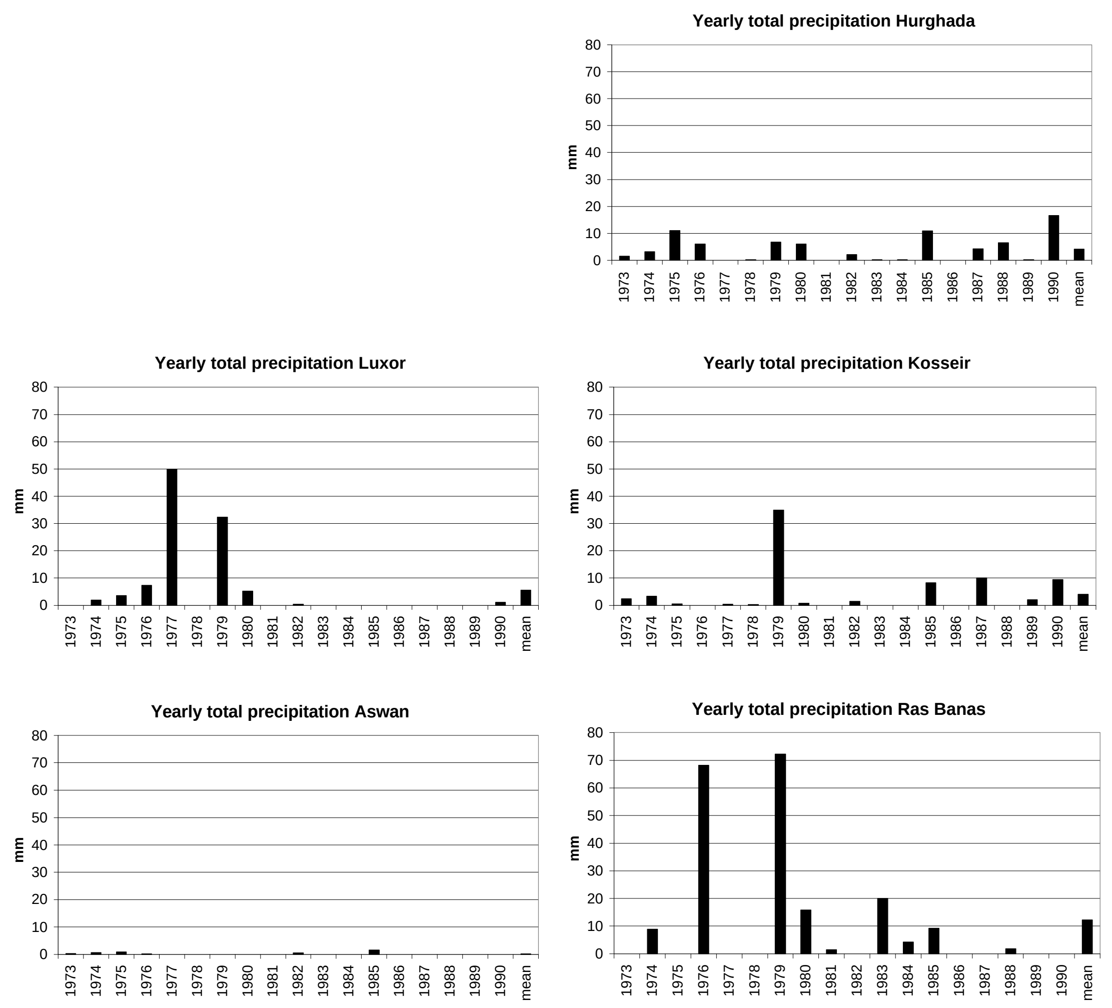


Figure 14 Yearly total precipitation, 1973-1990: Inland stations to the left, coastal stations to the right.

pattern of few rainless years is seen for Kosseir. In 1979 a maximum of 35 mm rain was received at Kosseir, and the years 1985, 1987 and 1990 were above the mean rainfall.

Ras Banas is the station closest to the study area. In terms of the number of rainless years, Ras Banas is more similar to the stations along the Nile than to the other coastal stations. In terms of yearly totals, this station shows the highest overall maximum. 1976 and 1979 received 68.2 and 72.3 mm rainfall respectively. Also 1980 and 1983 were above the mean of 11.2 mm.

Unpredictable rainfall and the lack of consistent patterns characterise the rainfall data. And this great variation and the generally extremely small amounts of rainfall are typical features of desert areas. This high inter-annual variation is usually described by the coefficient of variation, see eq. 2. The coefficient is high for all stations (Fig. 15). Even the lowest coefficient is above 100% and the maximum reaches 237% in Luxor.

Equation 2 Coefficient of variation, V

V=St.dev.*100/mean

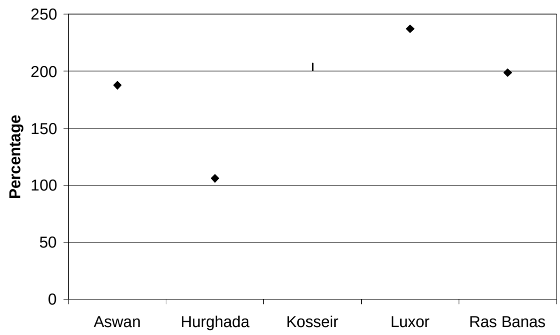


Figure 15 Coeffiecient of variation

Mean monthly rainfall for the stations is shown in the histograms in Fig.16. Maximum rainfall in Egypt is typically a winter event, and north of the 28th latitude at least 70% of the annual precipitation falls from November to March (Ali 1984). Another typical pattern for the whole country is the rainless summer months, nowhere exceeding 3% of the annual rainfall (*op. cit.*).

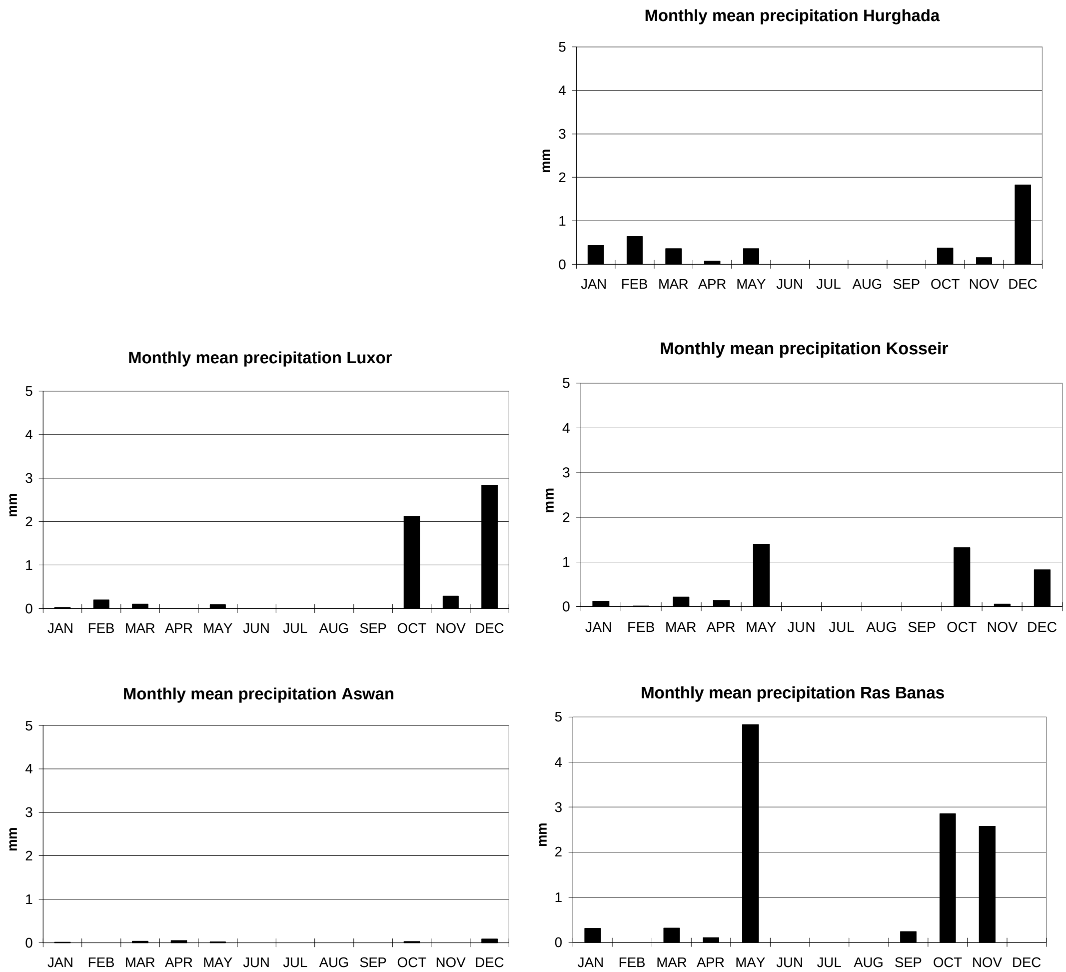


Figure 16 Monthly mean precipitation, 1973-1990

In the area covered by the five selected stations the peak rainfall comes during the autumn months. At Hurghada the peak is in December although at Kosseir and Ras Banas some rainfall is also received in May. Actually, all the 1976 rainfall and 17 mm of the 1979 rainfall at Ras Banas fell in May. The rest of the 1979 rain fell in January (5.5 mm) and in October (49.8 mm).

At all stations June, July and August are rainless. September is also rainless except for Ras Banas. At Hurghada these four summer months are in fact the only months without rain.

Information from the years after 1990 is not included in the dataset acquired. Some heavy downpours during November have, however, been recorded both in 1994 and 1997 (Egyptian Archaeology 1997).

Relative humidity

The monthly means of relative humidity are compared in Fig. 17.

The pattern seen for relative humidity coincides with the season of rainfall, *i.e.* maximum humidity occurs during the winter/autumn months. This pattern is also inversely related to the one seen for temperatures (Fig. 18). Relative humidity is influenced mainly by proximity to the Red Sea; the inland stations have the lowest minimum values, Aswan having a minimum value of only 16.5% for June. The amplitude for Aswan, Luxor and Ras Banas is higher than that for Kosseir and Hurghada. The values for Luxor and Ras Banas too become higher during some winter months than the values recorded at the remaining coastal stations.

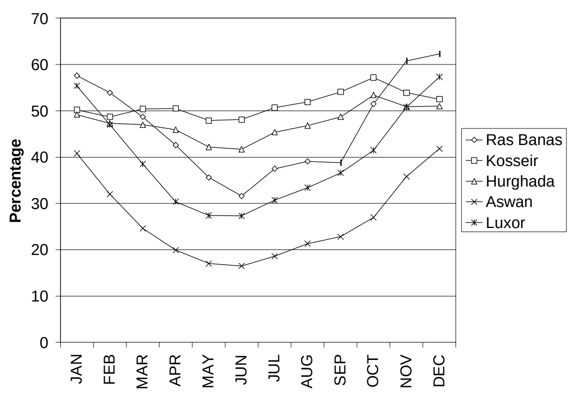


Figure 17 Comparison of relative humidity, 1973-1990

Temperature

Latitude, altitude and proximity to the coast are the main factors governing the temperature regime. Fig. 18 shows the monthly mean temperature ranges for the stations. Hurghada and Kosseir have a smaller range and lower mean values than the stations inland and to the south. The mean maximum is 33.3°C for July and 32.7°C for August. At both the Nile stations the mean maximum exceeds 40°C for the summer months, and the mean minimum is below 10°C in early winter. Ras Banas experiences temperatures lower than those seen along the Nile but higher than the stations further north on the coast. The maximum is reached in July at 38.7°C and the minimum in January at 11.9°C.

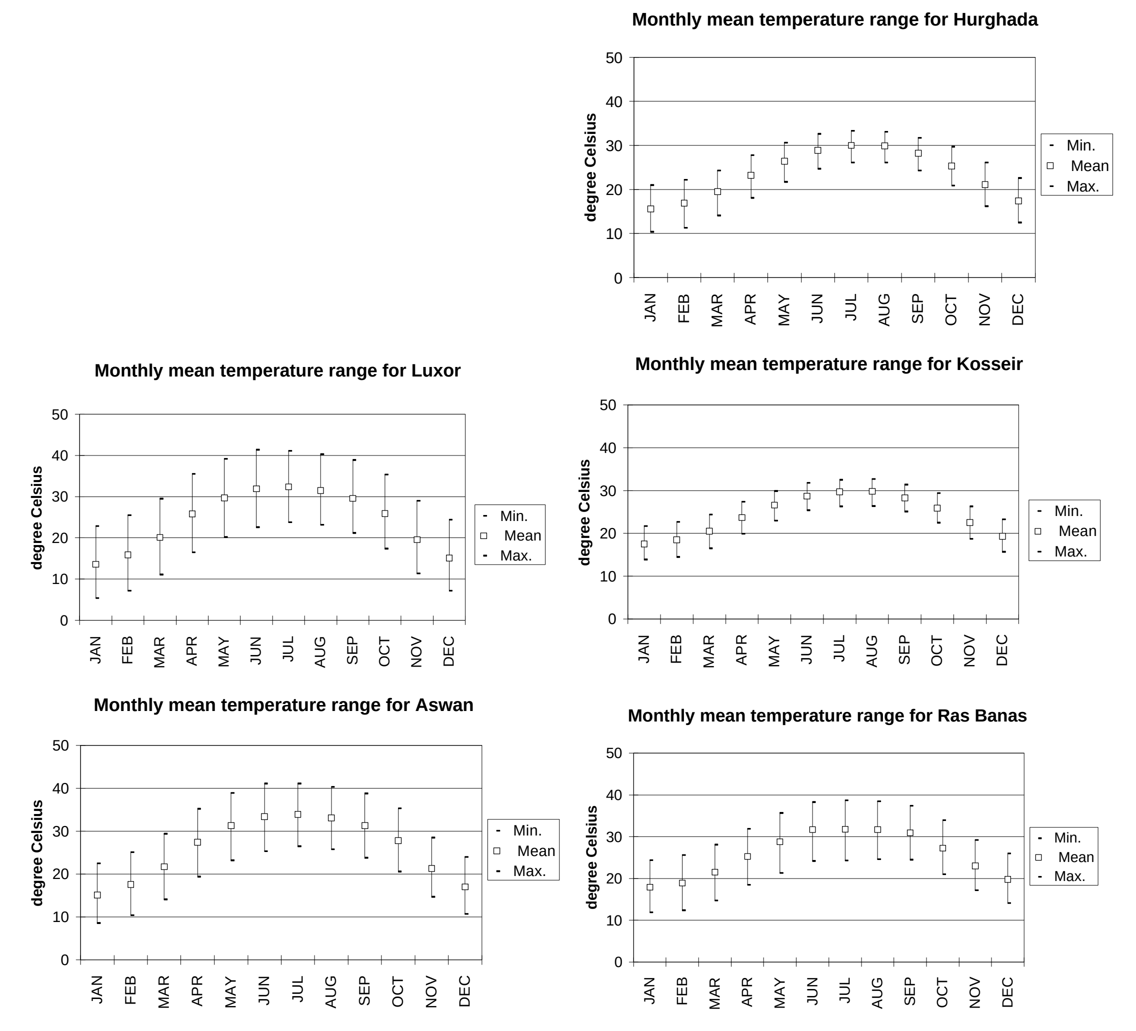


Figure 18 Monthly mean temperature, 1973-1990

Geology, landforms and water drainage

Viewed from the landscape of the western plateau, the Red Sea Mountains become the most prominent feature of the landscape.

The Mountains run parallel to and close to the coast. The mountain chain commences at about 28°30'N and extends southwards beyond the Sudanese border to Eritrea. In the study area the mountains are described as high and rugged, consisting of igneous and metamorphic rocks (Said 1962). "…the heart of the mountain system, is occupied mainly by primary rocks consisting of diorites (green-stone), dioritebreccias, and black or green-stone porphyries; with these are often intermingled very beautiful red-coloured granites and porphyries. Massive highly coloured veins and lodes everywhere permeate the dark rock. The chief masses, on which the others, so to speak, rest, are mainly composed of such granite, gneiss being less common." (Hassib 1950). The rocks are a part of the Pre-Carboniferous basement complex, the Arabo-Nubian massif that geologically separates this eastern complex from the western plateaux (Said 1962). In the southwestern part, a plateau of Nubian sandstone flanks the mountains, while in the north and northwest they are bordered by limestone plateaux (*op. cit.*).

Although dominant, the mountains are only one of several landforms that describe this desert landscape. According to Kassas (1952) the desert landforms are all part of a cycle of arid erosion. Other landforms having the same origin are the rocky plateau, the wadis (valley), the gravel desert and the desert plains. Of these, the wadis are the most pronounced feature in the mountainous landscape of the study area. The wadis are an erosion relict feature from past periods of heavier rainfall. However, even today torrential rainfall may strongly influence this landscape. Wadis and khors (ravines) dissecting the mountains are main channels for drainage of water and hence subject to water erosion: "..within a few minutes, dry wadis may become roaring torrents, removing any vestiges of top soil and eroding deep gulleys into the ravaged landscape" (Cloudsley-Thompson 1984)[43]. According to Hassib (1950) floods in the Eastern Desert may last up to two or tree days. Another description of the influence of water is given in Egyptian Archaeology (1997): "Torrential rain in Upper Egypt and Nubia during November again brought havoc for a number of archaeological missions. Many roads were washed away, including that linking Luxor and Baris in the south of the Kharga Oasis, while the loss of the road between Aswan and the Wadi Allaqi in Nubia prevented French archaeological work in the Wadi…..Some damage was also noted at the Red Sea site of Berenike…..The good news is that rain was only very light in the Luxor region and caused no damage, unlike the floods of autumn 1994…” Berenike (Berenice) is located just south of Ras Banas.

This kind of external/surface drainage is one of the features distinguishing the Eastern Desert from other arid zones[44] (Said 1962), and it is also a feature that makes the importance of the wadis and khors apparent. The water that flows through a wadi is collected from a huge area; as it flows downstream the volume of water passing a given point accumulates from increasingly larger areas.

However, as a resource for life the total volume of flood water is not fully utilised because nearly all of it runs off. More important as a water resource in this area is the seepage water, the infiltrated water flowing underground in the same wadi system (Hassib 1950). The heavy rainfall which causes the torrents also saturates the upper soil layers from which further water infiltration occurs. Torrents are, however, rare events; and the more frequent occasions of lighter rain, dew, mist and fog also supply seepage water (Ball 1912, Hassib 1950, Kassas and Zahran 1971). Impermeable rocks cause water from large areas to collect and infiltrate in khors and then collect in the larger wadis[45]. Thus, the sub-surface water resources at a given site in this mountainous landscape can be many times greater than the recorded rainfall. And where soil depth and texture are optimal this water allows deeper soil layers to be permanently moist.

The main water divide of the wadis in the Eastern Desert runs northwest – southeast, *i.e.* water flows either to the Red Sea in the east or to the Nile in the west. Ball (1912) describes forty-seven wadis draining east and three draining west in the area he surveyed south of 25°N[46]. The drainage systems between the 24th and 25th latitude are given in Fig. 19. Wadis draining east are generally steep and short (Al-Izz 1971) and also more numerous, due to the mountains, than on the western sandstone plateau. Thus, in the west the area of each drainage basin is much larger.

[43] This quote does not describe an event in the Eastern Desert, but the mechanisms are similar Hassib (1950).
[44] Sinai is recognised as belonging to the same geomorphological province as the Eastern Desert, and both these regions are characterised by the wadi-system Said (1962).
[45] “The stones of the pavement (on slopes of wadis) fulfil an important biological function, for run-off water seeps below them, forming water pockets which are exploited by plant roots. It may be that these water pockets are recharged during the dry season by “internal dew” formed below the stones.” Evenari (1985b)
[46] The area of this study stretches a bit more to the north into to the next Nile-draining wadi, the Wadi Abbad.

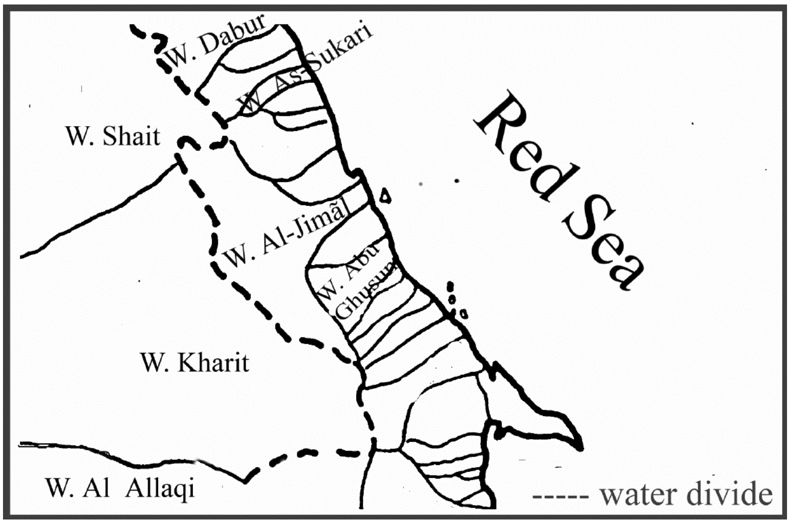


Figure 19 The drainage systems between 24° and 25° N latitude and the main water divide between the Red Sea- and Nile-draining basins, modified after (Al-Izz 1971).

The wadi ecosystem and its vegetation

Every landform defines a habitat (Kassas 1952); and together with its biotic and abiotic interactions it also defines an ecosystem. And of the aforementioned landforms and thus ecosystems, the wadi is characterised as one of the main ecosystems of the desert. Water is of paramount importance in the desert ecosystem, and the (relatively) optimal water conditions in the wadis explain the actual, or potential, richness of the wadi vegetation (Kassas 1954, Zahran and Willis 1992). They also explain the impression of astonishing verdance that meets you as you travel eastwards from the Nile into the desert. The green vegetation is in beautiful and strong contrast to the reddish mountains, and compared to one's expectations of vegetation in a hyper-arid desert, its abundance makes a striking impression.

Even if the richness of the wadi vegetation is mainly a function of the availability of water, the optimal conditions also depend on the interaction between water and the wadi as a landform, *i.e.* its topography, and the process of soil development. According to Kassas (1954) the "term wadi designates a dried river-bed in a desert area...Each wadi has a main channel and branched affluents or tributaries.". From a developmental point of view the affluents are in an earlier stage than the main channel. At the earliest stages the wadi bed is mainly rocky, but it differs from a plateau in that it is "more protected, has a more creviced substratum and receives more water."

(Kassas 1952). And with time, as mainly water[47] moulds the landscape, soil gradually accumulates. Finally its texture and depth will allow the creation of a deeply seated, permanently wet soil layer (Batanouny 1973, Kassas 1952, 1953a, 1954, Zahran and Willis 1992). The heterogeneity of the soil layer makes possible a more diverse vegetation in the wadi than in other ecosystems. Where water is available only for short periods after rainfall, *i.e.* in shallow soil and in the upper layers of thicker soil, ephemeral plants grow. In deeper soil, where texture allows better availability and continuity of water resources, perennials can grow. Thus, in relation to this edaphic succession the plant cover changes (Kassas 1954). Perennial frutescent vegetation grows on the most developed soils.

Besides being closely related to soil characteristics, the composition of wadi vegetation is a function of the available flora. According to Kassas (1952) two comparable wadis "`may house vegetation-types different in their floristic composition`". He relates this to cliffs surrounding the wadi, restricting seed dispersal between wadis.

There is also a feedback process between the perennial vegetation and the soil because trees and shrubs initiate a small-scale edaphic amelioration (Alstad 1994). By their presence trees and shrubs increase the availability of both water and nutrients; Vetaas (1992) reviews the mechanisms involved. Also on the macro-scale there might be an amelioration of the overall soil properties as vegetation cover increases. This seems, however, to depend on the effect of wind-sheltering, *i.e.* the ability to reduce loss of organic debris, which is a function of growth form and density of individuals (Alstad 1994). In general trees and shrubs are important in stabilising soil from both wind and water erosion, and they also play a role in trapping seeds and other dispersal units as well as fine soil particles that are spread by wind and water.

As already quoted from Cloudsley-Thompson (1984), torrents are strong agents of erosion. Thus, just as water is a main factor in formation of soil, it is also a main agent stripping soil from the wadi. Moreover, it destroys vegetation mechanically; uprooting is another process associated with torrents. This destructive influence of water is seen in the pattern of the perennial vegetation. The central part of a wadi, where the water flow is strongest, is usually devoid of perennial plant cover (Batanouny 1973, Kassas 1954). Perennial vegetation normally forms at the sides of a wadi or at other places where the water flow is less violent but where the subsoil is still moist. According to Kassas (1952), the repeated

[47] Sand dunes that are a consequence of wind transportation of sand are very rarely observed in the study area.

destruction and various stages of regeneration and development of wadi vegetation create a complex and confusing vegetation pattern in the larger wadis.

Both progressive and retrogressive factors influence and form the vegetation growing in the wadi ecosystem. In addition to the natural factors presented above, a group of human factors that are commonly considered to be destructive may be added (Kassas 1954, Zahran and Willis 1992).

Wadi vegetation as a resource for desert dwellers

The wadi landform is the main arterial road in the desert, due both to its friendly topography and to its richness and constancy of vegetation and water. "Ma'aza[48] toponomy is largely wadi-centric..;their lives are focused on drainages, where pasture for their animals is largely confined." (Hobbs 1989). Desert dwellers and their animals live in and rely solely upon the wadi and its perennial vegetation resources, for ephemeral vegetation cannot be counted on as a reliable resource; rather it is just to be enjoyed as a surplus whenever rain triggers its growth. Perennial species and their reliability as a fodder resource differ with their drought tolerance. The arboreal, deeply rooted species, *i.e.* mainly trees and larger shrubs, represent the most reliable resources. They are more or less green throughout the year, while the smaller shrubs may switch to dormancy or wither during longer droughts.

In addition to supplying charcoal, fuel and fodder for the desert dwellers and their livestock, perennial vegetation may also supply timber and food, and indirectly shade and shelter (Springuel and Abdel 1994).

Camels browse the trees, sheep only browse reachable branches while goats even climb the branches. Small stock also eat leaves shaken down by the shepherd's crook or from branches that have been cut from the trees. Later, cut branches supply fuel-wood. Cutting branches is mainly done in dry periods[49] when foliage is sparse and the normal shaking of trees yields little fodder. Also seeds and fruits are resources that domestic animals eat. The seeds (and pods) of *Acacica raddiana* are described as one of the most important sources in the food-chain of the wild desert fauna and are also consumed by domestic animals (Springuel. and Abdel 1994). After strong winds it was calculated that 4,837,500 seeds had been deposited under the crown of one *Acacia raddiana* tree (*op. cit*). Trees are the

[48] The Ma'aza is an Arab tribe of bedouins living to the north of the Ababda

drought period reserve fodder, but when other less drought tolerant species are available these are also grazed. According to Kassas (1952, 1954) and Zahran and Willis (1992) the most common species are the least grazed, *e.g. Zygophyllum coccineum*.

A more extensive use of trees is as a source of fuel. The hardwood species have a high energy potential and are collected either by cutting off branches or felling whole individuals. Springuel and Abdel (1994) describe the three acacia species, *A. tortilis*, *A. raddiana* and *A. ehrenbergiana* as the best fuel for cooking[50] and the main species for charcoal production. "The vegetation of these communities (perennial, frutescent shrubland), especially that dominated by *Acacia raddiana*, are (and for a long history have been) subject to extensive lumbering for fuel and charcoal manufacture." (Zahran and Willis 1992).

The collection of wood for fuel is not of recent origin. Christensen (1998) sums up the history of charcoal production in the Red Sea Hills. Already in the 4th century AD charcoal burners were included among the specialists and craftsmen in the Roman Imperial Army (*op.cit.*). At the stations along the trade routes Romans had blacksmiths and even Roman baths, both requiring large amounts of fuel. In several sources from the 19th century AD charcoal production among the Ababda is reported (Lane-pool 1854 - 1931, and Barth 1859, Belzoni 1820 and Floyer 1893, as referred to in Christensen (1998). Christensen (1998) states that there has obviously been a limited charcoal production throughout history and emphasises that the commercial production has intensified during the last decades. According to Hobbs (1989), who studied the Khushmaan people north of the study area, they said the heyday of their tree cutting was between 1910 and 1940. This was caused by a need for money, a relative abundance of trees, and a confidence that there would still be plenty of them afterwards. In the fifties, on the other hand, cutting was caused by a drought-induced despair, and resulted in an all-time low in perennial vegetation during that decade (*op. cit)*.

Today, the use of trees is also reflected on a spatial gradient. In the Wadi Allaqi, the wadi closest to the settlements was subject to the highest charcoal production (Springuel and Abdel 1994). Kassas (1954) describes the scrub-vegetation in desert wadis as being found only locally due to human destruction, but "in wadis far from human settlements as Gebel Galala district in the eastern desert, *Acacia tortilis* may be

[49] The Khushmaan people hacked off branches to feed their animals during the drought in the fifties Hobbs (1989)
[50] Especially this Acacia wood is good for preparing *gebana* – the traditional way to make coffee.

abundant". Such vegetation represents relicts of desert woodlands[51], a plant cover that may have covered considerable areas of the wadis (Kassas 1954). "One hundred and fifty years ago, Wadi Umm Anfii'a had so many trees that you could not see your camel; the acacia trees would hide it. But the people came, and cut and charcoaled." (Khushmaan statement, Hobbs 1989). Also in Sudan this is a common expression to describe dense forest (*pers. com.* K. Krzywinski, M. Babiker, A. Christensen).

Special parts of trees, for instance fruits used for medical or other purposes are also collected. If a species has such recognised qualities, it may be saved from lopping and charcoal production. This is, for instance, reported to be the case for *Moringa peregrina* that produces the valuable behen-nuts (Kassas and Zahran 1965, Zahran and Willis 1992). "The behen-nuts are collected by the local natives and sold at a good price. The ben-oil of these seeds is used for special lubrication purposes. This particular attribute has saved this plant which is too valuable to be cut for fuel." (Zahran and Willis 1992). Ababda informants also told us that people suffering from diabetes use *behen*-nuts.

The collection of *behen*-nuts from *Moringa peregrina* emphasises the desert dwellers' rationality / consciousness of conservation; if those trees are cut, no *behen*-nuts are produced, hence a resource is lost. However important the perennial plant cover in the desert is as a source of income, it is even more important as a life insurance for the desert dwellers: "Charcoaling is prohibited among us (Khushmaan) because without the trees, there are no animals, and no Arabs." This life insurance is even more urgently needed now because perennial vegetation cover is sparser than it used to be. The nomads also recognise that considerable time is required for regeneration (Hobbs 1989). In addition they know that only healthy trees survive long droughts. Among Khushmaan people there are several rules of conservation (*op. cit.*). The limbs of green trees and entire trees should under no circumstance be cut. "Only when no other food is available should a man take acacia or other tree leaves for his herd, and only then by shaking them of with his camel staff." These rules, which the nomads related to the Coran, apply to all trees growing on their land. But also larger areas with several trees or even a single tree might be under special protection. For a single tree this is based either on its rarity or on its historical importance. Trees are believed to

[51] Today, Kassas (1954) claims, these are represented by rare individuals of *Zizyphus spina-christi* and *Acacia tortilis.*

reach considerable age: “Cairo University botanists confirmed the plausibility of the Bedouin’s argument that trees date to Roman times, even though scientist’s and nomad’s time scales differ.” (*op. cit.*). Hence important episodes in a tribes’ history might have happened under a certain tree, in its shade. Trees are also used when naming places (Hobbs 1989) and as temporary local reference points (pers.com Krzywinski), thus emphasising their importance for people and episodes in their lives.

Today, the desert dwellers both use and conserve the wadi vegetation. Moreover, this is the way it always has been. As already seen, people have lived and travelled in the desert for millennia. The desert landscape and vegetation you encounter in the wadi is one formed not only by natural factors but also, even perhaps mainly, by its people, their life and culture for which this landscape has been the stage.

Vegetation and community types

Zahran and Willis (1992) sum up the vegetation and community types in the Eastern Desert, and what follows is based on their account. The current study area falls within three different areas: coastal desert wadis, mountains facing the Red Sea proper, and the inland desert. Two main types of communities characterise the vegetation: ephemeral and/or perennial communities. After rain the ephemeral growth is sometimes so rich that it may cover more than 80% of the ground. Kassas experienced this in 1952 and described the wadi as “a green lawn” (Kassas 1953b). The ephemeral type is not further discussed here. The perennial type is divided into two groups, the suffrutescent and the frutescent type. This vegetation has an open distribution with widely spaced individuals. However, in wadis with a rich suffrutescent layer a coverage of 30% can occur (Kassas 1953b).

In the coastal wadis there are three main groups of suffrutescent communities, the succulent half-shrub form, the grassland form, and the woody form. One example from each of these types is, respectively, the *Zygophyllum coccineum*-, the *Panicum turgidum*- and the *Zilla spinosa*- type. Normally there is also a frutescent layer of shrubs and trees associated with them (Zahran and Willis 1992). Some species found in this layer are *Acacia tortilis, A. raddiana, Leptadenia pyrotechnica, Lycium arabicum, Lygos raetam, Maerua crassifolia, Balanites aegyptiaca, Moringa peregrina* and *Calotropis procera*.

Of the frutescent, perennial community type, the scrubland form is the only one represented in the Red Sea coastal desert. For this type the frutescent layer is dense enough to produce the vegetation characteristics that distinguish it from the suffrutescent type.

Some of the communities are those dominated by *Acacia raddiana*, *A. tortilis*, *Lycium arabicum*, *Tamarix aphylla* and *Balanites aegyptiaca*. They are present in the channels of main wadis and larger tributaries.

The *Acacia tortilis* community is the most common scrubland type in the coastal desert area extending to the south of Marsa Alam. The cover is formed primarily by the dominant *A. tortilis*. Other species found in the frutescent layer are *A. raddiana*, *Balanites aegyptiaca*, *Leptadenia pyrotechnica*, *Lycium arabicum* and *Maerua crassifolia*.

In contrast to *A. tortilis*, which is present mainly on coarser deposits, *A raddiana* prefers softer deposits. In places where they grow together there is some evidence that *A. tortilis* is more drought tolerant, although both are included in the group of *Acacia* species that have low water requirements. Other *Acacia* species in this group are *A. ehrenbergiana* and *A. nubica*.

Patches of the *Balanites aegyptiaca* community are present in a few of the main coastal wadis, especially in the mountain range. According to Hobbs (1989) and Zahran and Willis (1992) these patches are clearly relicts of a much more widespread growth. The species is recorded in almost all the wadis of the southern section. The fleshy fruits are collected and eaten by nomads.

In the mountains there may be some influence from orographic rain. At the foot of high mountains (+1300 m asl.) *Moringa peregrina* is found (Kassas and Zahran 1965, Zahran and Willis 1992). In the wadis there are habitats consisting of various types of open shrub dominated by *Acacia raddiana*, *Balanites aegyptiaca*, *Leptadenia pyrotechnica* and *Salvadora persica*. *Acacia raddiana* is confined to westward draining wadis. *B. aegyptiaca*. *Leptadenia pyrotechnica* and *S. persica* are less common and confined to the channels of main wadis.

In the inland desert, Wadi Miyâh is recorded as one dominated by open scrub of *A. ehrenbergiana* with occasional individuals of *A. raddiana*.

Acacia tortilis (Forssk.) Hayne

According to El Amin (1990) there are three subspecies of *Acacia tortilis*: *ssp. raddiana* Savi, *ssp. spirocarpa* (Hochst. Ex A. Rich) Brenan and *ssp. tortilis*. The key differences between these subspecies are their height, the shape of their crowns, the number of main stems and the width of the pods at the widest (see Table 12).

Table 12 Characteristics of *Acacia tortilis* (Forssk.) Hayne (El Amin 1990)

<table>
<tr><td colspan="3">Acacia tortilis (Forssk.) Hayne:
Spinescent, inflorescent globose, white flowers, spiral pods, spines straight and hooked on same plant, olive green</td></tr>
<tr><td rowspan="2">ssp. raddiana
7-21 m high, crown irregular or round, one main stem, pods 6-9mm</td><td colspan="2">Shrubs or small trees, crown flat to spreading, commonly 2-4 stems from basis.</td></tr>
<tr><td>ssp. spirocarpa
4-7 m high, pods 3-6 mm</td><td>ssp. tortilis
1-4 m high, pods 2-3 mm</td></tr>
</table>

According to Täckholm (1974), there are the two species; *Acacia tortilis* (Forssk.) Hayne (=*A. spirocarpa* Hochst ex A. Rich) and *A. raddiana* Savi (= *A. tortilis ssp. raddiana* (Savi) Brenan). The main difference between the two is that the latter is altogether glabrous while the first is pubescent.

It is recognised that gradual transitions are regularly found and therefore that it is difficult to collect data on a sub-specific level (Kenneni and van der Maarel 1990).

In the current study, El-Amin’s system of is followed only to species level, however. Generally Täckholm’s taxonomy is used.

Study sites and their drainage systems

In some drainage systems a small number of sites have been studied, within the same or different wadis, in other systems only one site (Table 13). Drainage goes to the Red Sea except for W. Al-Miyâh.

Figs. 20 and 21 show drainage systems of the study sites. Names used in the following description are based on information retrieved from maps (E.G.S.A., cf. p. 75). There is, however, some inconsistency in the names and/or their spelling between this and other sources of information. Where other spellings or names are used this is indicated by its reference.

Table 13 Distribution of sites within drainage systems and wadis

Drainage system	Wadi	number of sites
W. Abbad	Al-Miyâh	1
W. Dabur	Dabur	2
W. As-Sukari	As-Sukari	1
W. Al-Jimâl	Gaedri	1
	Al-Jimâl	2
	Nuqrus	1
W. Abu Ghusun	Abu Ghusun	1

Wadi Abbad drainage system

This system (Fig. 20) drains a total area of 7000 km^2 into the Nile. It is situated in the northern part of the study area. Wadi Al-Miyâh is one of the tributaries of this system and

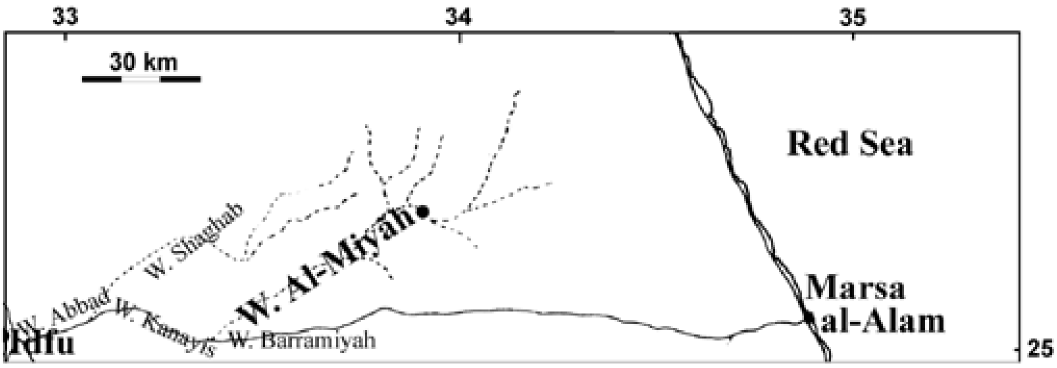


Figure 20 The W. Abbad drainage system and its tributary W. Al-Miyâh. Black dot indicates situation of site studied (retrieved from El-Sharkawi *et al.* 1982).

drains the northeastern parts of the basin. The name means `“the Valley of water”`, reflecting the abundant water resources of the wadi (El-Sharkawi *et al.* 1982b). W. Al-Miyâh originates in the basement mountain range and drains only igneous and metamorphic rocks (*op. cit.*). It heads southeast before it joins Wadi El-Barramiyah where the Idfu-Marsa Alam highway is situated.

The site is located in the upper part of the wadi where for some distance it runs in a northwestern direction. This is along a trade-route, and more specifically between the stations Daghbaj to the north and Abû Qurayyah to the south (cf. Fig. 13).

In their study of the vegetation in W. Al-Miyâh, El-Sharkawi *et al.* (1982b) recognised three distinct community types. Each type is considered to be a sub-type of a larger community dominated by *Zilla spinosa* and *Aerva javanica*.

Wadi Dabur drainage system

This drainage system drains the hill country between Jabal Atut (908 m asl.) to the southwest and J. Igli (975 m asl.) more northeast (Ball 1912). In its upper part the wadi heads east–south-east before it turns north-north-east at Ash-Shaykh Salim (25^{o} N) and enters the sea at about 25^{o} 16’ N. It receives numerous feeders as it nears the sea.

Two of the localities studied are in the upper part of Wadi Dabur, where it heads east–north-east. The Marsa al-Alam-Idfu highway follows this part the wadi. An ancient road to the gold mines of Sukari was also situated in this part of the wadi (Murray 1925).

Salama and Fayed (1989) studied the vegetation along the Marsa al-Alam-Idfu highway, *i.e.* including parts of the W. Dabur. Communities of *Zilla spinosa – Aerva javanica* and of *Acacia tortilis – Zygophyllum coccineum* are both registered in W. Dabur.

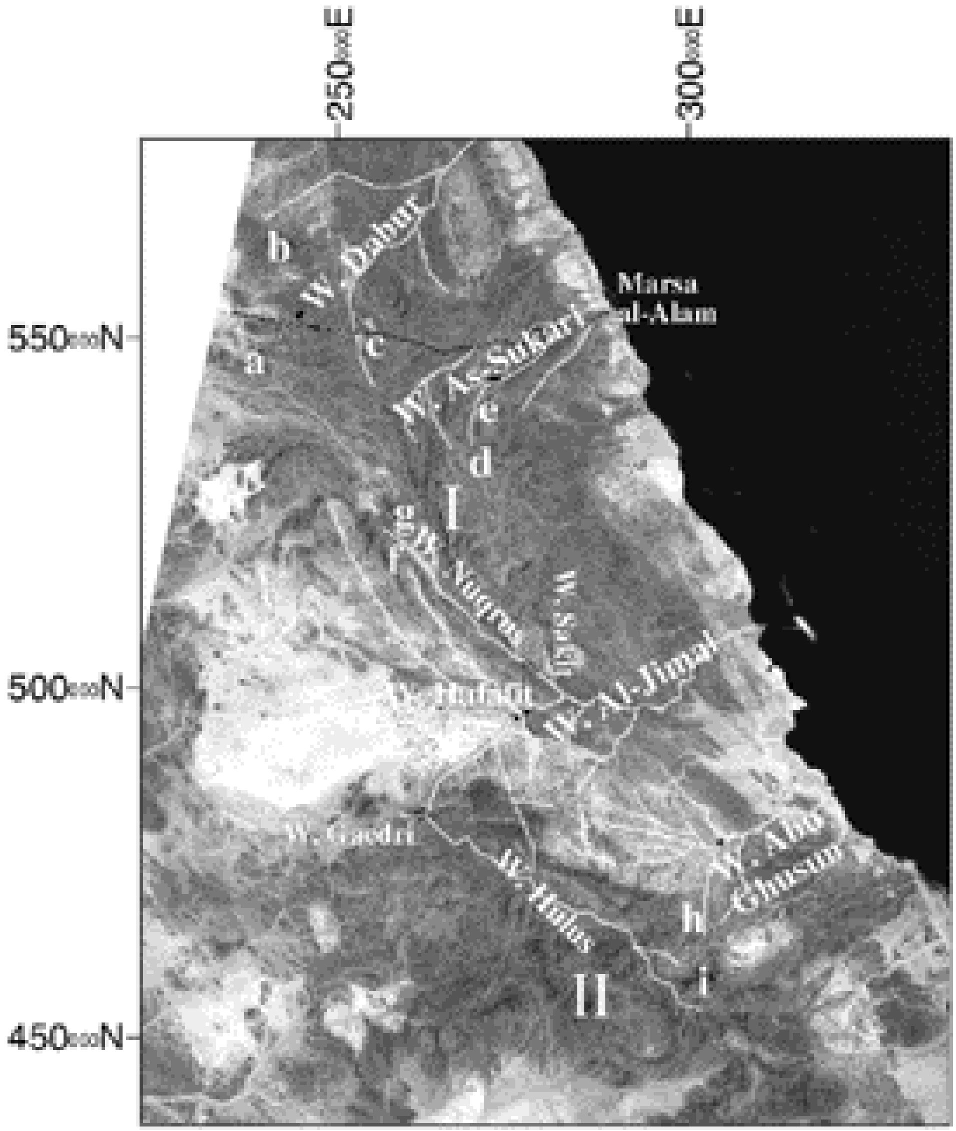


Figure 21 Area and eight of the sites studied (indicated by small black dots). White lines indicate main wadis in the drainage sytem, the dotted black line is the Idfu – Marsa al-Alam highway. I) area of Migif, Hafafit, Nuqrus, Hangalia, Zabara mountain group, II) area of Abu Hamamid, Hamata, Abu Gurdi group, a)Jabal Atut, b) J. Igli, c) Ash-Shaykh Salim, d) head of W. Ghadir drainage, e) J. Sukari and the gold mine, f) J. Hafafit, g) J. Nuqrus, h) J. Abu Ghusun, I) J. Hamata

Wadi As-Sukari drainage system

Wadi As-Sukari heads at a pass from Wadi Ghadir, the neighbouring drainage system to the south (Ball 1912). In its upper part W. As-Sukari runs almost straight north for some kilometres, before turning east; it runs along the granitic J. Sukari (630 m asl.). This craggy mountain which has the same name as the wadi, is famous for its gold mine and neighbouring ancient ruins (*op.cit*). The gold mine is probably the largest ancient gold working in Egypt (Klemm and Klemm 1994, Murray 1925), and remains of mining activity from all historical periods are found at this site.

The As-Sukari site is situated in the main wadi a few kilometres northeast of the Sukari gold mine.

The vegetation of W. As-Sukari, along with other wadis, has been studied by Springuel *et al.* (1991). According to this study the *Acacia raddiana–Zilla spinosa* community, described as “desert open forest”, is widespread in the main wadi channel of As-Sukari.

Wadi Al-Jimâl drainage system

This is the largest drainage system that flows into the Red Sea in this part of the Eastern Desert (see Fig. 19). Within this huge basin of approximately 2000 km^2 fall two of the northern mountain groups described by Ball (1912): the *Migif* - *Hafafit* - *Nugrus* - *Hangalia* - *Zabara* group and the *Abu Hamamid* - *Hamata* - *Abu Gurdi* group. They consist of several high mountains from which numerous larger and smaller water-courses drain before they finally reach Wadi Al-Jimâl, the terminal part of this wadi system. The three main wadis draining into W. Al-Jimâl are W. Hulus in the south, and W. Hafafit and W. Nuqrus in the north.

Wadi Hulus, the largest tributary, is a long, winding wadi, coursing northwest for more than 75 kilometers and with a total length of 80 kilometers (*op. cit.*). For the last kilometers it turns north, and then sharply to the east at which point it becomes Wadi Al-Jimâl. W. Gaedri is a small tributary that flows into W. Hulus where it turns north. W. Gaedri runs west–east and in its upper part it leads by a pass into more open country in the west.

The W. Gaedri site is situated in the lower part of this wadi where it joins W. Hulus.

The heads of Wadi Hulus are in the *Abu Hamamid* - *Hamata* - *Abu Gurdi* mountain-group[52]. These are high mountains that give the wadi a rather steep slope. In its upper part its slope is 50 m/km, while in the lower it is down to 6,5m/km (Ball 1912).

Wadi Hafafit and its tributaries drain the hills northeast of Wadi Al-Jimâl. On the eastern range of its catchment the gneissic rocks of J. Hafafit stretch southeast for more than thirty

[52] According to Ball (1912) J. Hamata (1979 m asl.) is the second highest mountain in the Eastern Desert, but the highest in this southern part.

km. This wadi is described as "barren" and as the only exception from all other tributaries to Wadi Al-Jimâl, which are "well supplied with trees" (*op. cit.*).

Wadi Al-Jimâl, the valley of camels, is, as stated, the terminal part of the wadi system. It runs sixty kilometres before debouching into the sea. In its upper part it runs northeast, and the country is rather open. Beyond Wadi Hafafit the wadi runs eastwards, is narrower and shut in by high hills. In its lower part it winds in a northeasterly direction. Due to its great length and varying topography the slope varies between a minimum of four and a maximum of about ten m/km, the average being six m/km (*op. cit.*).

The two sites in W. Al-Jimâl are situated close to the end-point of W. Hafafit. The Roman road station Apollonis is located a few kilometres upstream (cf. Fig. 13).

In their study of the vegetation in W. Al-Jimâl, El-Sharkawi *et al.* (1982b) recognise two distinct community types. The first, covering most of the course of the wadi, reflects the prevailing xerophytic conditions and is dominated by species such as *Cassia italica*, *Zilla spinosa*, *Pulicaria undulata* and *Panicum turgidum*. The second type, found in the deltaic part of the wadi in moister soil, is dominated by *Zygophyllum coccineum*, *Limonium axillare* and *Tamarix aphylla*.

Wadi Nugrus runs east of and parallel to J. Hafafit. It is more than forty kilometers long, commencing just east of J. Nugrus (1505 m asl.). This mountain is the highest of the *Migif-Hafafit-Nugrus-Hangalia-Zabara* group. Its northern parts are drained Nilewards, while Wadi Nuqrus and one of its upper tributaries drains the southern parts. The fall of Wadi Nugrus is on an average of ten m/km, and most rapid close to its head (Ball 1912).

The upper part of Wadi Nuqrus appears like a narrow gorge, but further down it broadens out. Near its terminus Wadi Sakit[53] joins the W. Nuqrus. There are abundant ruins and old emerald mines in this area. Common minerals are beryl, tourmaline, actinolite, various micas, talc and crystals of calcite (*op. cit.*).

The W. Nuqrus site is situated a few kilometres upstream of its confluence with W. Sakit. An ancient city is located in the northeastern parts of the locality. Also in the northeastern part of J. Nuqrus there are some ancient mines (cf. Fig. 13).

[53] The Sakit neighbourhood is described as one of the most highly metamorphic areas of the entire Eastern Desert (Ball, 1912).

Abu Ghusun drainage system

This drainage system commences among the high mountains of J. Abu Ghusun (1389 m asl.) (*op. cit.*). Wadi Abu Ghusun drains the northern side of this mountain range north of J. Hamata. It runs north for about ten km, then turns more east and winds sixteen kilometers in this direction before reaching the sea.

The locality is situated where W. Abu Ghusun turns east (Fig. 21). This is also where the Roman ruins of the station in Abu Ghusun are located. These are ruins of a large station.

Zareh and Fargali (1991) have studied the vegetation in W. Abu Ghusun. The vegetation is rich, and the alliance of *Acacia raddiana* and *Lycium shawii* that is newly recorded for the Egyptian desert (*op. cit.*) also grows here. According to these authors 'Ghusun' means branches of trees, and they interpret the name of the wadi as derived from its richness in trees and shrubs that that have many branches.

METHODS AND MATERIAL

Field method

Selection of area

In arid areas, as are found in North African deserts, vegetation change means long-term and/or permanent changes in vegetation cover. Variations caused by ephemeral vegetation do not constitute change (cf. Change in desert vegetation, p. 15). Thus, only the perennial vegetation, i.e. mainly trees, is of interest and focused on in this study. However, in the central Sahara trees are extremely rare and scattered.

Trees are restricted to wadis, plains and other landforms where run-on water is present. Studies of trees in an arid area require a study area where these landforms are frequent. Two gradients that influence tree growth and appearance are those of moisture and human interference. These gradients should be sharp if the diversity of conditions within a limited area is to increase. Such circumstances are found in the Red Sea Mountains.

As stated above, wadis are frequent in the mountainous landscape of the Eastern Desert; and they are diverse, both in terms of basin size and slope and consequently in water availability. Vicinity to the Red Sea influences and improves the moisture regime.

Gradients of human interference are both spatial and temporal. Trees are, and have been, the main plant resource used by the nomads (cf. p. 61). However, the utilisation of these resources has varied according to influence from and interference by non-nomads. This influence and interference varies both in time and space, but despite such changes there has been a stable, cultural backbone for several millennia. This is the case in our study area, now under the management of the Ababda and formerly of their ancestors, the Blemmyes.

Selection of sites

Two factors influenced the selection of sites.

The first factor addresses the spatial and radiometric resolution of remote sensing data. In hyper-arid areas, vegetation coverage is low, approaching a minimum level detectable by digital remote sensing. Theoretically, this limit is reached when vegetation within one pixel contributes less than one DN and consequently is not registered. In addition, the contribution of vegetation must be larger than the variations in the background. To reduce the effect of detection problems only relatively dense stands are selected for study. However, desert vegetation is scattered and heterogeneous; and variable coverage too is reflected at the pixel level. Thus, even for relatively dense stands pixels without vegetation will occur.

Secondly, because the focus is on change, the sites should, ideally, represent gradients that relate changes to their causes. Two gradients were kept in mind during the selection of localities, *viz.* one related to water availability, the other to culture.

One indicator of water availability that can easily be established is the location of a site within a wadi and/or drainage system. A station situated downstream of another, in a wadi of either equal or higher, rank receives water from a larger upstream area. Some of the sites studied are therefore situated within the same wadi or drainage system.

The cultural gradient has a spatial and temporal dimension and is defined by traditional vs. non-traditional land-use. Non-traditional land-use spreads from areas of commercialisation (Christensen 1998). The spread may pass over modern communication routes, such as roads and tracks, and it can also be related to historical locations, such as ancient cities and mines, or to ancient trade-routes. Present vegetation characteristics may be related to activity in historical times (cf. p. 62) Therefore a number of sites were situated near or beside historical or modern centres of activity in order to capture the temporal and spatial aspects of this cultural gradient.

On the basis of these criteria nine localities were selected.

Field variables and GPS-positioning

Field data were collected during the period from the 18th of March to the 9th of April 1996.

Within a naturally limited stand the appearance and distribution of each individual of woody perennial species, mainly trees, were registered and positioned. The variables selected for registration were chosen from two different points of view, one cultural, the other ecological.

The main variables that indicate cultural influence are signs of tree and branch cutting and browsing, but also the appearance of new trunk shoots and lowest branch height are indicative. The latter two are related to cutting and browsing. When browsing pressure is great, new shoots high up on trunks are absent because they have high browsing quality. Similarly, a low branch height generally indicates that trees have not been exposed to severe browsing and cutting pressure for some time.

Variables chosen to describe the population aspects of woody perennial species are measures of height, trunk diameter and crown diameter. Crown diameter and tree distribution are variables that link field observations to spectral data.

Marks of browsing and cutting were described qualitatively, as present or absent, and by recording the severity of damage inflicted. A measuring rod was used to measure branch height and new shoots appearing below the general branch height. The trunk diameter was measured by projecting the extreme outer limits of the trunk onto the measuring rod at breast height. When there was more than one main trunk, all were measured. Total tree height was estimated visually from a distance by comparison with an object of known dimensions (*e.g.* branch height). The diameter of the tree crown was calculated as the mean dimension of the longest axis and that of the axis at right angles to it. Field distances were measured by pacing. Step-length was measured as a constant of about 1 m. Panorama photographs were taken to give an overview of each locality.

The positions of each tree/shrub registered were recorded using a GPS (Global Positioning System) hand-held receiver (Garmin GPS 40, Personal Navigator and Garmin GPS 50, Personal Navigator). The Standard Positioning Service (SPS) was used normally to obtain

Figure 22 Field registrations

a position accuracy within 100 m. Each record was based on repeated positioning, and consequently the mean position is used so that even under Selective Availability[54] accuracy is expected to be better than 100 m. As a control and backup both distance (paced) and direction (compass) to the next registration were noted.

GPS-measurements were also used to register ground control points (GCPs). Characteristic features, such as small dark rock peaks surrounded by light sand were positioned. These were later used to control the rectification process.

All positioning data were logged automatically and saved in a hand-held computer; Psion Organiser II, Model XP. Other registered data were tape-recorded.

Datum and projection

GIS-integration of different data types such as field data, images (raster data), and maps (vector data) requires reference to a unique geographical framework.

The reference system chosen is that of the maps from the Egyptian General Survey Authority (E.G.S.A.), 1:50.000, 1989. The ellipsoid is Helmert 1906 and the projection is of the Transverse Mercator type. Map datum and projection parameters are given in Table 14[55].

Table 14 Projection and basic data of maps; Egyptian General Survey Authority, 1:50.000, 1989

	Name	Semi-major axis	Eccentricity	Flattening
Ellipsoid	Helmert 1906	6378200.0	0.0818133340	298.3
Horizontal datum	National Geodetic Net, Az Zahra, 1874			
Vertical datum	Mean sea level Alexandria, 1906			

	Name	False northing	False easting	Scale factor	Centre meridian	Centre latitude
Projection	Transverse Mercator	1100000.0	300000.0	1.000	35°	30°

Datum conversion of field positions

The reference system used by the GPS receiver during field-work was WGS 84, and positions are given in degrees of latitude and longitude. Measured positions of field observations are transformed from WGS 84 to Helmert 1906 to be compatible with the

[54] The level of the SA can vary and is set according to military decisions. SA level is sometimes reduced (or removed) during wartime; and since our observations were made during the Bosnian war, it is possible that they are more accurate than they would normally have been.
[55] The same datum and projection are chosen in ER Mapper; but here it is called TM-EGYPTG

E.G.S.A. maps. The method applied is a simple three-parameter transformation, using the translation parameters or the origo difference between the two data, *i.e* in this case between WGS 84 and Helmert 1906. This is accomplished by conversion through Earth-Centered, Earth-Fixed XYZ Cartesian coordinates[56]. The complete formulas for this conversion are given in Appendix 1, a simple visualisation of the process is given in Fig. 23.

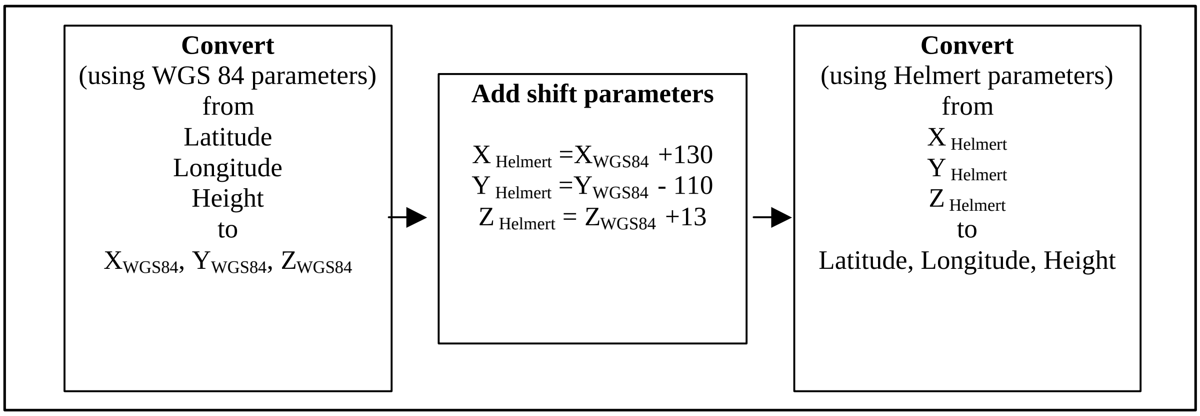


Figure 23 Three-parametric datum conversion of coordinates

Image material and pre-processing

To capture vegetation changes satellite images must be comparable, not only spatially and radiometrically but also in terms of vegetation cover recorded. These aspects of comparability are dealt with through the selection of image material and by pre-processing.

Image material

Only perennial, arboreal species are indicators of change. To avoid reflection from ephemeral vegetation, thereby insuring comparability of spectral vegetation data, the time of image acquisition time should fall within periods when the probability of rainfall is low. In our area of the Eastern Desert of Egypt there are two such periods, the summer-months, and the winter-months between February and April (cf. Fig. 16). The latter period was chosen since it is also the time when field-work conditions are optimal.

Four images were selected from the database of satellite image agencies. Three of these images are historical scenes and one is a contemporary scene, i.e. March 1996, the time of fieldwork. The historical scenes are from 1973, 1979 and 1984 and the set of images describes three time periods, 1973-1979, 1979-1984 and 1984-1996.

[56]These coordinates define three dimensional positions with respect to the center of mass of the reference ellipsoid. It is a right handed orthogonal system in which the Z-axis points towards the North Pole.

The data-set from 1973 is the first scene available that covers the study area at the optimal acquisition date. The previous period from the sixties had been one of drought and famine in sub-Saharan countries, the first Sahelian drought; but from 1973 until 1979 conditions improve in the northern African drylands. However, in 1979 a drought period commenced that again affected the sub-Saharan borderlands. This dry period, the second Sahelian drought, caused severe famine in many sub-Saharan countries and lasted until 1984. It is also of importance for the selection of these historical scenes that the same periods (1973-1979 and 1979-1984) have been used in similar studies in nearby areas to the south (Christensen 1998, Krzywinski 1993a, 1993b). The 1996 image was chosen to establish a link between field and digital data and to extend the trends to the present.

All images used in this study are Landsat images. Due to this satellite's sun-synchronous orbit and constant look angle, the relatively constant acquisition dates of the images, and the low latitude of the study area, sun and angular effects are relatively constant over the images.

Although the images were acquired from the same *type* of satellite (Landsat), they were acquired from different, specific satellites, sensors and agencies. The main characteristics of the four images are described in Table 15. All MSS data (historical scenes) were originally 6 bit data, the individual differences seen in Table 16 are due to different data processing at the agencies. The TM image (1996) is, however, 8 bit data.

As observed in Table 15 the images were received in three different formats. The first step in image processing is to read these raw images so as to make them compatible with image-processing software. This process is described in Appendix 2.

Table 15 Characteristics of images used in the study

	1973	1979	1984	1996
Satellite	L1	L2	L5	L5
Instrument	MSS	MSS	MSS	TM10
Date	February 23rd	April 15th	April 8th	March 24th
Path	186	186	173	173
Row	43	43	43	43
Pixel size (m^2)	56 x 79	56 x 79	56 x 81.5	30x30
Number of bands	4	4	4	7
Radiometric resolution	6 bit	6 bit	6 bit	8 bit
Raw format[57]	BIP-2	BIL	BSQ	BSQ
System corrected	no	Yes	Yes	Yes
Agency	EROS	ESA	EROS	EOSAT

Table 16 Bit-levels of images when received from agencies

Bands	MSS - 1973	MSS - 1979	MSS – 1984	TM – 1996
1	0-127	0-255	0-127	0-255
2	0-127	0-255	0-127	0-255
3	0-127	0-255	0-127	0-255
4	0-63	0-255	0-127	0-255
5	-	-	-	0-255
6	-	-	-	0-255
7	-	-	-	0-255

Geometric correction

Selecting GCPs is an essential part of the geometric correction. In this study all the GCPs were extracted from the E.G.S.A.-maps. A ruler with 1 mm as the smallest unit was used to read positions for the GCPs. The 1996 TM-image with the highest resolution and thus the most features that were also traceable on maps was rectified directly from the GCPs selected. To retain the relation between and the values of pixels, the rectification was linear, and the resampling nearest neighbour.

The MSS-images are registered relative to the rectified 1996 TM-image. In this image to image rectification, GCPs are either small features, covering only one, or at most a few pixels, or characteristic and easily recognisable patterns in both TM- and MSS- images. The same GCPs are used for all the subject images. As for the reference image, a linear rectification and nearest neighbour resampling was used. The output pixel size equals the input size: 56 m x 79 m for the 1973- and 1979- images and 56 m x 81.5 m for the 1984-image.

For radiometric correction and change analysis another set of 1996 images has been made. The rectified 1996-image was used as input. The output pixel size was chosen to equal the different MSSs, one image having a pixel size of 56 m x 79 m and a second of 56 m x 81.5

m. The resampling of these images is a bilinear interpolation; *i.e.*, the new values are derived from the four closest pixels in the old grid (cf. p. 41). In what follows the different resolutions of the TM-image are also referred to as TM_{79} and $TM_{81.5}$, while TM refers to the original resolution of 30 m x 30 m only.

Radiometric correction

According to Markham and Barker (1987) discrepancies between MSS readings of the same object, when only considering sensor effects and ground processing, is estimated at between 8 and 12 percent. In an arid area where vegetation cover is low and atmospheric conditions are stable, radiometric differences between images are due mostly to variations caused by the sensor and to differences in ground processing. The radiometric stability of desert areas is illustrated by the fact that in the quantification of sensor and ground processing effects a desert area was chosen as a reference area (*op. cit.*). The main radiometric errors are thus related to other than atmospheric factors, and a relative normalisation technique has therefore been selected in this study.

Because the stability of the area as a whole is high, a comprehensive method, using all data, is preferred. Areas of apparent change are, however, excluded (cf. below); and the method applied for correction is a linear least squares regression.

The regression approach is based upon the linear relationship between the digital numbers of two similar spectral bands acquired at different time over the same area (Elvidge *et al.* 1995). From this relationship a gain and offset data can be derived to normalise the slave to the reference image. The gain, a_k and the offset, b_k for the k^{th} band is given from the solution of the least squares regression equation Q_k, see eq. 3.

[57] A description of these raw formats is given in appendix 2.

Equation 3 The linear least squares regression equation and its solution for gain and offset.

$Q_k = \Sigma(y_k - b_k - a_k x_k)^2 = \min$
$a_k = s_{xy}/s_{xx}$
$b_k = y_k - a_k x_k$

where:
y = reference image
x = subject image; i.e. the image to be corrected
s_{xy} = covariance of x and y
s_{xx} = variance of x
y_k = mean of the reference image
x_k = mean of the subject image

Figure 24 The area for extraction of statistics used in the calibration process. (Skewness of image is due to correction for earth rotation).

The regression coefficients are calculated from a land area common to all the images in the change analysis. This area is selected from the rectified pictures and hence is the same for every band in all images. Clouds and their shadows are excluded from the area (Fig. 24). The statistics necessary for the final regression, *i.e.* means, variance and covariance (Tables 17 and 18), are extracted from this area.

The 1996 image is used as the reference image because it is the newest and thus has the highest radiometric quality. Since the final regression is done on a pixel to pixel basis, the TM_{79}- and $TM_{81.5}$- images are references in the process. Data extracted from these images are indexed with their pixel size. Note also that both the near-IR MSS bands are calibrated against TM Band 4. There is a slight difference in bandwidths between MSS- and TM-sensors, see Table 8. The bandwidths in Table 17 refer to the average width of the channel.

Table 17 Mean values for the different images

Mean (x)	$1996_{81.5}$	1984	1996_{79}	1979	1973
band 55 µm	56,574	50,825	56,575	99,954	48,366
band 66 µm	82,624	68,981	82,624	137,356	51,867
band 83_75 µm	69,09	63,248	69,09	130,864	44,563
band 83_95 µm	69,09	53,171	69,09	111,814	16,868

Table 18 Covariance and variance for the different images

	Covariance (s_{xkyk})			Variance (s_{xkxk})		
	1984	1979	1973	1984	1979	1973
band 55	172,297	283,636	170,429	138,293	387,125	140,915
band 66	473,284	801,99	396,392	363,194	1073,754	268,059
band 83_75	408,112	723,338	315,707	346,986	1128,297	220,836
band 83_95	355,32	653,877	126,493	261,099	918,947	36,183

The normalisation is done according to eq. 4:

Equation 4 The calibration formula

$x_{new} = a_k x_k + b_k$
where
x_{new} = normalised values
x_k = original values
a_k and b_k = regression coefficients

The normalisation is evaluated by calculating the following variables:

Equation 5 Mean Square Error, MSE

$MSE=(\sum(y-x_{new})^2)/(n-2)$

Equation 6 The coefficient of determination

$R^2=(1-MSE/MTO)*100$
MTO is the total variance of the reference image.

Sites and their catchment area

To outline the upper wadi system wadi-edges upstream of the localities were digitised from maps (E.G.S.A.). Digitised maps were overlaid on the TM image. Drawing local water divides identified limits of the catchment. The catchment area is measured as the area upstream of the drainage basin plus the area of the station itself.

The calculation of slope is based on height contours crossing the wadi in the vicinity of the locality. These contours are digitised from maps (E.G.S.A.), and distance between them is measured in ER Mapper. The difference in height is divided by total distance. This method gives a general impression of the slope for localities.

Field observations for sites

The distribution of recorded and positioned species within and among localities is derived from the field data. Other observed species at localities are also presented.

Qualitative observations establish human interference at the sites. For the most abundant species the variables measured are summarised statistically.

Maps based on the transformed positions of the recorded individuals, mainly trees, are made for all sites. These tree-maps are overlaid on the 1996 TM image, and each locality is delimited by a polygon that includes all the pixels with a recorded individual. The area of this polygon is the basis for vegetation coverage and density estimations, see eqs. 7 and 8.

Equation 7 Vegetation density of localities

Vegetation density = no. of individuals / area

Equation 8 Vegetation coverage of localities

Vegetation coverage = (∑crown area)/area

Crown area is calculated from the measured crown diameter. In this calculation the crown is assumed to be circular. In cases where individual crown data are missing they are replaced by the mean crown size for that site. If less than 5% of the observations have missing data on crown areas, no corrections are made.

Analysis of spectral vegetation signatures

Two aspects of spectral vegetation signatures are addressed in this section. Both are closely related to monitoring changes in vegetation.

First, it is important to choose the most appropriate indicator of vegetation when changes in it are monitored. This requires understanding how vegetation influences spectral bands in hyper-arid areas.

Second, it is of interest to interpret change in as much detail as possible. This may be achieved by establishing a relation between actual vegetation coverage and the spectral vegetation signature, i.e. the selected indicator. This permits an absolute, rather than a relative interpretation of changes.

Different areas are studied, on different scales, to bring into focus these aspects of vegetation signatures. The areas studied have been selected either from the imagery, referred to as the test area, or from among the field-localities.

The 1996-image links field observations and digital data, and is therefore the digital data source used in this section. Four different vegetation indicators are used: the Red band, the

IR band, the vegetation index (VI), and the perpendicular vegetation index (PVI) (see eqs. 9 and 10).

Equation 9 The vegetation index, VI

VI = IR/R

Equation 10 The perpendicular vegetation index, PVI

$PVI = (IR-a(red)-b)/\sqrt{(1+a^2)}$
where
a is the gain derived by simple regression and
b is the offset

Vegetation signatures – a test area

Globally, the study area is among the most sparsely vegetated areas found anywhere. The sparser the vegetation coverage, the more the pixel reflects the spectral influence of other features. At a given coverage threshold the limit of detection is reached (p. 72-73). Thus, a first step in understanding the spectral influence of vegetation in hyper-arid areas is to select an area of maximum vegetation coverage. The test area for this study was selected from the TM image on basis of its maximum VI-values and the presence of apparent red pixels (false colour display: red = band 4, green = band 3 and blue = band 2). Since the TM image was not received until the autumn of 1997 and thus could not be consulted before the fieldwork, it was not possible to use this area as a field locality (simply because it was not known until after fieldwork).

Red and IR signatures for the pixels of the test area were extracted and plotted as graphs to uncover spectral trends in the vegetation, *i.e.* for those pixels that were red and had high VI-values. Two threshold images are made to relate uncovered trends to selected band combinations, i.e. VI and PVI.

The change study utilises historical scenes and resampled TM-data, both at MSS resolution. To study the influence of resolution on spectral vegetation information the TM_{79}-image is compared with the TM-resolution over the test area.

Towards an absolute interpretation

An absolute interpretation of vegetation change requires that spectral vegetation signatures be related to actual vegetation coverage. Two levels are emphasised, the site level and the pixel level.

The site level

On the site level, the mean for each vegetation indicator is studied and related to overall vegetation coverage (cf. eq. 8). In addition, ranges of values are studied for the band combinations since those vegetation indices supposedly normalise background (cf. Vegetation monitoring, p. 32). Means and ranges for all vegetation indicators are extracted from the polygon outlining the area of the site (cf. p. 82).

The pixel level

To approach an absolute interpretation at the pixel level two requirements have to be satisfied:

1. There must be differences between pixels with and without trees.
2. There must be a uniform correlation between increasing vegetation cover and spectral vegetation reflection as expressed by the vegetation indicators selected.

The satisfaction of the second requirement is contingent upon the satisfaction of the first. Thus, only if both requirements are satisfied, is it possible to take the last step, the regression that is the key to the absolute interpretation of changes.

Testing differences between pixels with and without trees

To test the difference between pixels with (presence group) and without trees (absence group) a statistical approach is chosen. However, two different methods are used according to the type of vegetation indicators tested. In both methods radiometric resolution, positional accuracy and background variations are considered because they are factors that influence the registration of vegetation (cf. Vegetation monitoring, p. 32).

Band combinations

PVI and VI highlight vegetation and are considered to normalise background variations, at least to some extent. To further reduce the effect of background variation, only pixels of the same site are tested. The locality to be chosen is the one that proves to have the highest vegetation coverage (cf. p. 72-73, detection problems).

Firstly, to deal with positional errors, differences are tested at three spatial resolutions: TM-, TM_{79}- (equals MSS) and a 90 m x 90 m - resolution. Bilinear resampling is used for the non-TM resolutions. The parameters for calculating the PVI (a and b) are derived from the TM_{79} data-set for both resampled images.

Resampling usually decreases the effective radiometric resolution. To avoid loss of spatial and radiometric resolution, while still addressing the question of position accuracy, only pixels with trees and surrounded by trees are included in the presence group. Each pixel can usually be considered as the centre pixel in a block of nine pixels. If trees grow in all the nine pixels, there is a greater probability that at least one of these trees really is growing in the tested pixel, *i.e.* centre pixel, than if no trees are growing in the eight surrounding pixels. Based on this idea of an expected increase in probability as the number of neighbour pixels with trees increases, four different presence groups were selected. The first group excludes pixels which have no neighbour-pixels with trees, and the second group excludes central pixels which have fewer than two neighbour-pixels with trees, and so on.

Testing the spectral difference between the absence- and presence-group is done by the student’s *t-test*, two-sample type. Variance was first tested by the *f-test*, and a normal distribution confirmed by normal probability plots.

Single bands

Using single bands requires control of the background variation (it should be low or absent). Thus, the test applied to the single bands is based only on a block of nine pixels, the centre pixel including a tree, and its eight surrounding pixels. To assure that the block contains pixels of relatively low variation, *i.e.* having stable background, an unsupervised ISOCLASS classification (ER Mapper 5.0 Reference 1995) was performed. All the pixels in a tested block are within the same background class. The classification scheme comprises 6 classes where the desired percentage of unchanged pixels is 98, the maximum standard deviation is 4.5, and the minimum distance between class means is 3.2.

To test the difference between the central tree-pixel and its surrounding pixels, the statistical, non-parametric Walsh-test (Siegel 1956) was performed. The central pixel is subtracted from each of all the surrounding pixels and the difference scores are ranked.

The prediction for the red band is that the difference score will be less than zero. In this test n is 8 and H_0: μ_0=0 is rejected and H_1: μ_1<0 accepted at respectively 0.055 and 0.027 if equation 11 is satisfied.

The prediction for the IR band is that the difference score will be greater than zero. H_0: μ_0=0 is rejected and H_1: μ_1>0 is accepted at the same levels as above if equation 12 is satisfied.

Equation 11 Critical value for the Walsh test predicting a negative difference score

Max $[d_6, ½(d_5+d_8)]<0$

Equation12 Critical value for the Walsh test predicting a positive difference score

Min $[d_3, ½(d_1+d_4)]>0$

Correlation and regression

If it is accepted that there is a difference between pixels with and without trees, the second step of correlation and regression is taken.

Vegetation coverage for all pixels with trees is plotted against the vegetation indicator that hitherto proved to be most consistent. If the correlation is satisfactory, a regression analysis can finally establish the quantitative relation between the two variables studied.

Change analysis

Even if absolute analysis proves impossible, a relative, qualitative relation can be established; and hence a qualitative change analysis can be performed.

On the basis of the results from the “Analysis of spectral vegetation signatures” the most useful of the four spectral measurements is employed in the change analysis. First, the trends of the changes at all sites are described by comparing the means and ranges of the selected measurement. The polygon outlining the area of the site, extracted from the TM image and transformed to all other images, is used as basic area in the statistical analysis for all years.

Change images for all time-periods, including the whole period between 1973 and 1996, are produced in order to study changes on and between sites. Rather than giving only a general impression of the trend at each site a change image enables a more detailed interpretation and better spatial understanding of the processes of change.

Pixel-wise analysis of change is performed as a subtraction of the most recent image from the earlier image, *e.g.* 1973 minus 1979 and 1973 minus 1996. The resampled 1996-images are used as references: the $TM_{81.5}$ for 1984-data and TM_{79} for 1973-data. The range of values produced in this operation is rather large (max. $|-256 - 256| = 512$) and a classification of change-values is performed to make interpretation easier.

Not only periodic change at sites but trends across periods too are of interest. Therefore another set of images has been processed. For these images stable pixels are treated together with pixels of increase, and consequently there are eight different combinations of increase and decrease for the three consecutive periods. These eight cross-periodic trends are also compared with the overall trend for pixels (1973-1996).

Software

A Fortran-77 program was written (Thorkildsen 1998) to convert field positions to the selected geographical framework. Another program, C-code, was written (Hamre 1997) to read the BIP-2 raw format. Both programs and the entire procedure for reading raw formats are included in Appendices 1 and 2 respectively.

Panorama images were made using Photoshop, 4.0, which in addition to XV (Unix) was also used for other figure-related tasks.

Digitalisation from paper maps was done in Fysak 3.11, (Statens kartverk). SosiArc, SosiShape, Mapinfo, ArcView and PC ArcInfo were all used for transformations between different data-formats.

Pre-processing of satellite-images was done in ER Mapper, version 5.5 for Unix. This is also the main program for all image-related vegetation-, locality- and change-analyses. GIS-integration of different data sources and GIS-derivation between these sources are also done ER Mapper.

Statistical analyses of field variables and of digital vegetation signatures were performed using Minitab 12 and Microsoft®Excel 97.

RESULTS

The main product of the analyses is figures; *i.e.* most of them are included not as illustrations to text about the results but themselves embody the results. Explanations and interpretations of these figures are given in the text.

Results of the geometric correction

The rectification and resampling of images was stepwise. The first image to be corrected was the TM image. After each rectification the result was visually tested against digitised maps and against GPS-positions taken during fieldwork. The final correction also uses the corner points of the image which are taken from an earlier, satisfactory rectification.

The GCPs and RMS errors for the rectification are given in Table 19. Actual and polynomial coordinates refer, respectively, to those originally chosen and the regressed output coordinates. 'To-x' and 'To-y' are the geographical coordinates given in Easting and Northing.

Table 19 GCPs and RMS errors for the correction of the 1996 image

	-----ACTUAL-----				**---POLYNOMIAL---**		
Point	Cell-X	Cell-Y	To-X (E)	To-Y (N)	Cell-X	Cell-Y	RMS
Baranis	4610.07	4750.096	340925	434775	4610.073	4750.095	0.0031
Marsa Al-Alam	2271.955	1100.987	289025	554000	2272.13	1100.668	0.3642
Abu Ghusun quay	3678.96	3190.009	320750	485400	3678.722	3190.674	0.7063
Abu Ghusun roadcross	3655.996	3214.009	319960	484815	3655.769	3214.083	0.239
Sheik Salim	1076.287	1385.223	252300	551225	1076.526	1385.412	0.3046
Jabal Nusb al-'Abiad	1347.917	3070.947	252350	499990	1347.901	3070.908	0.0427
upper left corner	500	0	241796	595013	499.861	0.006	0.1394
upper right corner	6575	0	421556	566242	6575.029	-0.2	0.2021
lower left corner	151	5728	204357	426924	151.025	5727.752	0.2491
lower right corner	6224	5728	384055	398153	6224.15	5727.873	0.1966

One example of a visual test is seen in Fig. 25. Circular symbols are GPS-positions taken while travelling along the coastal road[58]. The darker pixels indicate the coastal road.

Also the 1973, 1979 and 1984 images were stepwise rectified. Due to lower resolution visual tests based on roads are difficult to perform. Therefore, a general fit of topographical features between the reference and the slave images was evaluated to determine the success of the rectification.

[58] Shadowing effects are low since this is a flat area; hence accuracy should be high (cf. p. 24).

Table 20 Total and average RMS errors for all images

RMS	1996	1984	1979	1973
Average	0,245	0,256	0,388	0,330
Total	2,447	3,844	6,206	4,616

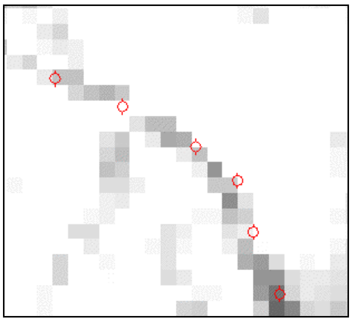


Figure25 A visual test; grey pixels indicate the coastal road (two lanes), circular symbols are GPS positions taken while driving north (north is up).

If the RMS errors are large, *i.e.* if there is a large spatial difference between old and new grids, resampling might introduce significant errors. As seen in Table 20 average RMS errors for all the rectifications are below 0.5, so resampling errors should be acceptably low for the images.

Detailed tables of GCPs and RMS errors from the 1973, 1979 and 1984 rectifications are given in Appendix 3.

Results of the radiometric calibration

Regression coefficients, a_k and b_k, are given in Table 21. The a_ks for all images are of relatively similar magnitude. The variation in b_ks is, however, quite large. Especially 1979 has much lower values than 1973 and 1984. This is an effect of the stretching of individual bands to an 8-bit range that sometimes is part of the processing done by agencies at the receiving station. Image characteristics after calibration are described in Table 22.

Table 21 Values of a_k and b_k used for the calibrations

	a_k			b_k		
	1984	1979	1973	1984	1979	1973
Band 55	1,246	0,733	1,209	-6,748	-16,659	-1,921
Band 66	1,303	0,747	1,479	-7,266	-19,968	5,926
Band 83_75	1.176	0.641	1.430	-5.300	-14.805	5.383
Band 83_95	1,361	0,712	3,496	-3,268	-10,471	10,121

Table 22 Means and standard deviations for images after calibration, subscripts refer to the pixel size of the resampled TM image; for the mean all values were, however, similar for the two resolutions

Mean	1996	1984	1979	1973	St.Dev.	$1996_{81,5}$	1984	1996_{79}	1979	1973
55	56.574	56.610	56.596	56.533	55	15.725	14.638	15.726	14.434	14.393
65	82,624	82,612	82,596	82,641	65	26,497	24,838	26,496	24,487	24,212
75	69,090	69,085	69,085	69,060	75	23,477	21,891	23,478	21,516	21,224
95	69,090	69,108	69,136	69,275	95	23,477	21,995	23,478	21,600	21,030

Table 23 The MSE, R^2 and the RMS error for the calibrations, subscript refers to the pixel size of the resampled TM image

Band	1984		$MTO_{81.5}$	1979		1973		MTO_{79}
	MSE	R^2		MSE	R^2	MSE	R^2	
55	35.68	85.57	247.28	42.601	82.77	44.613	81.96	247.31
65	67,15	90,44	702,08	108,19	84,59	121,58	82,68	702,05
75	59,24	89,25	551,19	92,46	83,23	105,28	80,90	551,23
95	71,97	86,94	551,19	90,84	83,52	114,48	79,23	551,23

The MSE and the coefficient of determination, R^2, calculated for an evaluation of the correction are given in Table 23. The coefficient of determination ranges between 79.23% and 90.44%. R^2 is generally highest for the Red band. The lowest coefficient registered for this band relates to the 1973 image and is 82,68%. This value indicates that the average difference between this band and the reference band is approximately 17%.

Calibrated and rectified images are seen in Figs. 26-28 where they are displayed as RGB colour composites. The same transformation is carried out for all images (see histograms), and they are thus comparable in terms of colours displayed. The first peak in the histogram is due to pixels of water (the Red Sea). These pixels were not part of the area from which calibration statistics were extracted.

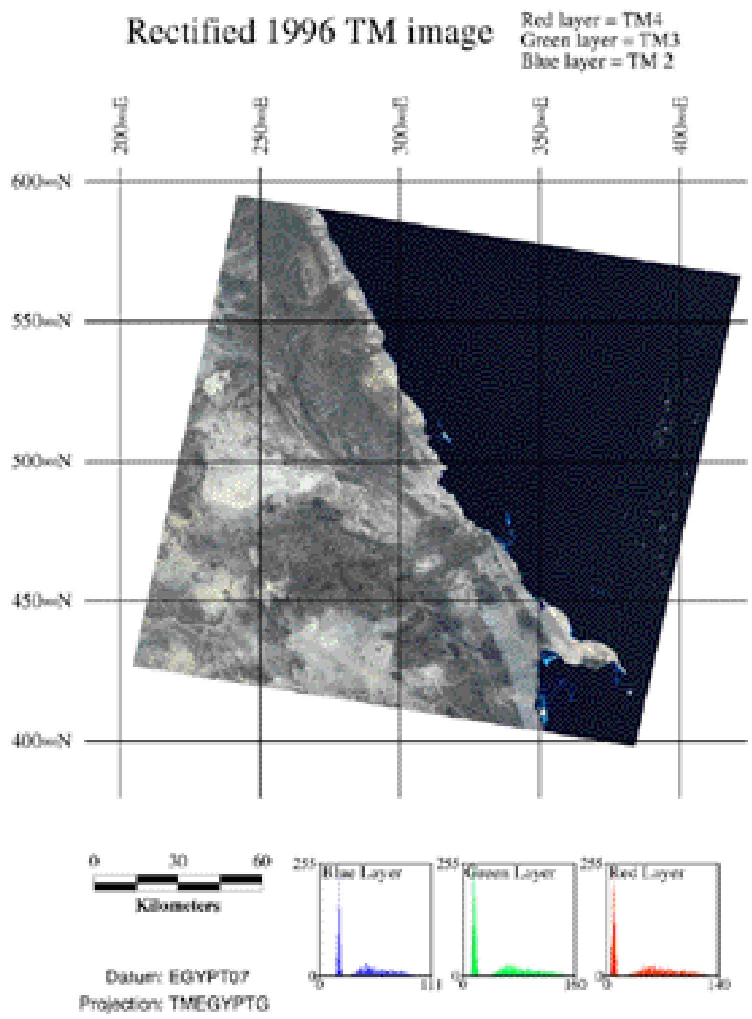


Figure 26 Geometrically corrected 1996 image.

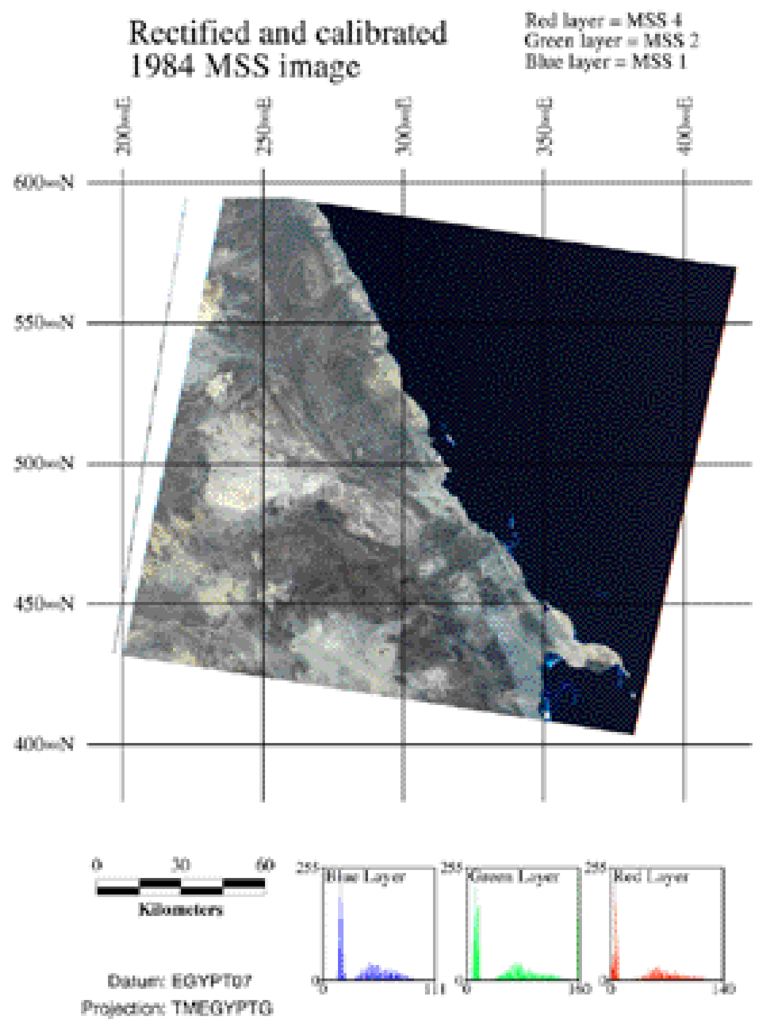


Figure 27 Geometrically and radiometrically corrected 1984 image.

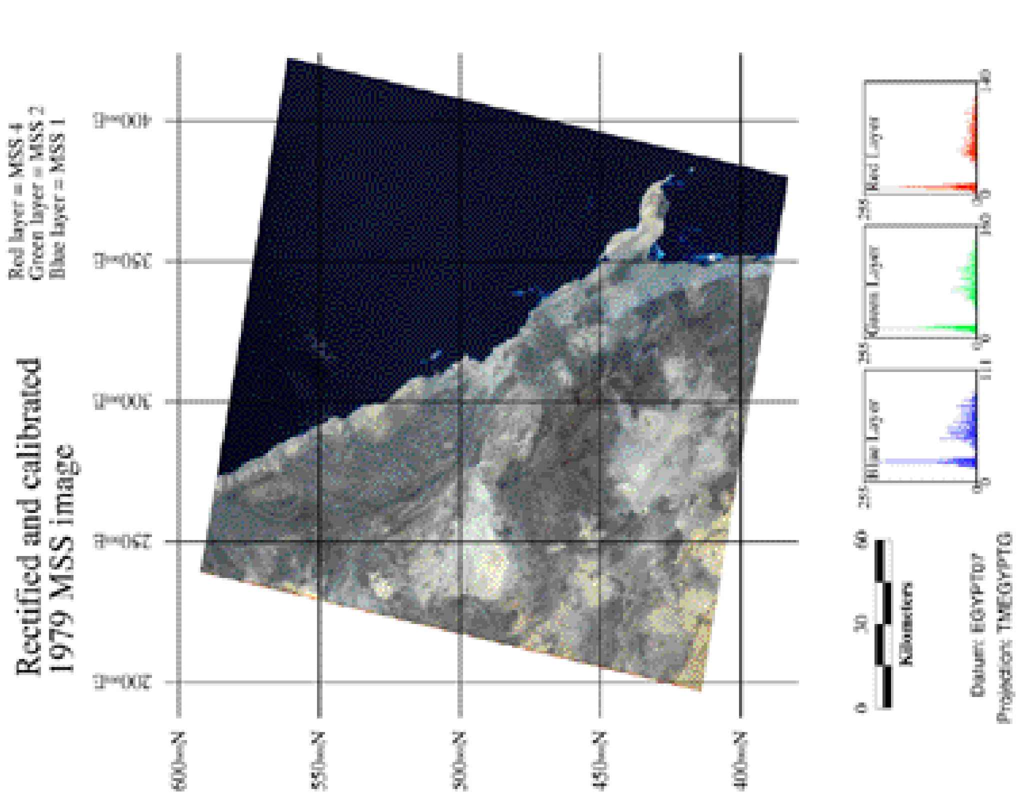


Figure 28 Geometrically and radiometrically corrected 1979 image.

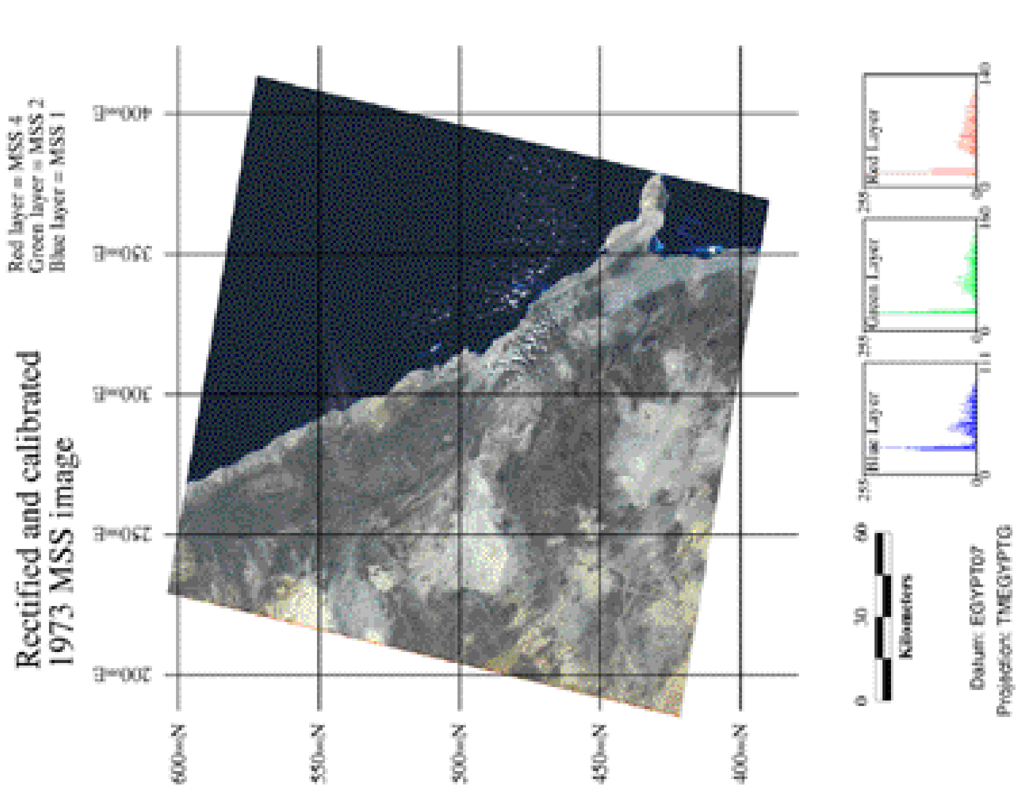


Figure 29 Geometrically and radiometrically corrected 1973 image.

The sites and their catchments

The location of a site within a wadi-system and the topography at that site are both important indicators of the magnitude of available water-resources. These two indicators are expressed, respectively, as catchment area and slope at the site.

Catchment areas for all sites within the area covered by the TM image are seen in Fig. 30. W. Al-Miyâh is located outside the TM-coverage. Some sites are situated downstream of others and in such cases receive water also from possible sub-catchments. Sub- and total catchment is given in Table 24. Table 25 gives height and slope information for the study sites. A more detailed picture of their location within the wadi-system is seen in Figs. 31-37. Solid black polygons delimit the area of the sites, *i.e.* the area within which trees are registered. In addition the edge of the wadis and the catchment boundaries (boldly dotted lines) are indicated. Finer dotted lines are contour intervals. Smaller, black or white squares indicate the point from were panorama pictures were taken. These are seen in Figs. 38-46. Sites as recorded by the TM sensor (March 1996) are seen in Figs. 47-54. Tree-maps are overlaid the images and trees registered are indicated by numbers. Each image is stretched to be comparable to historical scenes from the same site (see Appendix 5), *i.e.* in terms of their colours they are not comparable to other sites.

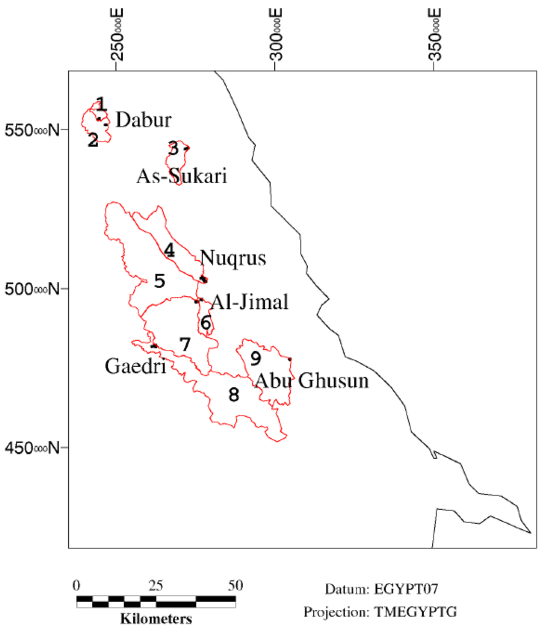


Figure 30 Sites and their catchment areas. The catchments are numbered from north to south within individual drainage system

Table 24 Catchment information for sites

Sites	Catchment no.	Sub-catchment (km^2)	Catchment (km2)
Al-Miyãh	-		156, min
Dabur I	1		13
Dabur II	1	13	
	2	57	70
As-Sukari	3		55
Gaedri	8		395
Nuqrus	4	176	176
Al-Jimal I	7	313	708
	8	395	
Al-Jimal II	5	422	1175, max
	6	45	753 min
	7	313	
	8	395	
Abu Ghusun	9		219

Table 25 Height and slope for sites, Distance is the length between two height contours and H-diff. refers to height-difference between contours.

Locality	Distance (km)	H-diff (m)	slope (m/km)	Height (m asl.)
Al-Miyah	6.9	20	3	380-400
Dabur I	3.1	40	13	500
Dabur II	2.8	20	7	480
As-sukari	1.7	20	12	300
Gaedri	2.2	20	9	450
Al Jimãl I	4.4	20	5	280
Al Jimãl II	4.4	20	5	280
Nuqrus	2.3	20	9	280-300
Abu Ghusun	2.6	20	8	220

Wadi Al-Miyâh

The catchment analysis for this locality is not complete because map- and satellite- data are lacking. However, on basis of available data a minimum estimation indicated a catchment area greater than 156 km^2. The slope is 3 m/km.

Wadi Dabur sites

Wadi Dabur I is located upstream of Wadi Dabur II in a wadi of lower rank. This site has the smallest catchment area of the localities studied (57 km^2 less than its downstream neighbour). As seen from Fig. 32 the wadi receives some smaller tributaries on the lower parts of the site. Thus small differences in the effective catchment are present within the locality. Such differences are not present for Dabur II. Both localities are at approximately the same height (Dabur I is 500 m asl. and Dabur II about 480 m asl.). The slope at the stations are 13 and 7 m/km respectively.

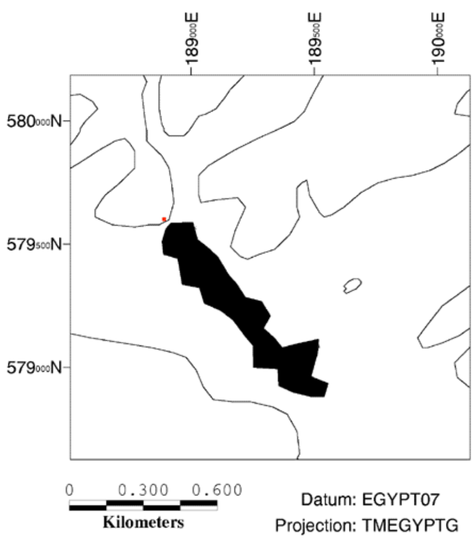


Figure 31 Wadi Al-Miyãh site

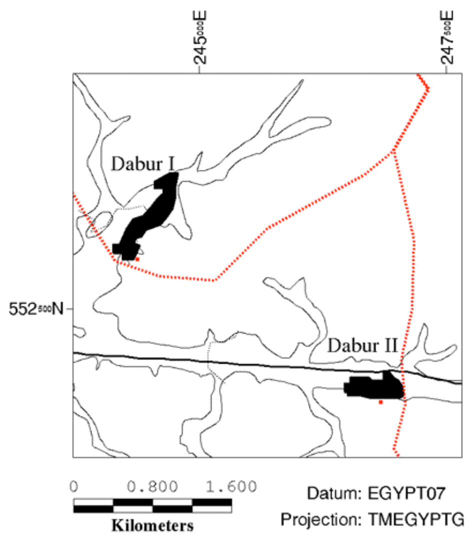


Figure 32 Wadi Dabur sites, the Marsa- Al-Alam – Idfu highway is indicated too.

Wadi As-Sukari

Like the Dabur sites that in Wadi As-Sukari has a catchment area of less than 100 km^2. Water drains north-eastwards. In its lower parts there are some smaller tributaries (Fig. 33). Thus there are smaller differences in water-availability within the locality. The locality is situated at 300 m asl. and the slope is 12 m/km.

Localities within the Al-Jimâl drainage

The huge drainage system of Al-Jimâl includes four sites: W. Gaedri, W. Al-Jimâl I and II, and W. Nuqrus. All the catchment areas numbered 4-8 (Fig. 30) are parts of the total Al-Jimâl basin.

The catchment area of Wadi Gaedri is the upper and southern parts of the basin. The main flow comes from the southeast, turning northeast from the eastern part of the locality. W. Gaedri itself drains towards the east, and the site lies in a tripartite watershed (Fig. 34). The western parts of the locality receive far less water than the eastern parts. The area of this western sub-catchment amounts to approximately 20 km^2 (see Fig. 30, this refers to the northwestern part of the catchment no. 8, the small part above the locality) while including the basin of the southeastern tributary increases the total area to 395 km^2. The height of the locality is 450 m and the slope is 9 m/km.

Both the W. Al-Jimâl localities drain catchments 7 and 8. Catchment 7 drains the plains along the main water divide, bordering the Nile-draining Wadi Kharit system (see Fig. 19). Al-Jimâl I only receives water draining these two sub-catchments; however, the

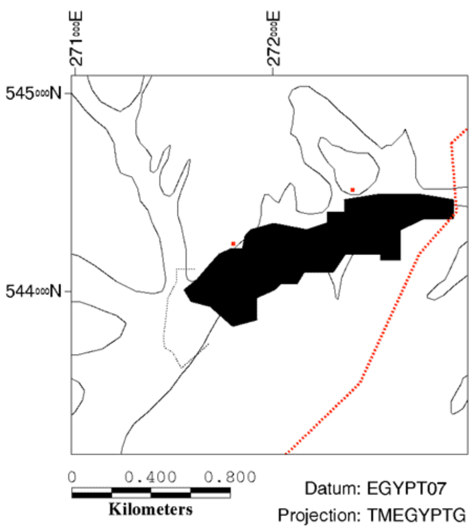


Figure 33 Wadi As-Sukari site

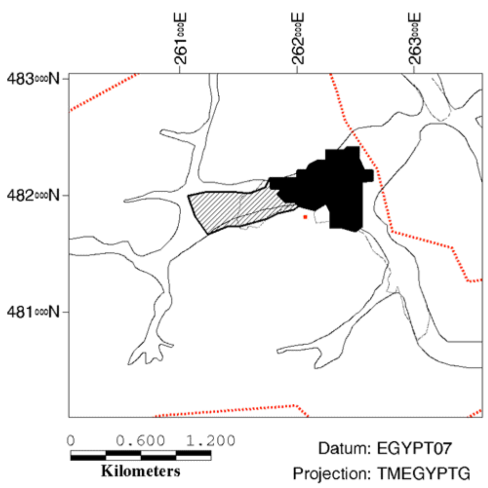


Figure 34 Wadi Gaedri site, hatched area covers Gaedri West.

neighbouring Al-Jimâl II also drains the area of catchment 5 and 6. Thus there is a huge difference in terms of catchment area for these two closely neighbouring localities. Water draining catchment 6 reaches Al-Jimâl II through both the southern tributaries seen in Fig. 35. Just opposite the western of these two tributaries another one, leading water from catchment 5, reaches the wadi. During fieldwork it was noted that only one tree grew in the area between the two localities.

Al Jimâl II is situated on the southern side of an elevation, a "wadi-island". Thus water draining catchment 5 has two possible routes into the main wadi, on the western side and thus influencing the water resources of the locality and/or on the eastern side downstream of the locality. Catchment 5 amounts to 423 km^2 and is thus the largest of all the catchments measured. The actual influence of the water draining this catchment on the Al-Jimâl II locality is, however, difficult to determine since the underground topography not is known. Anyway the least difference in catchment area between this locality and Al-Jimâl I is 44 km^2. Al-Jimâl II is thus the locality having the largest catchment.

The height of the Al-Jimâl localities is approximately 280 m and the slope 5 m/km.

Wadi Nuqrus drains an area of 176 km^2 and thus has the smallest catchment of the localities within the Al-Jimâl drainage. It is the locality with the largest area and all the trees in the wadi between its southern and northern boundaries have been registered. Some smaller tributaries reach the locality, and the actual catchment thus varies slightly within the locality. The height of the locality is 300 m in the north and 280m in the south. The slope is 9 m/km.

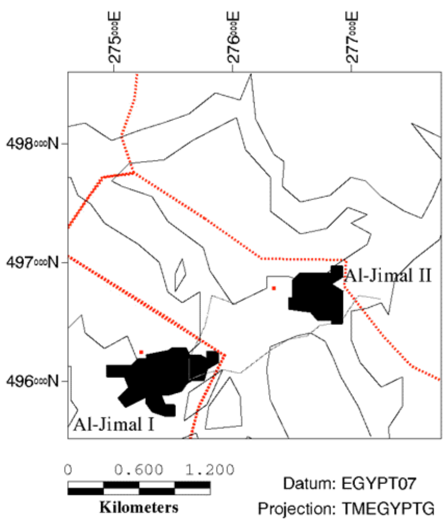


Figure 35 Wadi Al-Jimâl sites

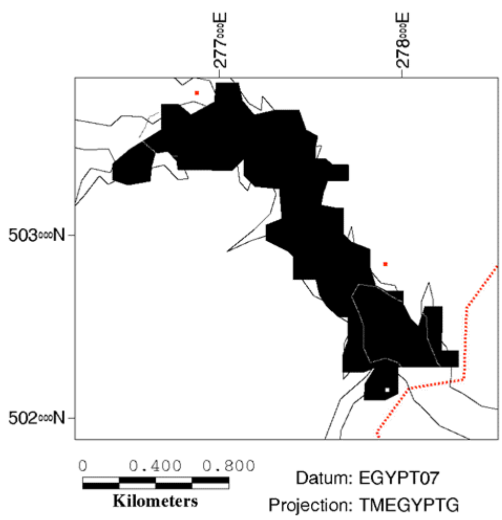


Figure 36 Wadi Nuqrus site

Wadi Abu Ghusun

The study locality in the Abu Ghusun basin is the southernmost locality studied and the only one in its drainage system. Three wadis join upstream close to this locality (Fig. 37), and they drain an area of 220 km^2. The height of the locality is 220 m and the slope 8 m/km.

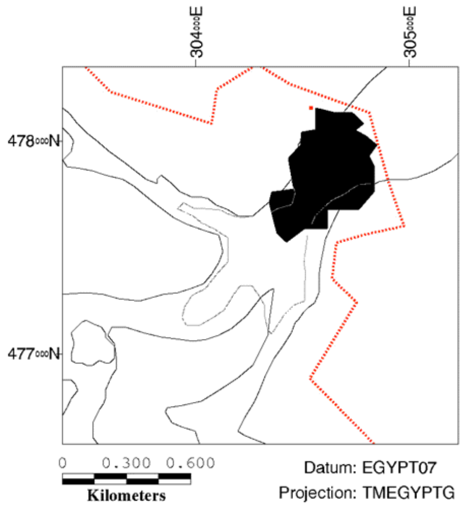


Figure 37 Wadi Abu Ghusun site

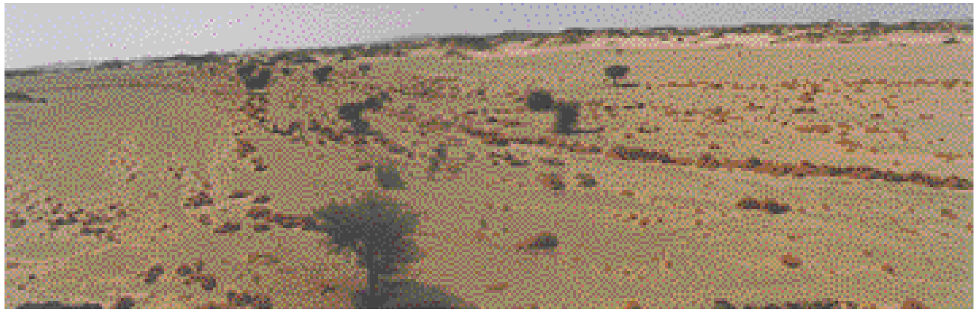


Figure 38 (Image to the left) The Wadi Al-Miyâh site (looking southeast)

Figure 39 (Image below) The Wadi Dabur I site (looking west) Trees registered are in the northern (right) part of the wadi.

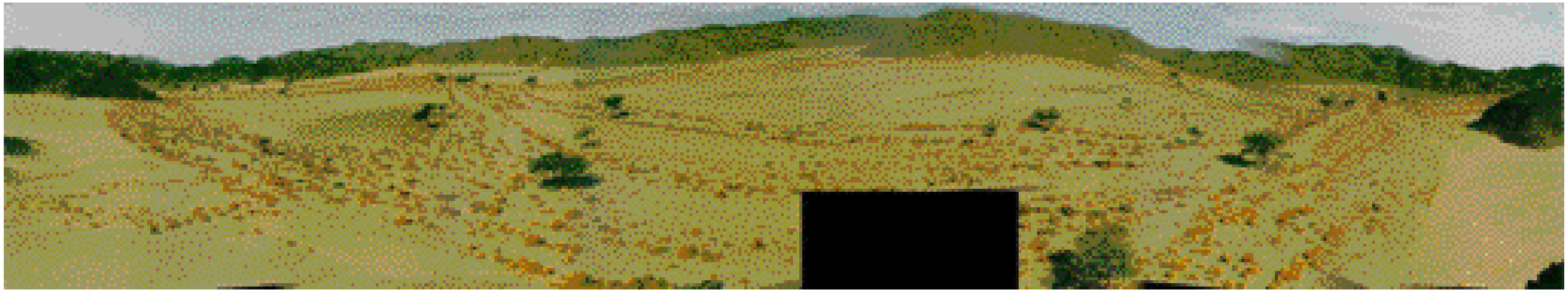


Figure 40 The Wadi Dabur II site (looking north)

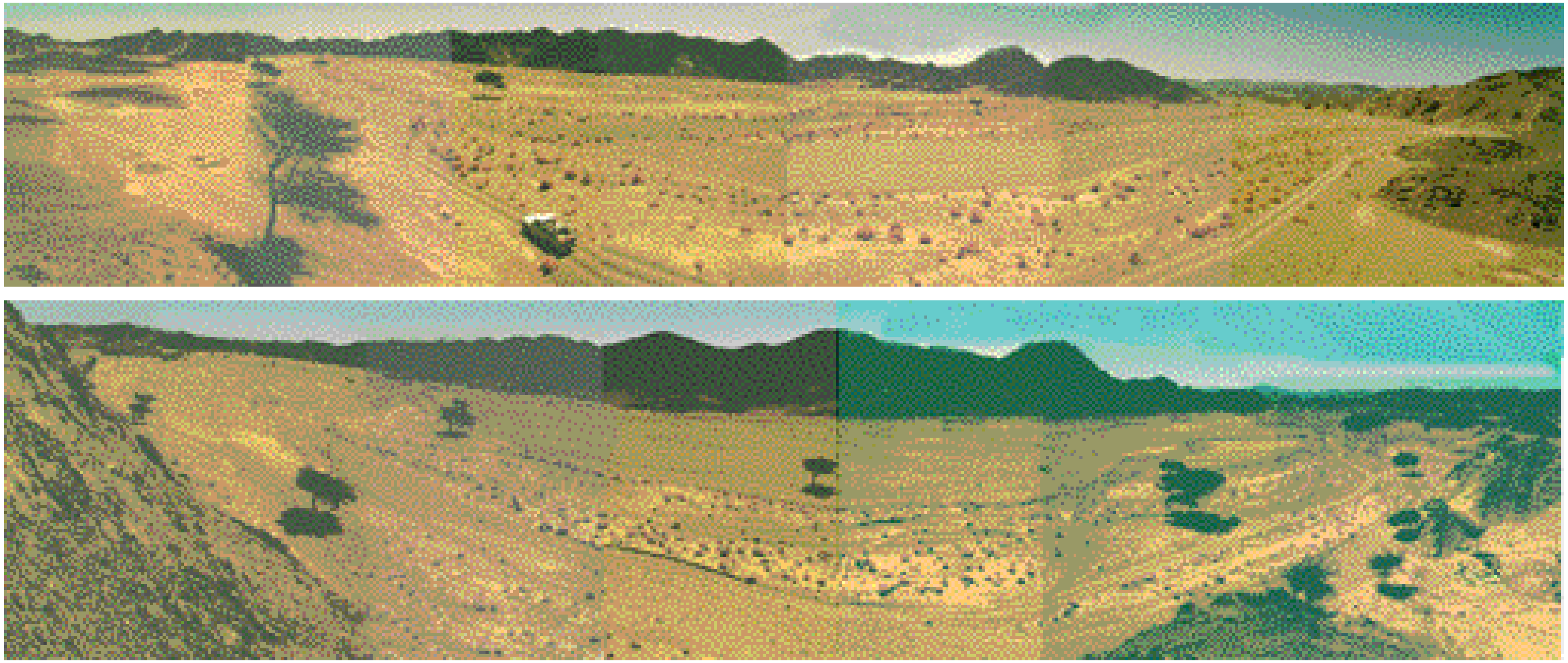


Figure 41 The W. As-Sukari site. Upper image is from the northern part of the locality and the lower one from the southern part (both lookng south).

Figure 42 The W.Gaedri site (looking north). Gaedri West is to the left.

Figure 43 The W. Al-Jimãl I site (looking south)

Figure 44 The W. Al-Jimãl II site (looking west)

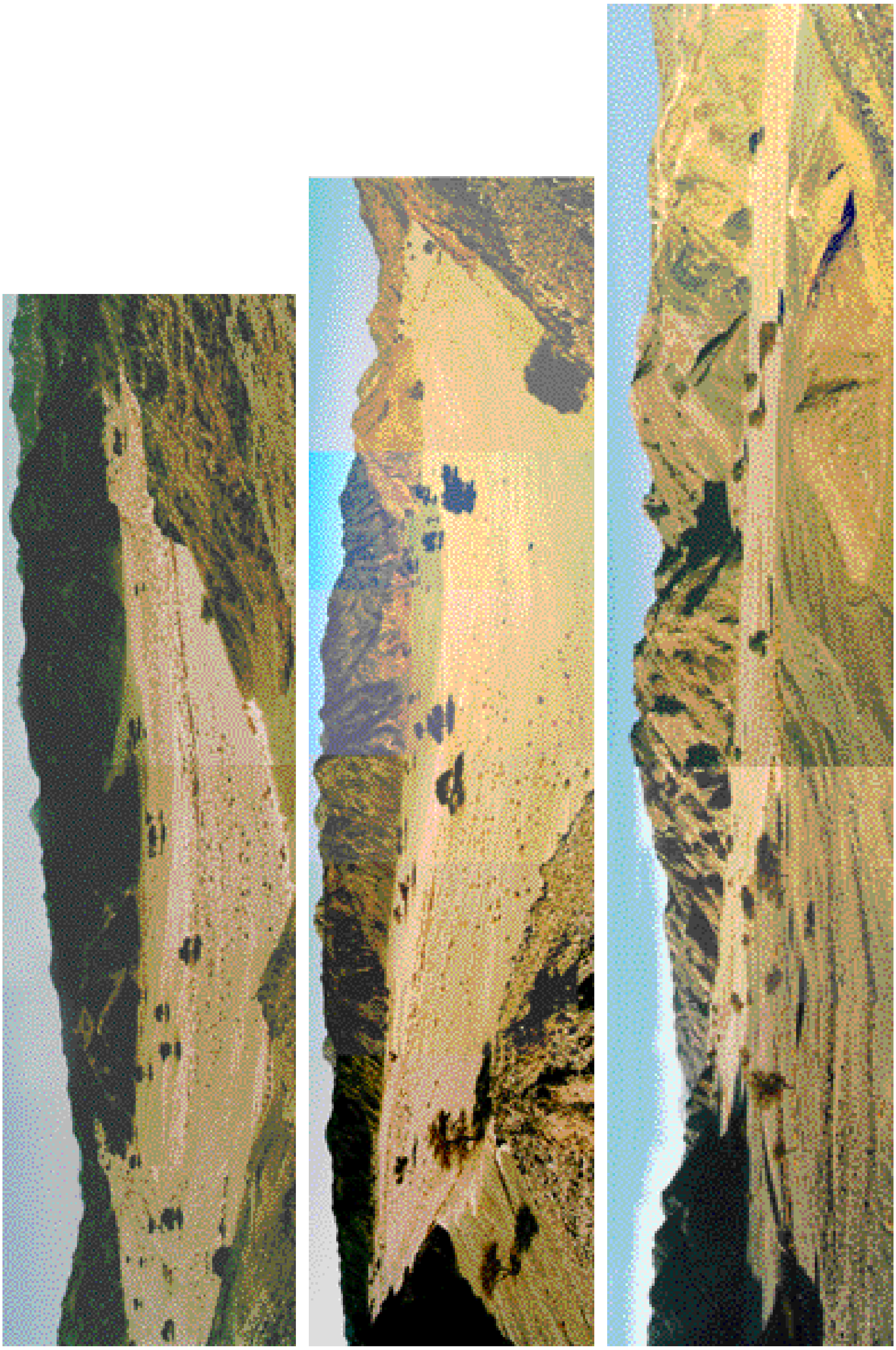
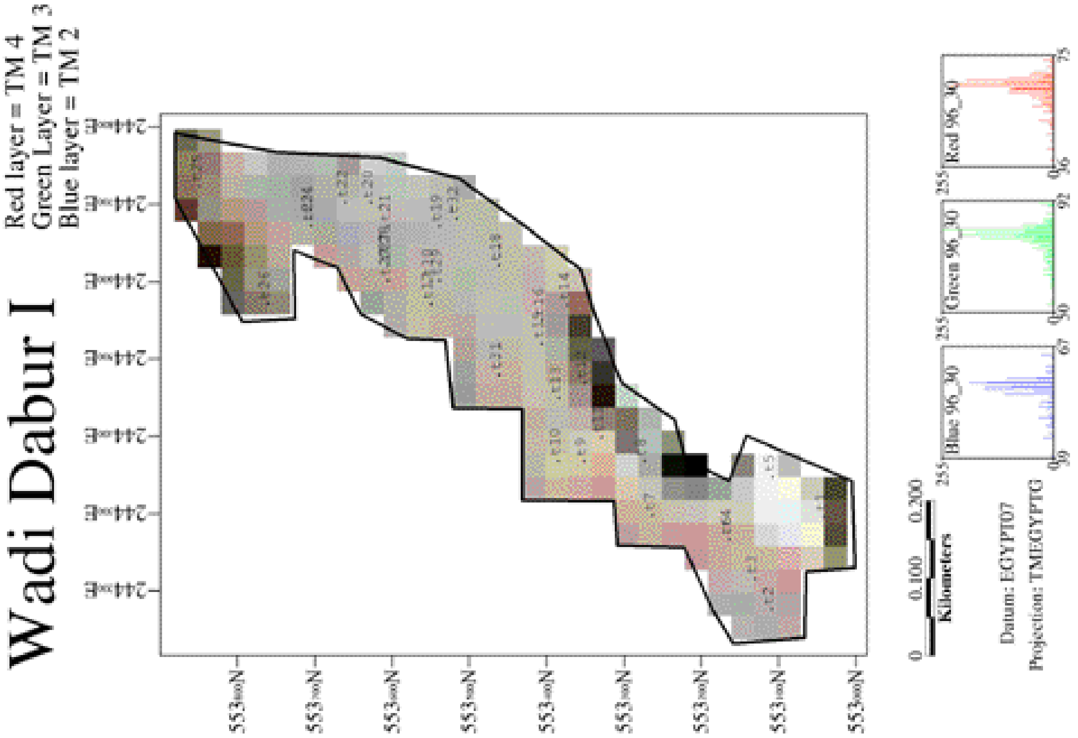


Figure 45 The W. Nuqrus site. Images are arranged from north to south (upper looking south, middle looking east, lower looking northeast).

Figure 46 The W. Abu Ghusun site (looking south)



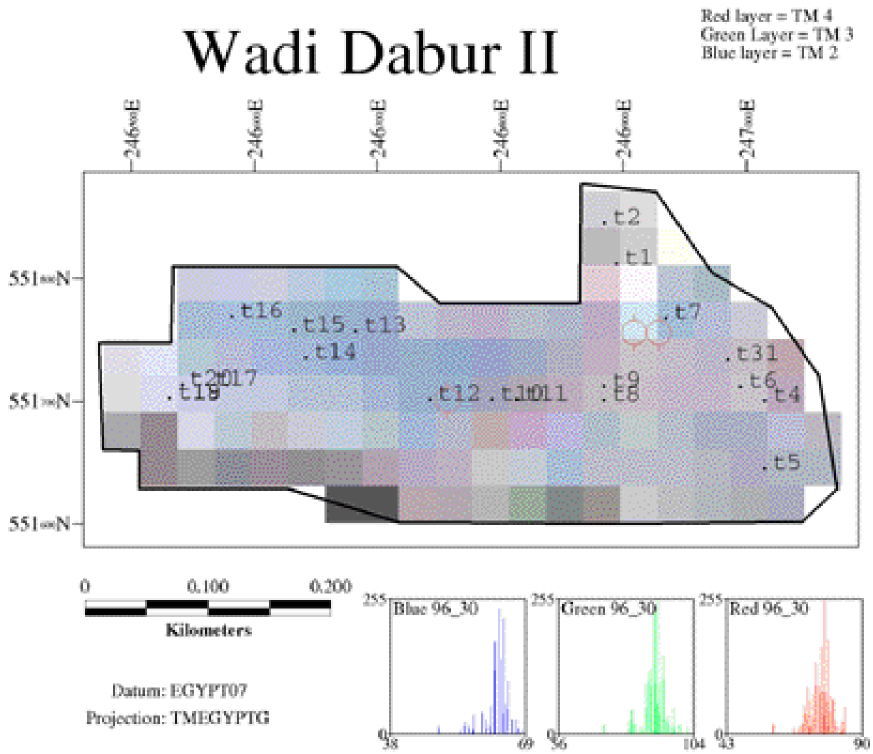


Figure 48 W. Dabur II as recorded by the TM sensor. Red symbols indicate remains from a tree and a charcoal pit.

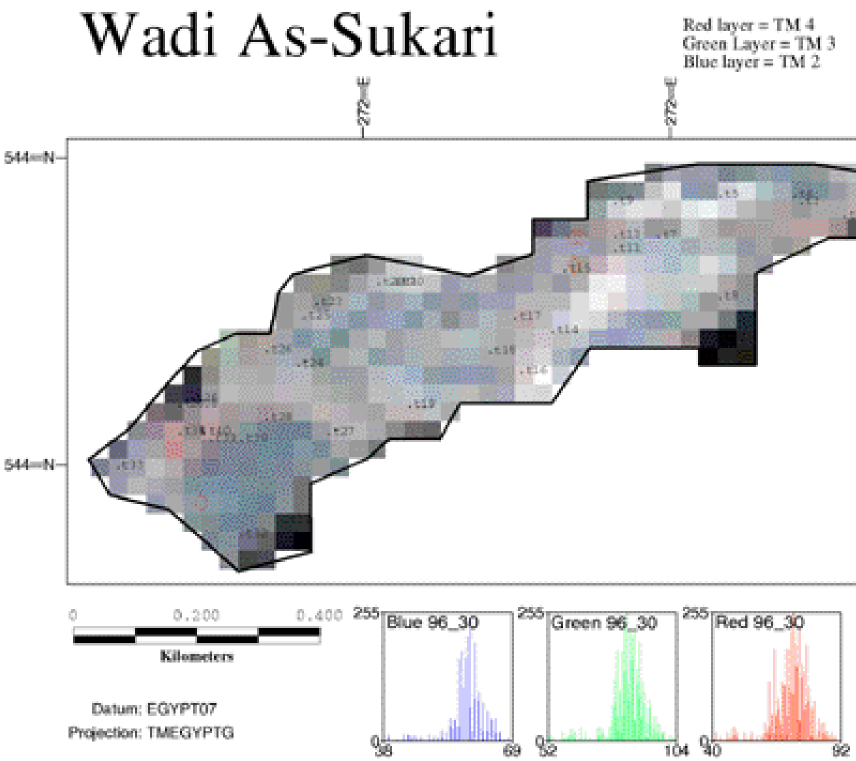


Figure 49 W. As-Sukari as recorded by the TM sensor. The four red symbols indicate the charcoal pits recorded.

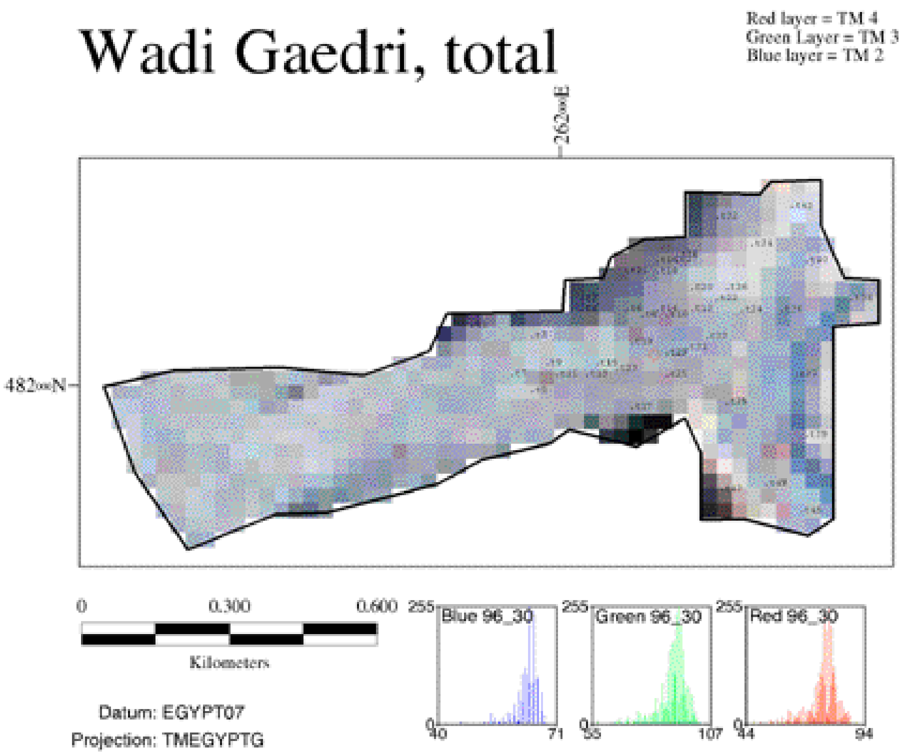


Figure 50 W. Gaedri as recorded by the TM sensor. The red symbol indicates a burnt trunk (see fig. 42, there seen in the central part of the image).

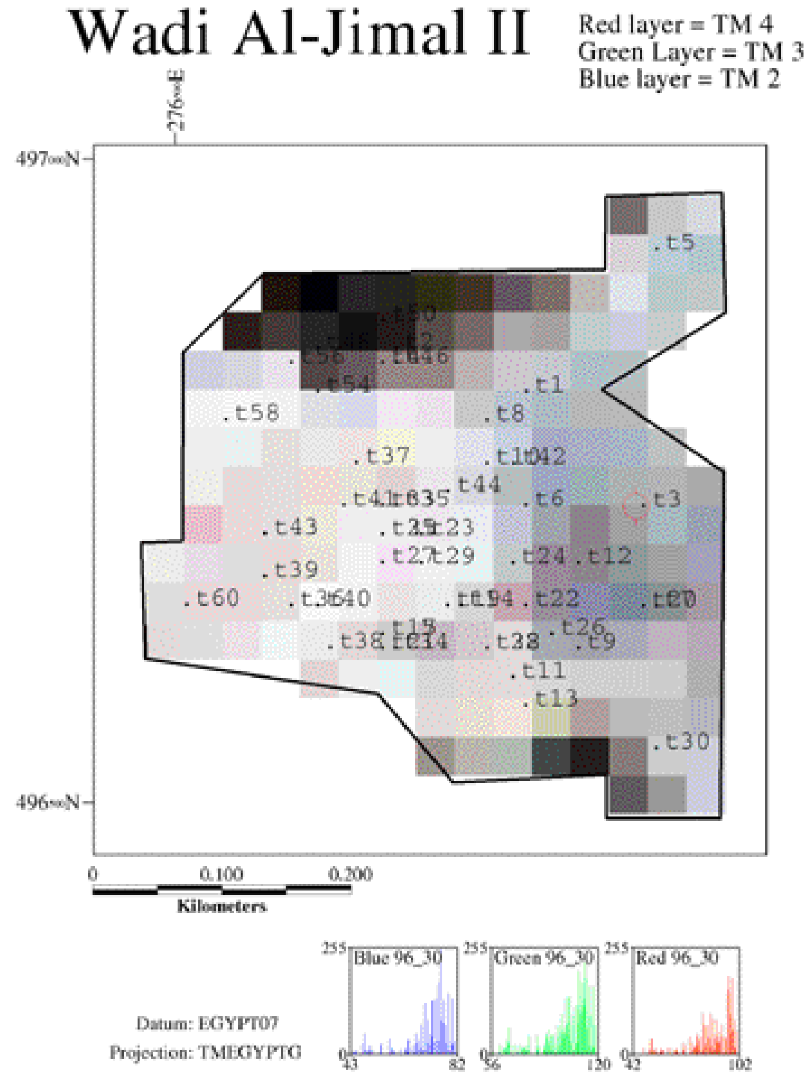


Figure 51 W. Al-Jimâl I as recorded by the TM sensor. The central red symbol indicates a chopped, dead trunk. The other two symbols

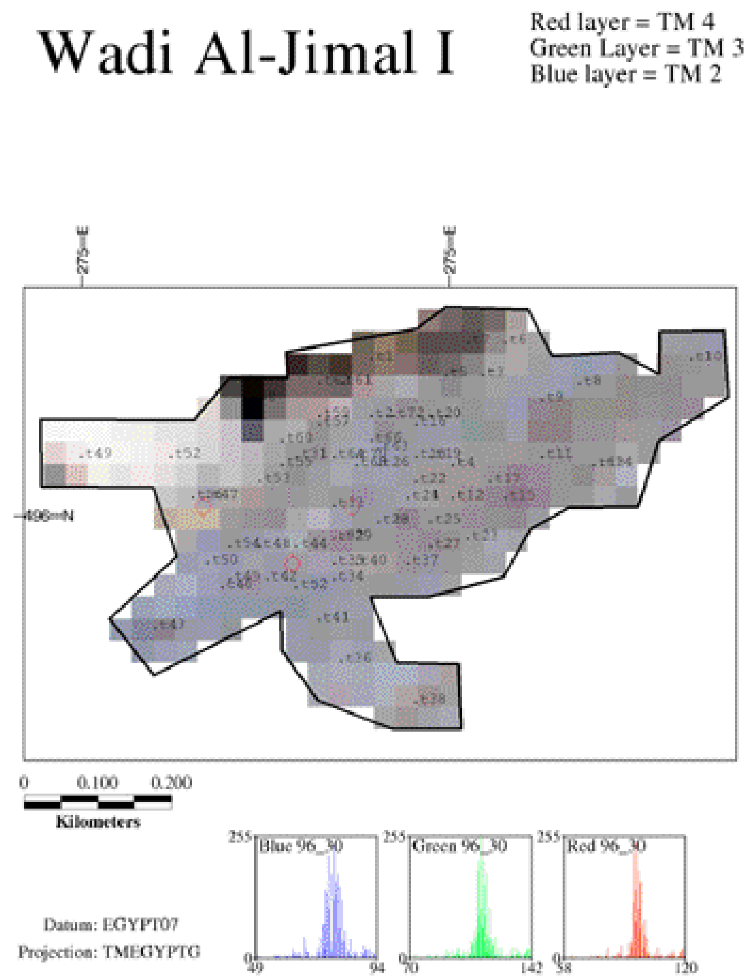


Figure 52 W. Al-Jimâl II as recorded by the TM sensor. The red symbol indicates a dead tree.

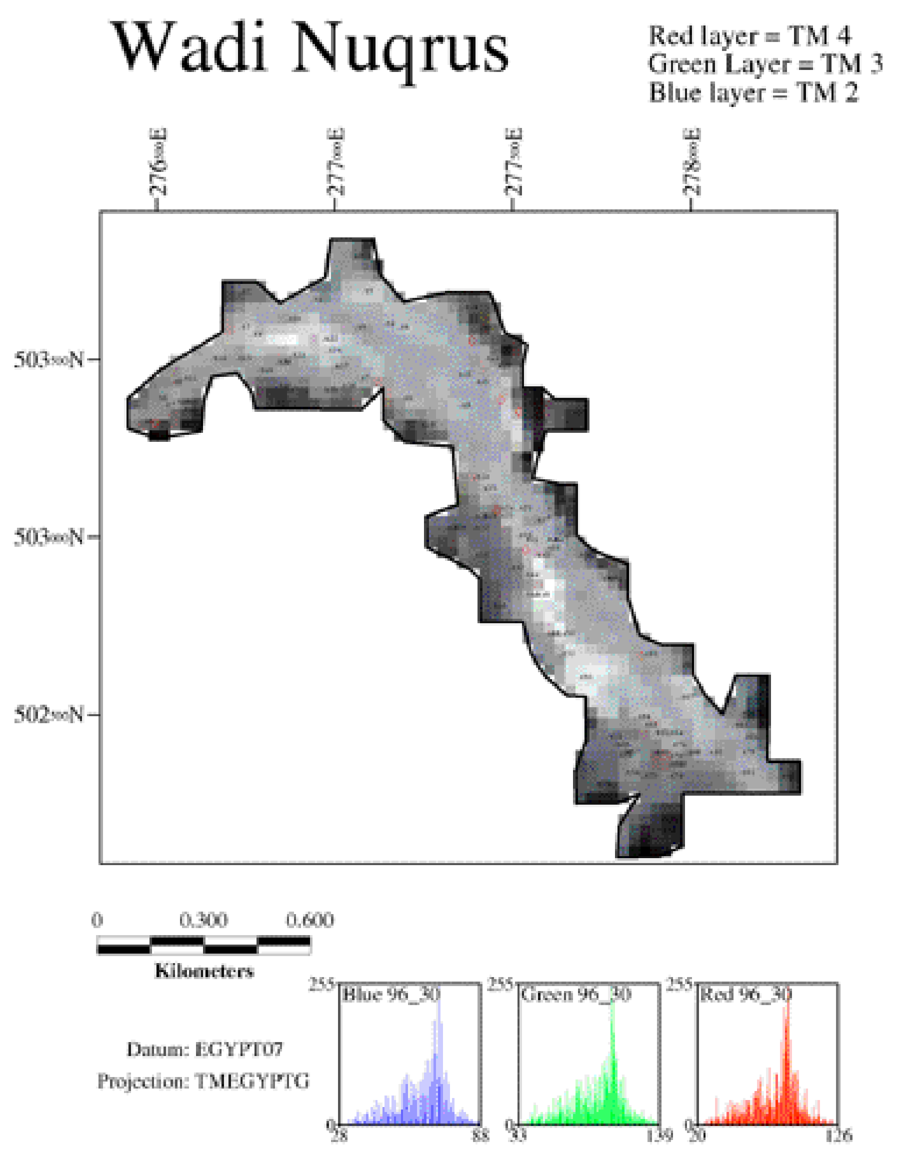


Figure 53 W. Nuqrus as recorded by the TM sensor. Going downstream the red symbols indicate: a burnt trunk, remains of a *Lepatadenia pyrotechnica*, a

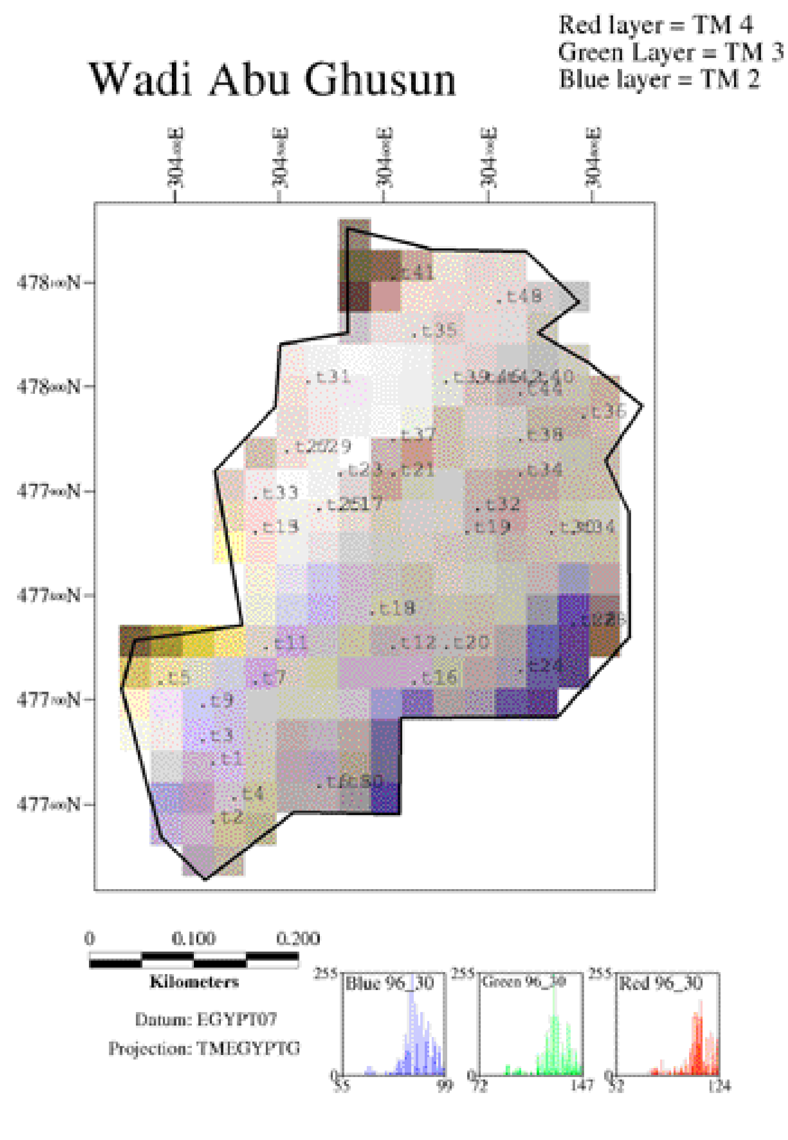


Figure 54 W. Abu Ghusun as recorded by the TM sensor.

Field observations for sites

Recorded species

Acacia tortilis and *Balanites aegyptiaca* are the two most abundant perennial, arboreal species recorded at the sites studied. Other recorded and positioned species are *Acacia ehrenbergiana*, *Leptadenia pyrotechnica*, *Lycium shawii*, *Ochradenus baccatus* and *Solenostemma argel*. The distribution of these species is presented in Table 26, which also shows the total number of individuals recorded at each site, the number of observations lacking species data and the cases in which the species were not identified. The "no data" category consists mainly of trees for which data were lost due to tape-recording problems (cf. p. 75).

Table 26 Arboreal perennial species recorded at sites including the total number of species and the number of species lacking data.

Species	W. Al-Miyâh	W. Dabur I	W. Dabur II	W. As-Sukari	W. Geadri	W. Al-Jimâl I	W. Al-Jimâl II	W. Nuqrus	W. Abu Ghusun
Acacia ehrenbergiana	6								
Acacia tortilis.	28	18	23	39	44	7	5	107	40
Balanites aegyptiaca					1	50	29	4	
Leptadenia pyrotechnica	3					5	6	3	
Lycium shawii									5
Ochradenus baccatus						2			
Solenostemma argel								3	
No data	5	12			3	6	12	12	3
Unknown		2					1		
Total	42	32	23	39	48	70	53	129	48

The most frequent non-arboreal species at the sites is *Zilla spinosa*. At the time of the field-work it was dry in most places. *Pulicaria undulata* and *Franceuria crispa* were also frequent. Some other less frequent species recorded are *Pteranthus dichotomous*, an annual herb found at Abu Ghusun, *Aerva Javanica*, *Citrullus coloquinthus* and *Zygophyllum coccineum* recorded at Wadi Dabur, *Bergularia tomentosa* and *Reseda stenostachya* registered at Al-Jimâl, *Cassia senna* and *Chrozophora plicata* at noted at Gaedri, and *Paronychia sinaica* and *Blepharis ciliaris* observed at Nuqrus.

A total list of all species recorded is included in Appendix 4.

Qualitative signs of human interference at sites

Signs of both browsing and lopping were looked for on every tree recorded, and the general observation was that every individual had at least some traces of both. Figs. 55 and 56 show specimens of *Acacia tortilis* and *Balanites aegyptiaca* that show cutting.

Figure 55 Cut *Acacia tortilis*

Figure 56 Cut *Balanites aegyptiaca*

Signs of browsing are easily seen at the frayed ends of branches (Fig. 57). If a tree is already sparsely branched, cutting is easily seen at distance; otherwise a more thorough examination is necessary. If the tree has been recently cut, branches are often still left on the ground. However, in time these will be removed and used as firewood. At Wadi Al-Jimâl I some trees were heavily lopped, and several branches were still found on the ground (Fig. 58).

Figure 57 Browsed *Acacia tortilis* branch

Figure 58 Heavy lopping in W. Al-Jimâl I

At W. Al-Jimâl II, at short distance from these trees, the general picture was different. Even though the effects of cutting were observed, the majority of trees had not been cut for a long time; and on some trees it was not possible to detect any signs of cutting at all. Also, on many *Balanites aegyptiaca* the branches hung down to near the ground (Fig. 59). This was, however, the only locality with few traces of cutting. The individuals had some marks of browsing.

The trees in both Dabur sites had generally been both browsed and lopped. However, several new shoots were seen at the Dabur I site. One tree in Wadi Al-Miyâh also had new shoots and even low branch-heights. In Wadi As-Sukari some trees were observed with only a few traces of cutting, and on one tree no traces could be found. Some of the trees growing in the downstream part of the locality also showed some signs of browsing. The other trees at As-Sukari were generally both cut and browsed.

Wadi Abu Ghusun had a relatively high number of severely cut trees. Main branches were removed and some had been cut at the root level. The main trunk of one tree had been removed by burning. In Wadi Nuqrus too large branches had been removed. A three meter long main branch was observed partly torn off at a height of two meter up. A branch of 2.5 m had been left on the ground.

Wadi Gaedri also had a large number of heavily lopped trees, and traces of browsing were registered on all individuals. A *Balanites aegyptiaca* with few leaves, exposed horizontal roots and looking as it were dead had a new, 1 m high shoot growing from one of the exposed roots, see Fig. 60. One other example of shoots from trunks that looked dead was studied in detail. This tree was recorded outside the sites studied. An unsuccessful attempt to remove it for charcoal production had severely damaged it; only the broken main trunk

Figure 59 *Balanites* in Al-Jimâl II with no recent cutting and with branches down to near the ground.

Figure 60 New shoots from exposed roots on a *Balanites aegyptiaca*. One is zoomed in (upper left).

Figure 61 A heavily damaged *Acacia tortilis* that will soon become charcoal

Figure 62 It is still vital –insets zoom in on new shoots

was left (see Fig. 61). Despite this treatment and its poor appearance it was still vital and had produced new shoots (see Fig. 62).

Another observation from outside the sites studied also deserves attention. On the foothills of J. Umm Naqqat (223,000 E, 601,000 N) *Moringa peregrina* was recorded. Some branches had been cut off from some individuals.

The Wadi Gaedri story

According to local nomads who were temporarily camping in W. Gaedri (see Figs. 63 and 64) trees having exposed roots were considered dead and thus available for cutting and charcoal production. Also leafless trees were included in the same category. From green trees branches are only removed for fodder. This practice, as observed in W. Al-Jimâl I, leaves ample amounts of dry branches on the ground for domestic energy use.

These nomads referred to themselves as Ababda, not Egyptians. Although they were at first reluctant to tell about charcoal production, they finally told stories about how Egyptian policy forced them to overexploit their tree resources in order to survive. Taxes

Figure 63 Nomads in W. Gaedri I

Figure 64 Nomads in W. Gaedri II

Figure 65 Charcoal production in W. Hulus

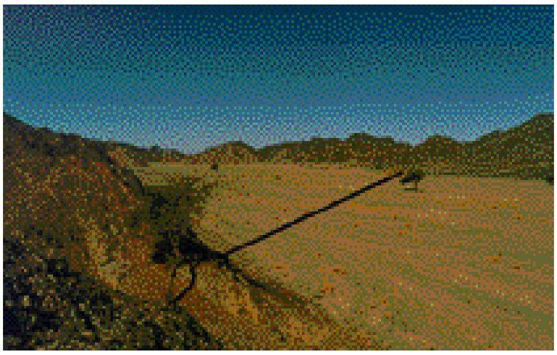


Figure 66 The western part of W.Gaedri, left

on their goods (mainly charcoal and goats) had been increased to stop their nomadic lifestyle. However, to compensate for lost income they produced more charcoal, because trees were a resource available at no investment cost and gave a greater return than their goats. They know charcoal production is not a sustainable use, but "Insh'Allah" (Good willing) they hope to survive the present. The future, however, is in the hands of Allah, and if there will be enough trees in the future, that is Allah's will.

Charcoal production was observed at several places as we travelled down the W. Hulus on our way to W. Gaedri. Close to a place were charcoal was being burned not less than twenty bags of charcoal were stored, waiting for transportation, see Fig. 65. In the central part of the W. Gaedri (see Fig. 42) we observed a burnt trunk indicating charcoal production. Nomad informants told us that in the western part of the locality there used to be "a lot" of trees. This area is now all but completely deforested due to charcoal production. In March 1996 only four trees and a shrub were left in this large part of the wadi, see Fig. 66.

At other sites too signs of charcoal production were recorded, *i.e.* charcoal pits and/or charcoal and soot on the ground. Dead trees were also recorded at some localities. Table 27 shows a summary of recorded incidents for all localities.

Figure 67 An axe left on a tree in W. Nuqrus.

Figure 68 A shepherd feeding his goats by shaking leaves down from a tree with his crook.

Table 27 Signs from charcoal production and dead trees that were recorded at sites studied

	W. Al-Miyâh	W. Dabur I	W. Dabur II	W. As-Sukari	W. Gaedri	W. Al-Jimâl I	W. Al-Jimâl II	W. Nuqrus	W. Abu Ghusun
Trunk/dead remains			1	2	2	1	1	2	
Charcoal related observations			1	4	2			4	1

Other signs of human interference with vegetation were also seen at the sites studied. Among these were an axe left in a tree (Fig. 67), the shepherd's crook (Fig. 68), and a camel saddle, each object representing three important ways nomads used the trees: as energy, fodder and shelter.

Summary statistics for measured variables

For the most abundant species, statistics were calculated separately for each site. As already seen, the localities were dominated by *Acacia tortilis* and/or *Balanites aegyptiaca*. *Balanites* was most frequent at the two W. Al-Jimâl localities, while *Acacia* dominated the others.

The following presentation is based on tables and figures. The figures are boxplots: the box is divided by the median, the length of the box is the inter-quartile (IQ) range, the 'whiskers' extend to the largest/smallest observation within 1.5 IQ range of the top/bottom of the box. Outliers are found beyond this range, and are symbolised by stars. The inner box is the 95% confidence limit of the median.

The varying number of observations, n, is due to incomplete records, which, as explained earlier, were due to tape-recording problems. However, there is no reason to believe that the lack of some data influences the general picture to any appreciable degree.

Branch height

Branch height was measured to indicate the degree of browsing and lopping. Low branches are assumed to indicate that there has been little human interference.

Wadi Al-Miyâh is the only example of an *Acacia*-locality where trees with low branches dominated (Fig. 69). Trees with low branches were rarer at other stations. For Wadi Dabur II, Gaedri and Nuqrus such low heights are considered statistical outliers. Wadi As-Sukari and Abu Ghusun are in many respects opposites to Wadi Al-Miyâh. Those localities also show a great variation in branch heights. However, in general trees have high branch

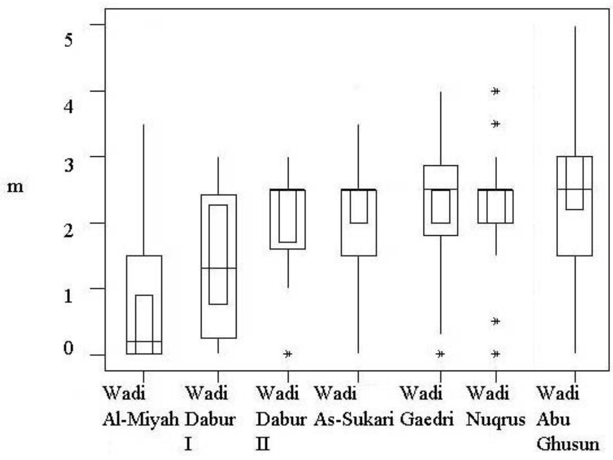


Figure 69 Comparison of branch heights for *Acacia tortilis* among localities

Table 28 Branch heights for *Acacia*-dominated localities

Branch height	n	Mean	St.Dev.
Wadi Miyah	25	0.73	1.02
Wadi Dabur I	16	1.44	1.11
Wadi Dabur II	17	2.04	0.75
Wadi Sukari	32	2.09	0.94
Wadi Gaedri	40	2.18	0.99
Wadi Nuqrus	87	2.19	0.76
Wadi Abu Ghusun	39	2.24	1.10

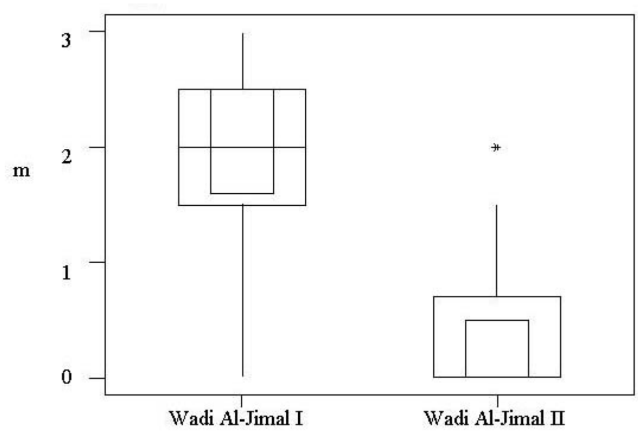


Figure 70 Comparison of branch heights for *Balanites aegyptiaca* among localities.

Table 29 Branch heights for *Balanites*-dominated localities

Branch height	n	Mean	St.Dev.
Wadi Gimal I	49	1.84	0.92
Wadi Gimal II	27	0.52	0.76

heights. This is also seen at Wadi Dabur II and Nuqrus. Extremely low branches are present only on a few trees (statistically they appear as outliers). Wadi Dabur I is the only station where intermediate branch heights are most frequent, and where both higher and lower branches are also common.

The difference in the branch height at the two W. Al-Jimâl stations is very pronounced (Fig. 70). Station II has a clear dominance of trees with low or even zero branch level. This is in accordance with the very sparse signs of cutting. There are only a few trees with such low branch heights at site I. Here, the dominating branch height is about 2 m which is the highest observed at W. Al-Jimal II.

Height

One clear trend seen at all localities is the absence of short, *i.e.* young trees (Fig. 71). Four stations have trees shorter than 2 m: Abu Ghusun, Al-Miyâh, Nuqrus and As-Sukari. Both

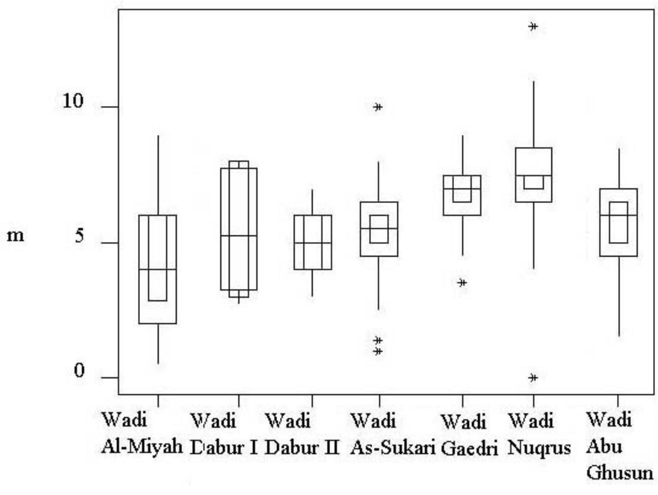


Figure 71 Comparison of heights for *Acacia tortilis* among localities

Table 30 Tree heights for *Acacia*-dominated localities

Height	n	Mean	St.Dev
Wadi Miyah	29	4.22	1.76
Wadi Dabur I	8	5.40	2.11
Wadi Dabur II	19	5.05	1.19
Wadi Sukari	39	5.52	1.79
Wadi Gaedri	39	6.87	2.59
Wadi Nuqrus	99	7.48	1.83
Wadi Abu Ghusun	32	5.61	

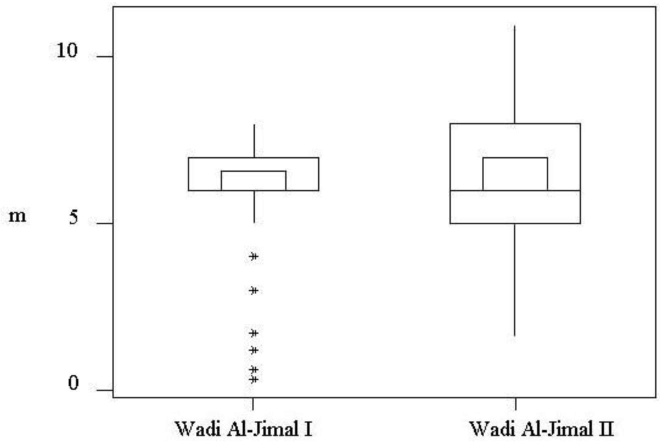


Figure 72 Comparison of heights for *Balanites aegyptiaca* among localities

Table 31 Tree heights for *Balanites*-dominated localities

Height	n	Mean	St.Dev.
Wadi Gimal I	48	5.97	1.80
Wadi Gimal II	27	6.35	2.18

at Nuqrus and As-Sukari these trees are, however, statistical outliers; there are one and two individuals there respectively. It must be added that two small *Acacia*s also were recorded at Dabur II, but the exact heights are unfortunately lost and are thus not part of the data-set represented in fig 71.

Tall trees with rather similar heights dominate at Gaedri and Nuqrus. At Dabur I trees within the IQ-range show great variation in height; and the median size seen is similar to that at Dabur I and As-Sukari. W. Al-Miyâh is the locality with the smallest median tree size.

Short trees grow in both Al-Jimâl localities (Fig. 72). Actually, the shortest trees are recorded at Al-Jimâl I; however, there all trees below 5 m are statistically categorised as outliers. The shortest tree recorded at Al-Jimâl II is 1.6 m. Tall trees are also taller there and the heights of the majority of the trees are more variable than at Al-Jimâl I, but the median height is similar for both *Balanites* localities.

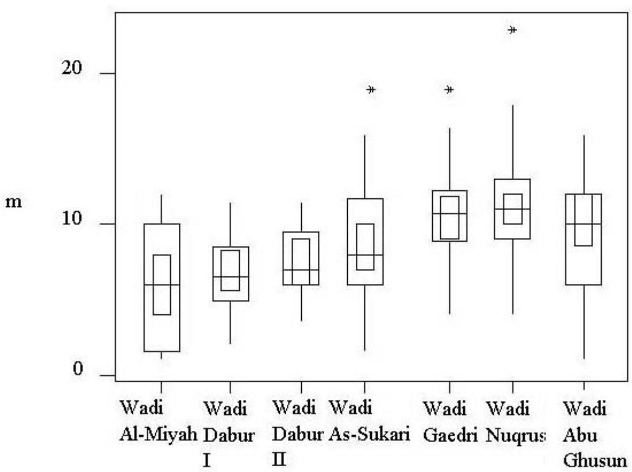


Figure 73 Comparison of crown diameters for *Acacia tortilis* among localities

Table 32 Crown diameters for *Acacia* dominated-localities

Crown Diameter	n	Mean	StDev
Wadi Miyah	30	6.02	3.87
Wadi Dabur I	18	6.71	2.51
Wadi Dabur II	19	7.58	2.45
Wadi Sukari	37	8.85	3.70
Wadi Gaedri	30	10.78	3.17
Wadi Nuqrus	100	11.11	3.24
Wadi Abu Ghusun	35	9.46	3.90

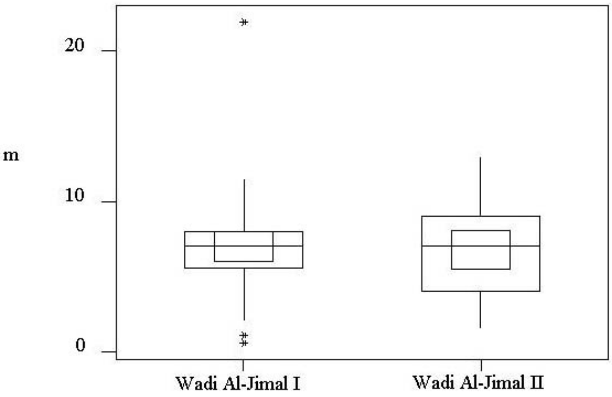


Figure 74 Comparison of crown diameters for *Balanites aegyptiaca* among localities

Table 33 Crown diameters for *Balanites*-dominated localities

Crown Diameter	n	Mean	StDev
Wadi Gimal I	50	6.81	3.31
Wadi Gimal II	27	6.76	3.05

Crown diameter

For the *Acacia* localities, the largest crown diameter was that of a tree growing in W. Nuqrus (23 m). Such large crowns are, however, uncommon and are treated statistically as outliers (Fig. 73). Trees growing at Nuqrus, Abu Ghusun and Gaedri show a great variation in crown diameter, and large crowns are more common here. Trees with smaller crown sizes dominate the Al-Miyâh, As-Sukari and the Dabur localities. The inter-quartile variation in crown size is, however, less for the Dabur localities than for both Al-Miyâh and As-Sukari.

For the trees at the Al-Jimâl stations, crown sizes and their variations are quite similar (Fig. 74). Al-Jimâl I has one tree with a very large crown and two trees with very small crowns; however, all these are treated statistically as outliers. The median crown sizes are similar for the localities.

Trunk diameter

Wadi Nuqrus is clearly seen to be the locality with the largest Acacia trees (Fig. 75). The

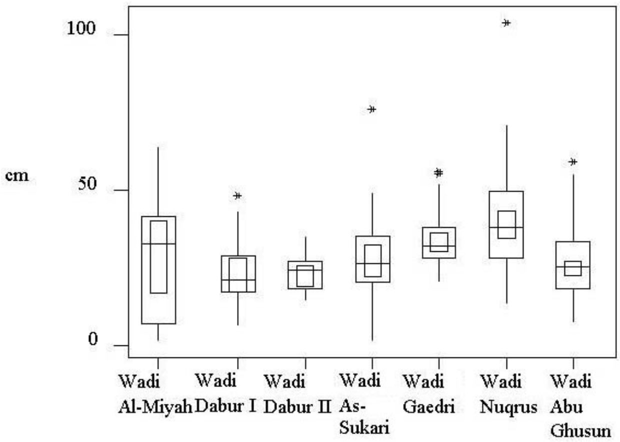


Figure 75 Comparison of trunk diameters for *Acacia tortilis* among localities

Table 34 Trunk diameters for *Acacia*-dominated localities

Trunk Diameter	n	Mean	St.Dev.
Wadi Miyah	26	28.17	11.36
Wadi Dabur I	17	23.47	11.16
Wadi Dabur II	21	22.90	6.31
Wadi Sukari	39	27.90	11.55
Wadi Gaedri	43	34.56	18.77
Wadi Nuqrus	101	40.10	15.15
Wadi Abu Ghusun	40	26.25	

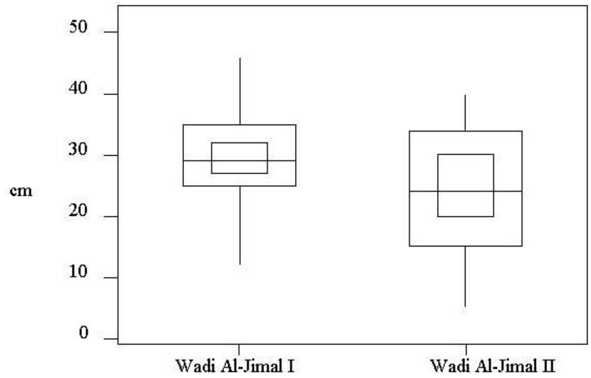


Figure 76 Comparison of trunk diameters for *Balanites aegyptica* among localities

Table 35 Trunk diameters for *Balanites*-dominated localities

Trunk Diameter	n	Mean	St.Dev.
Wadi Al-Jimâl I	47	29.96	9.16
Wadi Al-Jimâl II	27	24.04	9.98

thickest trunk among all sites is recorded here, but in general too trees here have thicker trunks than at other places. Wadi Gaedri is another locality that is dominated by large trees; even the thinnest trunks at this station are large. The distribution of trunk size for the trees at Wadi Al-Miyâh is different from that at all other localities, but in terms of the presence of several trees with large trunks it is similar to Nuqrus and Gaedri. Large trees are a rare observation at the other stations. The shortest trees grow in the Dabur localities; Abu Ghusun and As-Sukari are in an intermediate class of trunk size.

The recorded *Balanites* generally have thicker trunks at Al-Jimâl I (Fig. 76). The inter-quartile variation in trunk size is, however, greater at Al-Jimâl II. The average difference among the localities is approximately six cm.

Comparison of the mean and median distribution of variables

Acacia tortilis

The data for most localities and variables are not normally distributed; thus the following comparison is based on the median (Fig. 77).

For all those variables, the As-Sukari value is also identical with the grand median. However, for branch heights only Dabur I and Al-Miyâh depart from the grand median and both have lower values.

Dabur I and Al-Miyâh also have lower values than the grand median for both height and crown diameter. However, a third station joins them below the grand median: Dabur II. Comparison of the Dabur localities shows that the median tree is slightly taller at Dabur I; however, the median crown diameter is greatest at Dabur II. And as Al-Miyâh has the lowest median branch height, it also has the lowest median height and crown diameter.

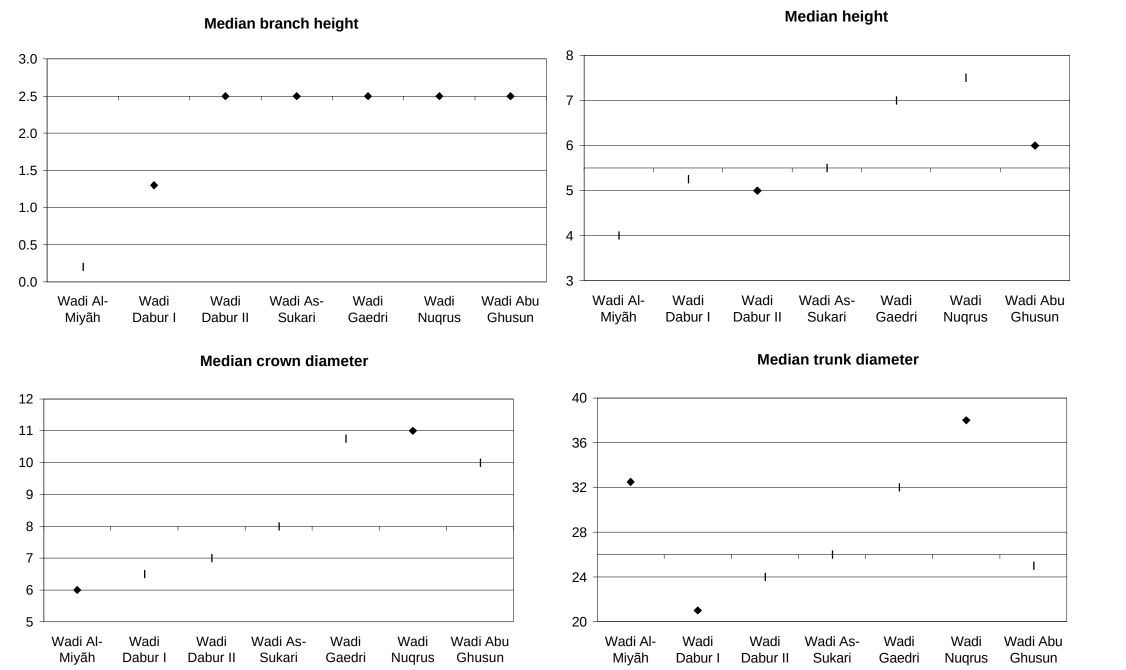


Figure 77 Comparison of median distribution for *Acacia*-dominated localities. The category axis indicates the grand median of the variable.

The pattern of median distribution above the grand median size is also similar for height and crown diameter. The ranking of the localities is, in increasing order, Abu Ghusun, Gaedri and Nuqrus.

Trunk diameter, does, however show a different median distribution among the localities. As-Sukari still represents the grand median size, but both Al-Miyâh and Abu Ghusun have changed their relative ranks. The median trunk size of the trees growing in Abu Ghusun is below the grand median size, while the median trunk size at Al-Miyâh is above the grand median. It ranks second, just above Gaedri and below Nuqrus. The Wadi Dabur localities have medians below the grand median.

This comparison is based on the median distribution, but emphasising the distribution of the means gives the same two patterns: distribution of branch height, height and crown size are more similar than the distribution of trunk size. The similarity in the three first variables is even more pronounced when means are compared, since also the mean distribution of branch heights exhibit the same pattern as height and crown size (see Tables 28, 30, 32 and 34).

Balanites aegyptiaca

Height and crown-size are similar for both the Al-Jimâl localities (Figs. 72 and 74). In terms of the median they are equal; but if means are compared, the trees are slightly shorter at Al-Jimal I (cf. Table 31). As a percentage of the highest mean the difference amounts to 6 percent. The difference in trunk size is much larger (Table 35), 20 percent for both the mean and the median; and it is the trees at Al-Jimâl I that have the generally largest trunk size. Thus *Balanites* too are more similar in height and crown size than in trunk size.

Arboreal vegetation coverage and density for localities

The area of each polygon, *i.e.* locality area, and calculated crown area are given in Table 36. Many individuals in Gaedri and Dabur I lack crown size data[59]. They have been replaced by the mean crown area. Derived vegetation coverage and density are visualised in Figs. 78 and 79 respectively.

Vegetation coverage and density clearly indicate the aridity of the study area. Vegetation coverage is less than 2% for all localities. The greatest crown coverage is found at Wadi Al-Jimâl II where it amounts to 1.95%. Wadi Dabur I is the most sparsely vegetated locality, with crown coverage of only 0.58 %.

The general tree density is less than four trees per ha. Al-Jimâl still ranks highest, but in this case it is As-Sukari that has the lowest density. Thus there is a slight change in the relative ranks from that seen for vegetation coverage. In addition to As-Sukari, Gaedri and Nuqrus also have relatively lower ranks for density than for vegetation coverage.

Table 36 Crown- and locality area for sites

	W. Al-Miyâh	W. Dabur I	W. Dabur II	W. As-Sukari	W. Gaedri	W. Al-Jimal I	W. Al-Jimal II	W. Nugrus	W. Abu Ghusun
Crown area (m^2)	1265	1030	942	2735	4460	3386	2976.5	6771	3370
Locality area (m^2)	122738	177300	108900	337500	331200	268200	153000	840600	184500

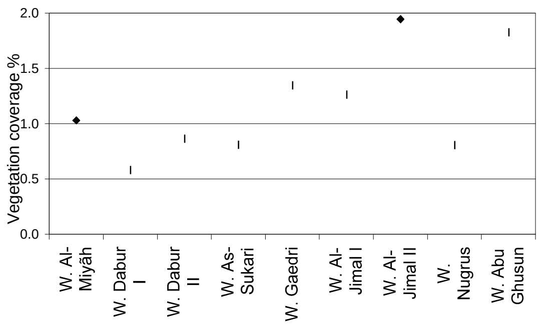


Figure 78 Vegetation coverage for sites

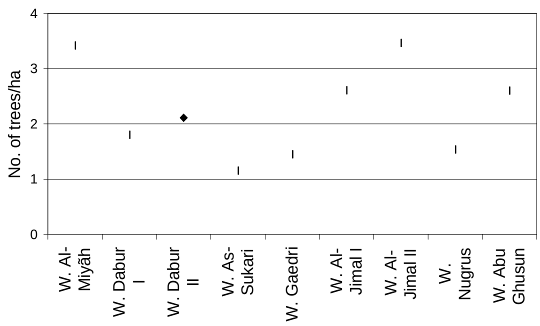


Figure 79 Vegetation density for sites

59 For Dabur I and Gaedri, respectively, 10 and 14 values were lacking.

Analysis of spectral vegetation signatures

In arid lands, vegetation reflectance in satellite images is reported (cf. Vegetation monitoring in dry environments, p.38) to show different characteristics from those observed in areas of high vegetation cover. The selected study area, as described by stations, has a vegetation cover of only a few percent. Hence, understanding the actual influence of vegetation on spectral records is important for making and interpreting change images.

In the following, the spectral vegetation signatures of the selected test area (cf. p. 82-83) are presented. Then the pattern of the means for vegetation coverage for each station is related to different bands and band-combinations. Further, the results of the deductive process leading to an absolute interpretation of vegetation change are presented.

Coefficients, a and b, employed in the calculation of the PVI are derived by regression between the Red and IR bands. Coefficients for the different data-sets are given in Table 37.

Table 37 Coefficients employed in calculation of PVI

	TM	TM_{79}	TM (90 m x 90 m)
a	0.882	0.881	0.881
b	-3.715	-3.696	-3.696

Vegetation signatures – a test area

A rather striking feature of the TM-image is an almost total absence of red pixels; *i.e.* the pixels with high vegetation coverage (cf. p. 33) when the image is displayed as a false colour composite (IR channel as red, the Red channel as green, and the Green channel as

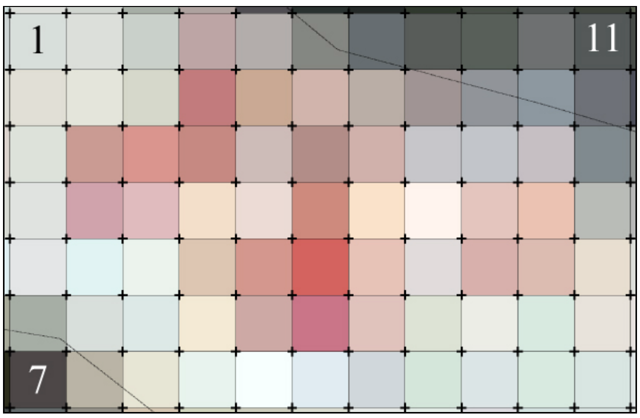


Figure 80 RGB colour composite of the area with the reddest pixels and the highest VI seen on the TM image. Lines indicate the edge of the wadi. Numbers refer to rows, and columns to the image-grid.

blue). A few pixels do, however, appear as bright red (see Fig. 80) and have the highest VIs in the image. This selected test-area is located in Wadi Al-Jimal (283,929 E, 497,962 N) further downstream from the localities investigated. Signatures for this area have been extracted and are plotted as profiles shown in Fig. 81

From the first and seventh profiles it can be seen that there is a generally high correlation between the Red and IR band. Another apparent feature is the generally higher Red DN level.

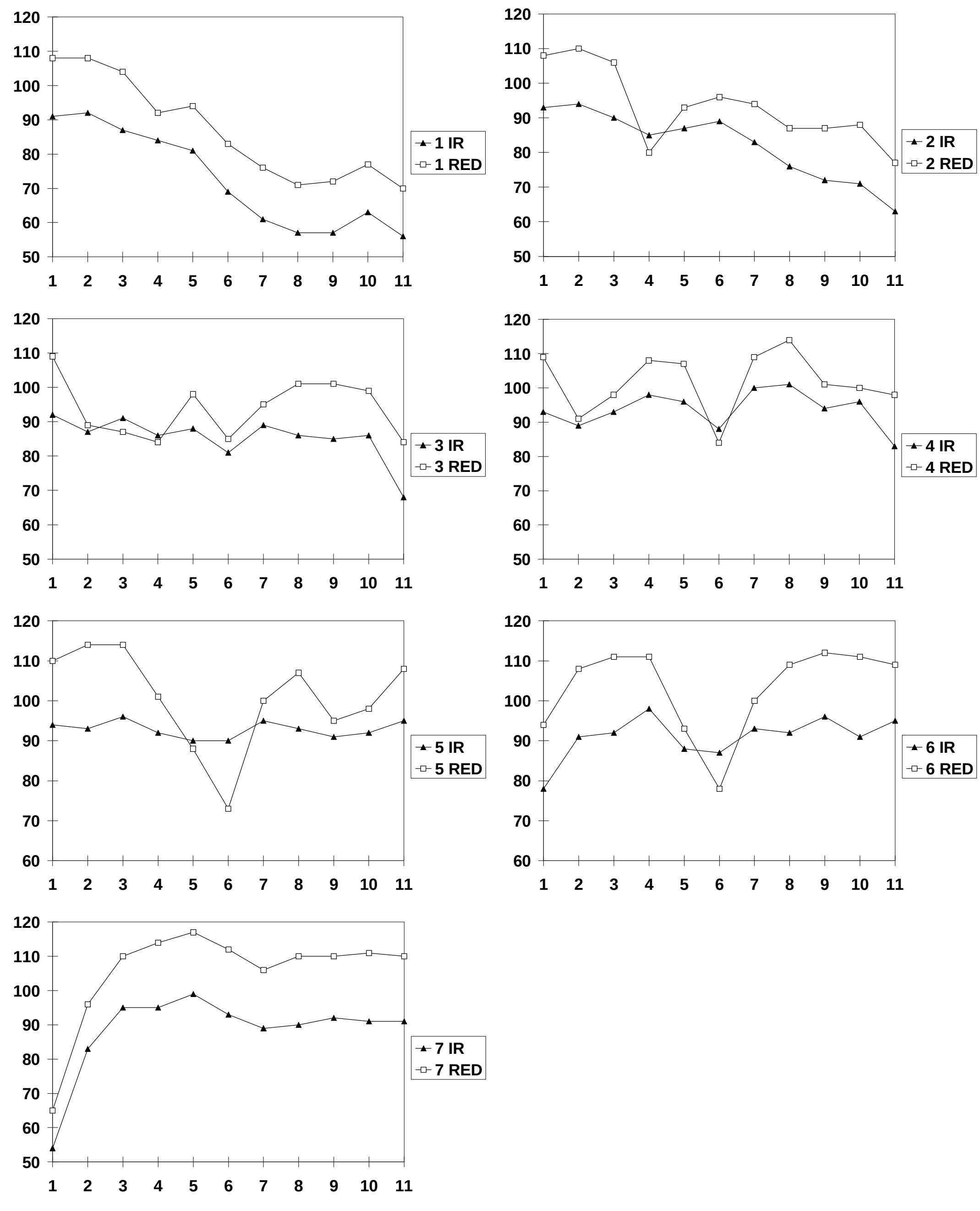


Figure 81 Red and IR signatures seen as a traverse of each row. Legend number refers to rows and x-axis to the column number (cf. fig 80). Y axis refers to DN for pixels.

The reddest pixel is located in row five, column six. If one assumes that the pixels in columns 1, 2, 3 and 11 represent the background reflectance, a very marked decrease in Red is seen towards column six. A background reflectance of about 110 DNs is also seen in the majority of the profiles and very clearly in profile seven. The lower values of the first pixels in this profile are due to their location on the edge of the wadi (cf. Fig. 80). The same trend is seen in the last pixels of profile one. On comparison with the general background reflectance, pixel no. six in profile five is actually almost 40 DNs lower.

Studying the IR profile does not, however, present an equally marked trend for pixel no. six in profile five. The background reflectance for IR is just above 90 on the DN scale and as the traverse moves towards the sixth pixel, there seems to be a small decrease. This is the case for most reddish pixels although the magnitude of the decrease varies. For profile three, pixel three there is a small increase in the IR reflectance.

Figs. 82 and 83 show two threshold images for the selected vegetation indices. In Fig. 82 the VI-threshold is equal to or greater than one and thus displays only pixels where Red has fallen below IR DNs. The equivalent PVI is equal to or greater than 10. In Fig. 83 a lower threshold is chosen; VI is greater than 0.925, and PVI greater than 6. In this latter case the majority of the pixels showing a marked deviation from the general Red-IR correlation lies above the threshold.

In profile one there is, however, one pixel (no. four) that departs from the general correlation trend but is not above the latter threshold. For the Red band the departure is approximately 5 DNs, and the VI and PVI for this pixel are 0.913 and 4.928 respectively.

The spectral effect of vegetation is expressed as a deviation from the correlation between the Red and IR bands. This correlation is related to the level of background reflection. Of the individual bands Red is obviously the one with the most pronounced response to

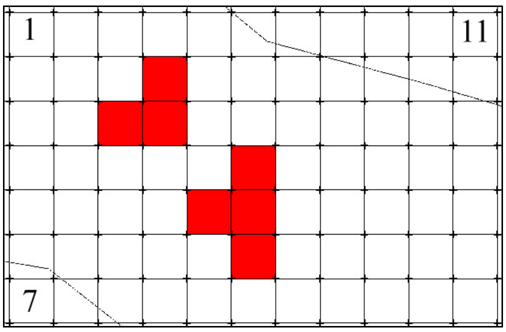


Figure 82 VI ≥ 1 and PVI ≥ 10

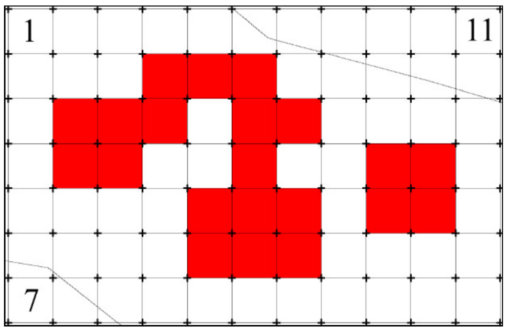


Figure 83 VI > 0.925 and PVI > 6

vegetation. For the amounts of vegetation present at this locality the Red reflectance shows a clear negative deviation from the general background level. The IR reflectance is almost stable, although small and erratic fluctuations around the background level occur. The two vegetation indices, VI and PVI, show similarities.

Fig. 84 shows a comparison of the TM- with the TM_{79}- image for the test area. The comparison is based on pixels having a VI ≥ 1 and a PVI ≥ 10. Pixel values for the six TM_{79}-pixels that spatially overlap the highlighted TM-pixels are given in Table 38.

Two TM_{79}-pixels, *viz.* 4 and 6, have values above the threshold selected for VI and PVI. However, spatially these are not the TM_{79}-pixels with the largest overlap with the TM-pixels shown in Figs. 4 and 5; *i.e.* those above the same threshold. Nor does the magnitude of the vegetation indices of these TM_{79}-pixels have similar levels to those of the TM-pixels. In all the highlighted TM-pixels Red values were lower than their IR values (see Fig. 82); hence their VIs were above 1. For the resampled TM_{79}-pixels Red and IR values are equal, and the VI is 1. Thus, on the assumption that spatial inconsistency between the original TM resolution and the resampled MSS resolution is due to a southward grid-displacement, there is a loss of vegetation information in this resampling process.

The other resampled pixels not only have values under the emphasised threshold but also under that including most reddish TM-pixels of the test area, *i.e.* VI > 0.925 and PVI > 6 (see Fig. 83). So for these pixels too vegetation information is reduced in the resampling process.

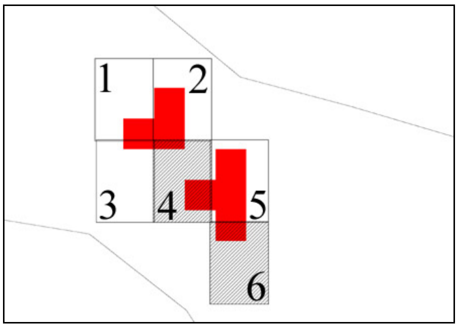


Figure 84 Comparison of resolutions: Background image is similar to figure 82. Large grid is the resampled (56 x 79 m) image. Hatched pixels have a VI ³ 1 and a PVI ³ 10

Table 38 Red and IR DNs and VIs and PVIs for numbered pixels in fig. 84.

Pixel (TM_{79})	Red	IR	VI	PVI
1	107	91	0.850	0.322
2	94	79	0.840	-0.089
3	103	90	0.874	2.216
4	89	89	1.000	10.720
5	96	87	0.906	4.592
6	89	89	1.000	10.720

Towards an absolute interpretation

The locality level

Single bands

The Red and IR means for the study localities are seen in Fig. 85. Since there is no background normalisation when single bands are used, only means are graphed.

The means for the localities vary by approximately 50 DNs, Wadi Dabur I has the lowest Red and IR means, and Abu Ghusun has the highest values. The high correlation between Red and IR is again seen (Fig. 85). This high correlation is also reflected in a comparison of Fig. 86 with Fig. 87, both showing scatter-plots of vegetation coverage and the band means. Both plots show a generally positive correlation; the only difference is a lower off-set for the IR band.

This is a striking result, for a positive correlation between Red and vegetation cover is not expected. Theoretically, and as indicated in the test area, there is an inverse ratio between Red reflectance and vegetation coverage. In this case, however, Dabur I has the lowest vegetation coverage *and* the lowest mean Red reflection. Al-Jimâl II has the highest vegetation coverage and an intermediately high Red mean. Thus, it seems that the presence of trees does not move the mean away from the general background level, and the information about vegetation disappears if sites exhibit large background differences.

Wadi Gaedri west is undoubtedly the area that has the lowest vegetation coverage (see Fig. 42). Wadi Gaedri and Gaedri West exhibit a weak indication of an inverse proportion between Red means and vegetation coverage (Fig. 85). However, as seen from Fig. 94, the

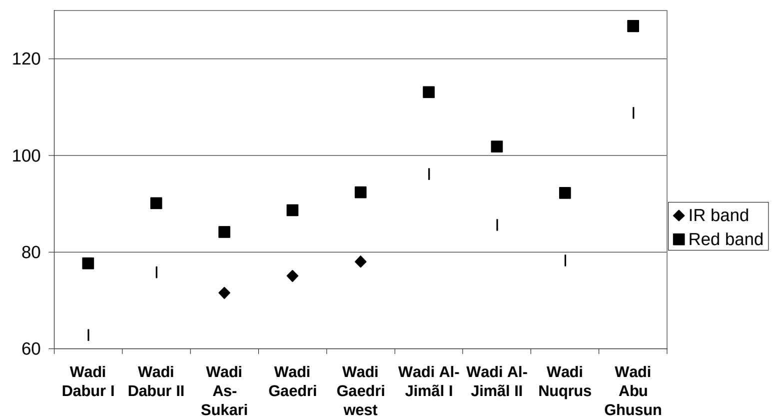


Figure 85 Comparison of Red and IR means for all localities. Values are extracted from the 1996 image, 30 m resolution.

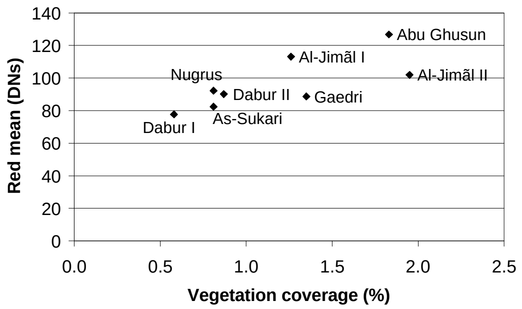


Figure 86 Vegetation coverage plotted against Red means for localities.

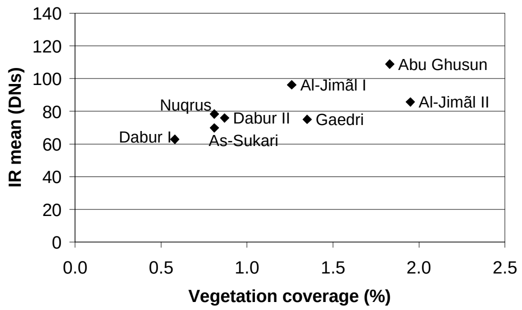


Figure 87 Vegetation coverage plotted against IR means for localities.

background in the western part of the wadi belongs to classes that indicate a brighter background.

For Gaedri and Gaedri West the same negative correlation is also seen for the IR band. Rather than being an indication of vegetation coverage, both this inverse ratio (Fig. 85) and the positive relation between IR and vegetation cover (Fig. 86) seem to be a result of the generally high correlation between Red and IR, that is caused mainly by the background.

Band combinations

Variation in background reflectance is a problem when the means for single bands are compared. After a normalisation of background, *i.e.* applying a vegetation index, vegetation coverage should, in theory, be better expressed. The VI and PVI express vegetation by high values, and thus a locality with vegetation should have a higher mean than localities without or with less vegetation. The mean and ranges for VI and PVI are presented for all localities.

The mean and range of VIs is calculated and graphed for all localities in Fig. 88.

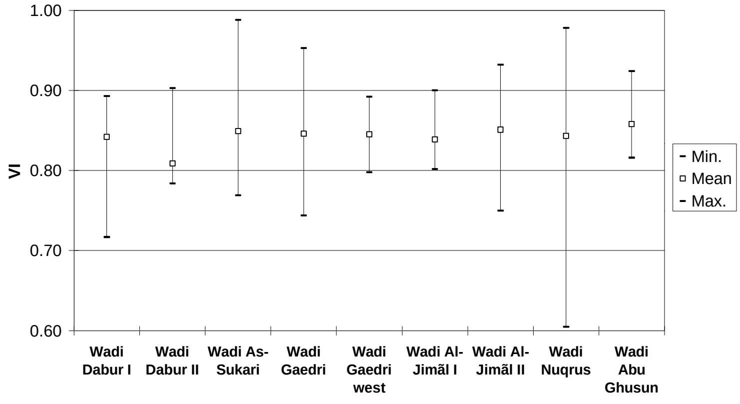


Figure 88 Comparison of VI ranges for all localities, at 1996, 30m resolution

Table 39 Standard deviations for VI for all localities

	St.Dev.
Wadi Dabur I	0.027
Wadi Dabur II	0.026
Wadi As-Sukari	0.032
Wadi Gaedri	0.031
Wadi Gaedri west	0.016
Wadi Al-Jimâl I	0.018
Wadi Al-Jimâl II	0.027
Wadi Nuqrus	0.044
Wadi Abu Ghusun	0.016

Although Wadi Gaedri West is the area having the lowest vegetation coverage (see Fig. 42), the mean VI is higher than for other localities. Deviations from the expected positive correlation are also seen in the scatter-plot for calculated vegetation coverage and means for VI (Fig. 89). Dabur II, for example, has higher vegetation coverage, but lower VI than Dabur I, As-Sukari and Nuqrus. The slope of the correlation is also close to zero indicating only small differences in VIs at this low coverage.

The range of VIs varies among the localities. Theoretically, high values indicate greater vegetation coverage than lower VIs do. Maximum and minimum VIs for sites do not, however, give a general impression of a site; they only represent the extremes for two individual pixels. Nevertheless, the range of values presents an interesting point about Wadi Gaedri West. Its maximum value is lowest compared to those of other localities, but only slightly lower than the maximum values of Dabur II and Al-Jimâl I. The mean for Al-Jimâl I is slightly lower than for Gaedri West and the standard deviations (Table 39) are similar, but the vegetation coverage is very different for the two localities. The few trees growing in Gaedri West could perhaps produce a similar maximum; but a higher mean is not expected. On this basis, it must be questioned how well background is normalised and vegetation registered.

The PVI range plot is seen in Fig. 91. The pattern is similar to that seen for the VI. However, the range for Al-Jimâl I is now greater than for Gaedri West. Also Al-Jimâl II and Dabur I have relatively lower means for the PVI than the VI. This is seen more clearly in Fig. 90, which shows a scatter-plot of the vegetation coverage and mean PVI for all localities. This index too has a low correlation with vegetation coverage, and once again the effect of normalisation can be called into question.

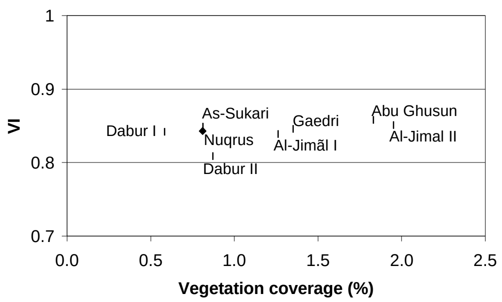


Figure 89 Vegetation coverage plotted against mean VI

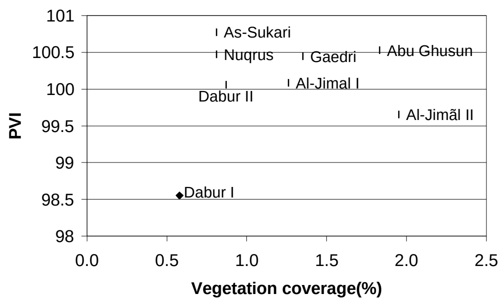


Figure 90 Vegetation coverage plotted against mean PVI (100 was added to the PVI to avoid negative values).

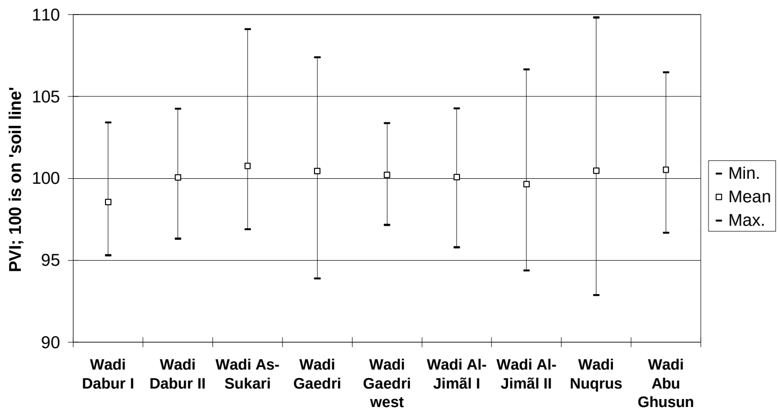


Figure 91 Comparison of PVI ranges for all localities, at 1996, 30m resolution (100 was added to avoid negative values).

Table 40 Standard deviations for PVI for all localities

Locality	St.Dev
Wadi Dabur I	1.493
Wadi Dabur II	1.750
Wadi As-Sukari	1.882
Wadi Gaedri	1.914
Wadi Gaedri west	1.098
Wadi Al-Jimâl I	1.606
Wadi Al-Jimâl II	1.847
Wadi Nuqrus	2.184
Wadi Abu Ghusun	1.425

The pixel level

Testing differences

Band combinations

The locality with the greatest vegetation coverage, Al Jimâl II, is selected here to test the effect of the presence vs. absence of trees on the two vegetation indices.

The first test is made on the assumption that tree-position is sufficiently accurate. Difference is tested by the *t-test*. The second test takes lower accuracy into account by resampling the image to MSS-size and a 90 m^2 pixel size. Fig. 92 shows the trend of the t-test probability for increasing pixel size.

Neither VI nor PVI show significant differences between pixels with and without trees at the TM-resolution. Resampling decreases the effect of low positioning accuracy; however, the groups become statistically more similar as resolution decreases (Fig. 92).

The third test works at the TM resolution, but includes positioning errors by introducing

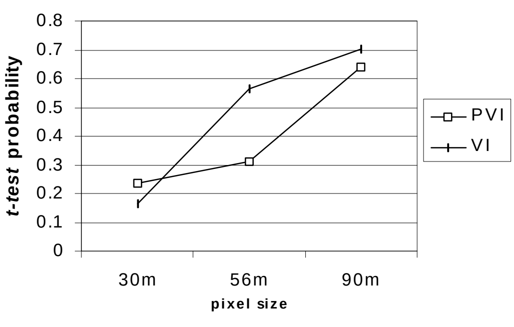


Figure 92 ***t-test*** **probability for VI and PVI as pixel size increases**

Figure 93 ***t-test*** **probability for VI and PVI when tree presence group is selected by neighbours**

neighbour pixels. The *t-test* probability reaches significant levels when the presence group excludes pixels with no or only a small number of neighbour pixels, see Fig. 93. The difference between pixels with and without trees is significant for VI and PVI when only pixels with at least three or four neighbouring pixels, respectively, are included. The constantly lower probabilities for VI indicate a better response for his index than for the PVI. This was also the case for the first test performed, at TM resolution, see Fig. 92.

Single bands

In dealing with single bands only, background normalisation is essential before attempting to detect differences between pixels with and without trees. Wadi Gaedri is used as a test locality. The western part of the locality is also included in the unsupervised classification, see Fig. 94.

Three different classes dominate Wadi Gaedri, *viz.* background-classes 4-6. Background 4 is associated mainly with a water-erosion zone in the eastern part of the wadi (see figs. 42 and 50). Backgrounds 5 and 6 are found both in the main part of the locality and in the western part. Trees are associated with both types. Thus, with the classification scheme employed here, trees are not so different from the background surrounding them that they belong to a single class.

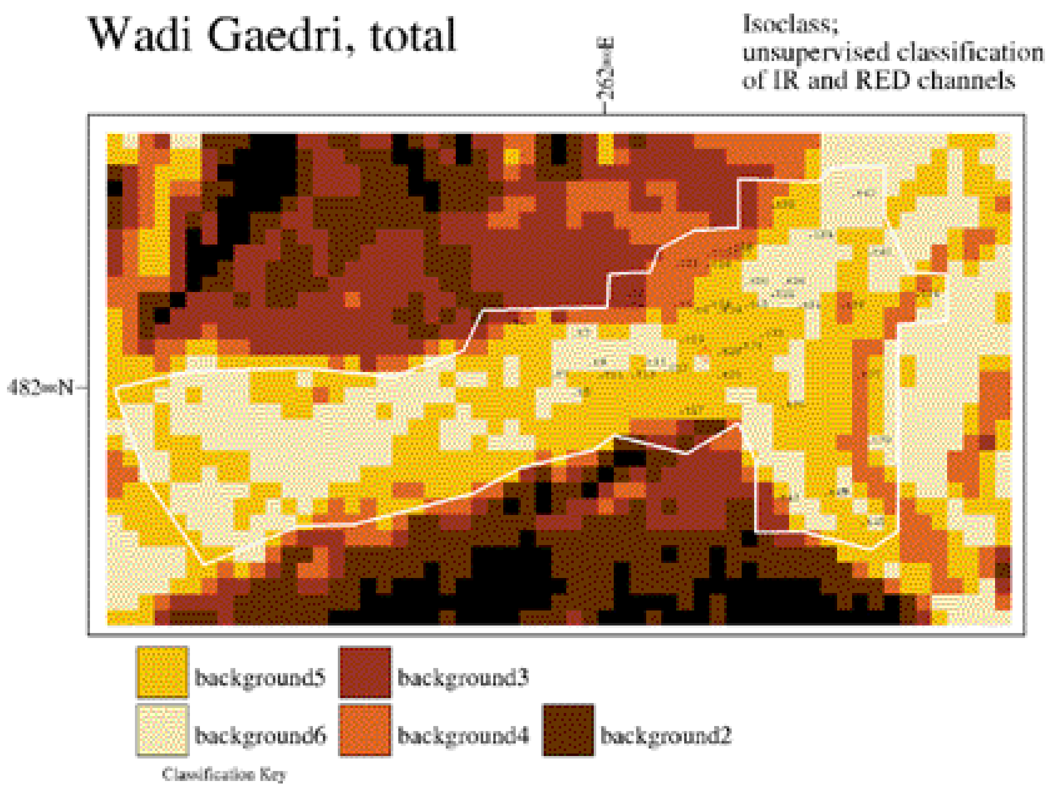


Figure 94 Unsupervised classification of Wadi Gaedri and Gaedri West.

Table 41 Characteristics of trees tested

	T10	T26	T31	T33	T42
Background	5	6	5	5	6
Neighbours	1	2	1	0	0

Table 42 Results of the Walsh test for the Red and IR bands

	t10	t26	t31	t33	t42
Max Red	-*3*	2	2	3.5	0
Min IR	-1	0	-3	-0.5	-4.5

The pixels of five trees, and their eight surrounding pixels, all falling within one background type, were selected; and a Walsh test was performed. Background class and number of neighbour pixels for the pixels tested are given in Table 41. The results for Walsh test are seen in Table 42.

Only t10 is in a pixel that has significantly lower Red DN than its surrounding pixels. For IR, however, there is no significant difference between the tree-pixels and the surrounding pixels.

Correlation and regression

The method selected for testing differences between pixels with and without trees indicates that there are some differences. However, due mainly to position error at the pixel level a consistent difference for a larger data set could not be established. Reducing resolution and therefore positioning error increases the influence of other factors, and no consistent difference is found in those cases. Accordingly, the first requirement is not satisfied; and therefore the final correlation and regression analysis cannot be carried out (cf. Discussion).

Temporal and spatial vegetation change at localities

The signature studies (cf. p. 120) show that Red reflectance is consistent in its vegetation information, *i.e.* vegetation reduces its DN. The information content of IR reflectance, however, seems to vary over vegetation. A major problem in using single bands for vegetation monitoring is the absence of background normalisation. However, this is not a problem when temporal changes in vegetation coverage are monitored. If it is justifiable to assume that the background is stable between the two images describing the period studied, background is automatically normalised. In the study area the background is assumed to be stable. Since vegetation indices also include the inconsistent vegetation information of the IR band, the Red band is preferred as an indicator of temporal vegetation change and is therefore basis for the present change analysis.

Periodic trends

The following presentation of the results is given locality by locality and is based on two different data-sources.

First, for all localities graphs comparing ranges and mean values for all years were prepared. There are three different records for 1996, each based on the different resolutions: TM, TM_{79} and $TM_{81.5}$. Low DNs indicate more vegetation.

Secondly, change images are presented (Figs. 96-127, data, *i.e.* images, that they are derived from are seen in Appendix 5.). While the graphs only give an idea about the trends in the localities, these change images give a more detailed picture of changes and variations in each locality. The change images have been classified into fifteen classes to make visualisation and interpretation easier. For these fifteen classes the colour scheme chosen exhibit three main types of change:

1. Reduction in vegetation coverage is indicated by a shift from yellow to red, from classes 9 to 15; class 9 represents the least reduction and class 15 the greatest reduction.
2. Increase in vegetation coverage ranges from light green to dark green, classes 7 to 1, where class 7 represents the least increase and class 1 the greatest.
3. No change is grey: class 8.

The range of values for each class is given in Table 43. Note that the range of values increases for the most extreme classes. ‘Display value’ refers to the scale of the histograms seen on the change images (Figs. 96-127). These histograms range from 0-255, and each class is displayed as one of these 256 colours.

Table 43 The subjective classification scheme for the change images

Range of values	Display value	Class value	Change trend
-100≥Diffxy≥-300	248	15	Decrease
-50≥Diffxy>-100	231	14	-
-30≥Diffxy>-50	214	13	-
-20≥Diffxy>-30	197	12	-
-10≥Diffxy>-20	180	11	-
-5≥Diffxy>10	163	10	-
-1≥Diffxy>-5	146	9	Decrease
Diffxy=0	129	8	No change
5>Diffxy≥1	112	7	Increase
10>Diffxy≥5	95	6	-
20>Diffxy≥10	78	5	-
30>Diffxy≥20	61	4	-
50>Diffxy≥30	44	3	-
100>Diffxy≥50	27	2	-
300≥Diffxy≥100	10	1	Increase

Wadi Dabur I

The means for the time sequences show that vegetation has both increased and decreased at this locality (Fig. 95). There is an overall increase in vegetation from 1973 to 1979, before a decrease brings the locality to its lowest vegetation coverage in 1984. Then, until 1996 there is another small increase in mean vegetation cover.

During the first period, 1973-1979, the majority of the pixels shows an increase (classes 5 to 7, class 6 being the most frequent one), see Fig. 96. Some pixels of stability occur in the southern and northern part, while pixels of slight decrease are scattered in the middle part (three pixels all of class 9) and located along the extreme southern edge (two pixels of each class 9 and 10).

Between 1979 and 1984 the picture changes (Fig. 97). The dominating trend is a decrease (classes 9 to 11). Three stable pixels are scattered in the central north, and only two pixels of increase (class 5 and 7) are seen.

In the final period, 1984-1996, the dominating trend is again increasing vegetation cover (classes 4-7), see Fig. 98. However, there is a central part dominated by stability, and in the south there is a vertical cluster of decrease (classes 9 to 11) around the eastern edge.

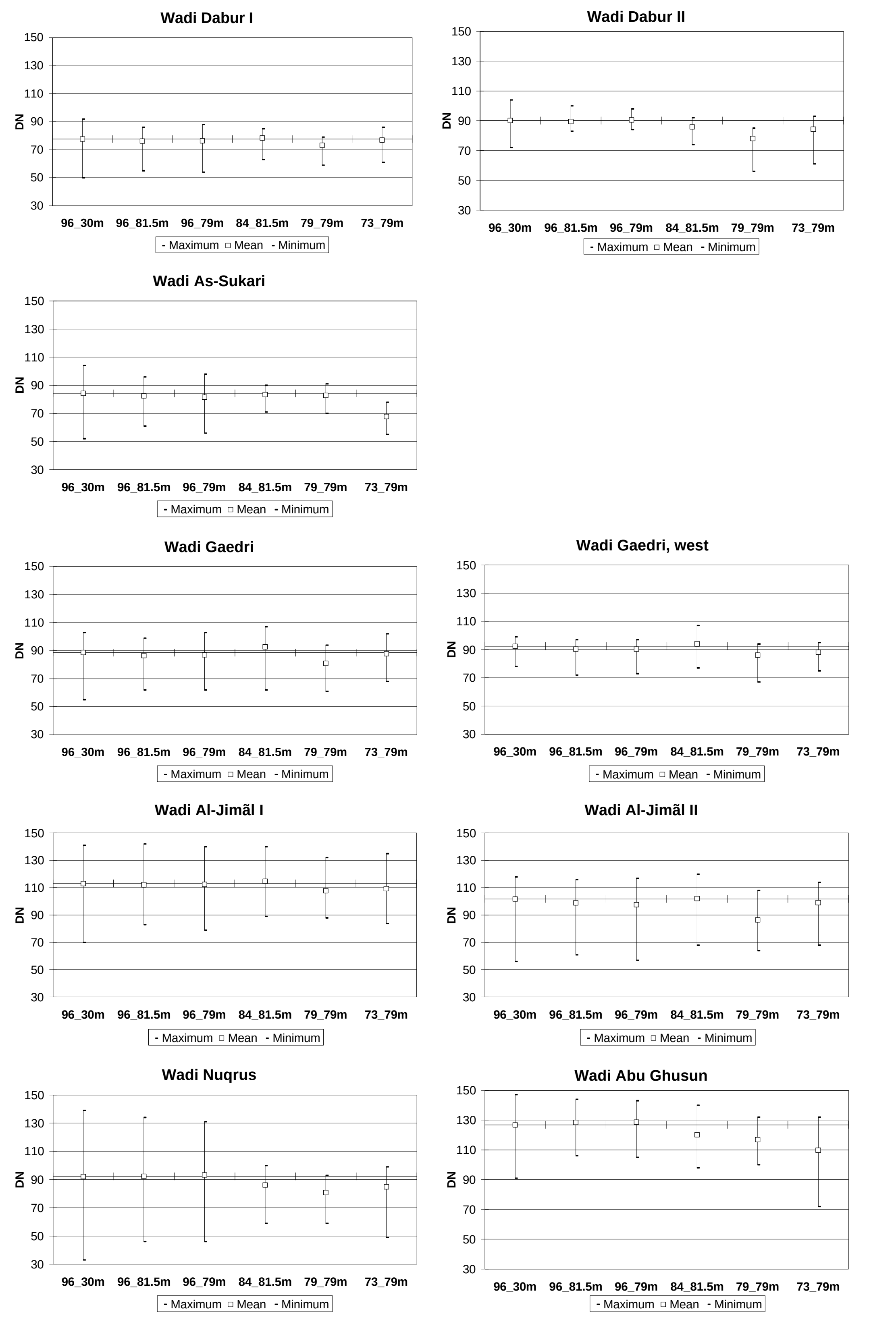


Figure 95 Comparison of Red ranges and means for all localities; all years and resolutions.

The change image for the whole period (1973-1996) is much like that between 1984 and 1996, see Fig. 99. In sum the locality is dominated by increase (classes 4-7), a trend that is most frequent in its northern part. Its central part is dominated by a decrease in vegetation (classes 9, 10 and 12), while its southern part is a mixture of all trends.

Wadi Dabur II

The general trend at Dabur II also shows maximum vegetation coverage in 1979 (Fig. 95). However, unlike Dabur I, the average for 1984 indicates greater vegetation coverage than in 1996.

Between 1973 and 1979 the trend is uniform. All pixels show an increase in vegetation cover (classes 5 to 7), see Fig. 100.

The trend during the second period (1979-1984) is, however, one of decrease (classes 9-11), as seen in Fig. 101. Only three pixels show an increase in vegetation (classes 6 and 7) from 1979 to 1984.

In the last period (1984-1996) the dominant trend is again a decrease in vegetation (classes 9-12), see Fig. 102. The central northern part has, however, a majority of pixels in classes 6 and 7.

Also in the image for the whole period (1973-1996) all three trends are represented (Fig. 103). In its eastern and southwestern part the locality is dominated by a general decrease (classes 9-12), while in its central and northwestern part there is a mixture of classes 6 to 9. However, the two classes of increase dominate.

Wadi As-Sukari

The average trend (Fig. 95) is one of decrease both during the period 1973-1979 and during the period 1979-1984. Data extracted from 1973 do, however, show a far greater difference in both mean and range of values than that seen for both 1979 and 1984. The average trend during the last period depends at what resolution the data from 1996 are extracted. Based on the data extracted from the TM-resolution, there is a slight decrease in the average vegetation cover. However, based on resolutions equal to MSS, a general increase is suggested. In all cases, the average difference is very small; the greater range of values for 1996 represents a more pronounced difference between 1996 and the other years.

Both the Red average and the range of values for 1973 are characterised by low DNs, indicating high vegetation cover. The change image between 1973 and 1979 clearly visualises a pronounced rise in Red DNs towards 1979 (Fig. 104). Only one pixel in the eastern part of the locality shows an increase in vegetation (class 6). Apart from this, decreasing vegetation cover dominates (classes 9-13), and the most frequent classes of decrease are classes at higher DN-levels, classes 11 and 12. The lower classes are found mainly in the central and eastern parts of the locality.

The next period (1979-1984) shows greater variation; and pixels of increase, stability and decrease are all present, see Fig. 105. No pattern is clear since areas of both increase and decrease are randomly scattered throughout the locality. Even so, there is a larger area of decrease in the central part and also some clusters of increase along the southern boundary. The decrease is not as severe as seen in the previous period; now only classes 9 to 11 are represented, class 9 being the most frequent. Increases are within classes 5 to 7.

Also the last period, between 1984 and 1996, shows great variation (Fig. 106). Areas of stability are fairly centrally located; and while there is a slight dominance of decrease in the east, the trend towards increase is more pronounced in the western part. Classes 9 to 11 are the classes indicating decrease, and of these class 11 is more frequent than it was during the previous period. Decrease in vegetation is represented by classes 4 to 7.

The change image between 1973 and 1996 mainly visualises decreasing vegetation coverage, see Fig. 107. Only along the northern boundary are there areas of increasing vegetation (classes 6 and 7). Areas of decrease are represented by classes 9-13, and as in the first period class 11 is the most frequent class.

Wadi Gaedri

The general trend for Wadi Gaedri and Gaedri West (Fig. 95) is similar to that seen for Dabur I although the average difference between 1979 and 1984 is more pronounced for this locality.

The first period, 1973-1979, is dominated by increase in vegetation cover (Fig. 108). Four classes of increase (4-7) are present and the highest classes of increase are most frequent in the eastern part of the locality. Pixels indicating decrease in vegetation cover are scattered among pixels of increase. Both classes 9 and 10 are present, the first being the more numerous. In the southern parts of Gaedri west there is a cluster of pixels showing a decrease in vegetation. Only this western part has pixels of no change.

The next period, 1979-1984, shows a nearly complete dominance of decrease in vegetation coverage (Fig. 109). Five classes of decrease are present (classes 9-13), the highest ones scattered along the northern and eastern edges of the locality. The few pixels of increase (classes 4-7) are found mostly along the central part of the southern edge.

As in the previous period, classes of great change are found along the edges of the locality also on the change image of 1984-1996 (Fig. 110). However, the dominant trend for this period is increase in vegetation cover. All classes from 3 to 7 represent the increase at the locality. Decrease in vegetation too is represented by 5 different classes (9-13). Some of these pixels are scattered within the locality, and some are found as larger clusters along its southern edge.

The 1973-1996 image again shows a more complex pattern of change than the other periods do, see Fig. 111. The eastern part shows a mixture of decrease and increase in vegetation coverage, although the majority of the pixels show an increase. Classes represented in this part of the locality are all from 4 to 11. In the western part, however, the dominating trend is decrease in vegetation cover, and only classes 9 and 10 are present. Some pixels of increase and stability are also present, and these are located mainly in the northern part of the western area.

Wadi Al-Jimâl I

The general trend is again similar to that of W. Gaedri and Dabur I (Fig. 95); 1979 has the highest average vegetation cover, 1984 the lowest.

The first period is dominated by increase in vegetation (classes 4-7), see Fig. 112. The higher classes are found along the edges in the north. Pixels of decrease belong to classes 9 to 12, and the majority of them are located as a large cluster in the southwestern part of the locality.

The second period, from 1979 to 1984, is dominated by uniform decrease (classes 9-12); only a couple of pixels indicate increase or no change in vegetation, see Fig. 113. All pixels of increase belong to class 7, and they are all scattered as single pixels. In the eastern part of the locality, at the same spot where there was an increase in vegetation during the previous period, a more pronounced decrease, dominated by the higher classes 11 and 12, is now seen. Class 11 also dominates the southwestern corner of the locality.

In the period between 1984 and 1996 too increase dominates in vegetation cover as it did during the first period (Fig. 114). However, pixels of decrease (classes 9 and 10) now cover other and larger areas than between 1973 and 1979. The central parts and the northwestern corner are especially dominated by decrease. The southwestern corner, as opposed to the two previous periods, is now dominated by an increase of classes 5 to 7.

For the whole period between 1973 and 1996, as for 1979-1984, the dominant trend is decrease in vegetation, see Fig. 115. Only a row of pixels in the central part in the north shows increasing vegetation coverage, ranging from class 5 to 7 with one pixel of class 3. The decrease is represented by classed 9 to 11.

Wadi Al-Jimâl II

Again the average trend is one of an increase to a maximum in 1979, then a decrease to a minimum coverage in 1984, and finally another increase in vegetation until 1996 (see Fig. 95).

The first period, 1973-1979, is almost completely dominated by increase in vegetation cover; only four pixels of class 9 indicate decrease (Fig. 116). The increase is, however, spread over five different classes (3-7); and classes 3 to 5 dominate the northern part of the locality.

For the next period, 1979-1984, the trend is reversed, see Fig. 117. Only a few pixels indicate increase in vegetation, two of them being located where there was a decrease in the previous period. Pixels showing decrease belong to classes 9 to 13, and as in the previous period the classes indicating greater changes dominate partly the same areas as then.

In the last period, 1984-1996, the majority of the area is dominated by increase in vegetation (Fig. 118). However, for some smaller parts in the central west and south and along the eastern edge vegetation cover decreases. The decrease falls into classes 9 to 11, while the increase ranges between 5 and 7.

In sum, changes for this site between 1973 and 1996 are intermediate to high increase (classes 4 to 6) in vegetation in the north and low to intermediate increase (classes 6 and 7) in the east (Fig. 119). Decrease in vegetation (classes 9 to 11) dominates along the southern and western edges of the locality.

Wadi Nuqrus

The average trend in W. Nuqrus (Fig. 95) also shows maximum vegetation coverage in 1979: However, the minimum vegetation coverage is not in 1984 but in 1996 as it was for W. Dabur II. The 1996 images have the highest averages for the locality, but they also have the lowest minima. The ranges of values for these three images are much greater than those of all the MSS images.

The change-image of the period between 1973 and 1979 (Fig. 120) shows a clear increase in vegetation. All classes 4 to 7 are present. A central core of increase (classes 4 to 6) runs through most of the site. A decreasing trend, represented by classes 9 to 11, is scattered throughout the locality. However, except for a few pixels in the central part, they are most frequently associated with the edges of the locality.

For the next period, 1979-1984, the trend is opposite, see Fig. 121. Three classes of decrease (classes 9-11) dominate the locality. Areas of increase are, however, also present; and as in the preceding period, most of the pixels of the minority trend of change are located along the edges of the locality. However, in the middle and in the southern parts of the locality there are also interior areas of increase.

In the last period, 1984-1996, there is a mixture of decrease and increase (Fig. 122). However, decrease is the dominant trend. A central core of decrease (classes 9 to 13) runs through the locality. Again the areas of decrease are found mostly along the edges of the locality; but some larger clusters of increase too are seen in the central parts and in the southwest. The classes of increase range from 4 to 7, all classes 5 to 7 being of roughly equal frequency.

The change image of the period between 1973 and 1996 is rather similar to the previous one (Fig. 123). There are again interior areas of increase that range from classes 9 to 13, while pixels of increase are scattered mostly around the edges. The southern part of increase is also seen for this period; and there is a central part of increase, but it has moved slightly. The classes of increase range from 5 to 7, and class 7 is most frequent.

Wadi Abu Ghusun

The overall trend of the mean for Abu Ghusun is a steady decrease in vegetation for all the time-periods between 1973 and 1996 (Fig. 95).

Between 1973 and 1979 the difference in means is approximately 10 DNs. As seen from Fig. 95 the absolute range of values for 1973 is greater than for 1979, and the difference in means is due to more low values in 1973. Some areas of high decrease (classes 12 and 13) are seen in the central north and the southwestern corner (Fig. 124). As the mean indicates, most pixels show a negative trend in vegetation coverage, and the remaining areas of decreasing vegetation are represented by pixels of classes 9-11. The pixels indicating an increase in vegetation are found mainly in the western and southeastern part of the locality, and they range between classes 5 and 7.

The decrease continues in the next period, between 1979 and 1984, see Fig. 125. However, the pattern of change has moved somewhat. While the central northern part still shows a decrease in vegetation (classes 9-11) there is stability and increase (classes 5-7) in the southern part. Two pixels indicating increase (class 5) are also seen on the northern edge of the locality.

In the last period, from 1984 to 1996, all the southern pixels indicating increase for the preceding period, now present a decrease in vegetation cover (classes 11 and 12), see Fig. 126. Pixels of decrease (class 11) also dominate the eastern part of the locality, while the two lowest classes of decrease (9 and 10) dominate the central western part. The three lowest classes of increase (5-7) are also present in this period, scattered in the central part, along the northern edge and in the southwest.

The 1973-1996 change image (Fig. 127) sums up the trend for this locality. The only pixels of increase are found along the western border (class 5 or 7). The rest of the locality shows a decrease in vegetation (ranging from class 9 to 14). There is a central, diagonal cluster of classes 11 to 14 spreading northeast from the southern extreme.

Changes for all localities and periods are summarised in Fig. 128. The three main groups of increase, decrease and stability are indicated; and quantification is in accordance with the number of pixels in each group.

The main pattern of change for the majority of the localities is an increase during the first period, 1973-1979, then a decrease between 1979 and 1984, and finally a new increase during the last period, 1984-1996. The overall trend, between 1973 and 1996, is one of decreasing vegetation coverage.

However, some localities depart from this pattern. W. Abu Ghusun is dominated by decrease for all periods. W. As-Sukari too is dominated by a decrease between 1973 and 1979, but for the other periods it is similar to the majority of localities. W. Nuqrus and Dabur I both show a decrease between 1984 and 1996. W. Dabur I shows deviant trends for the period as a whole.

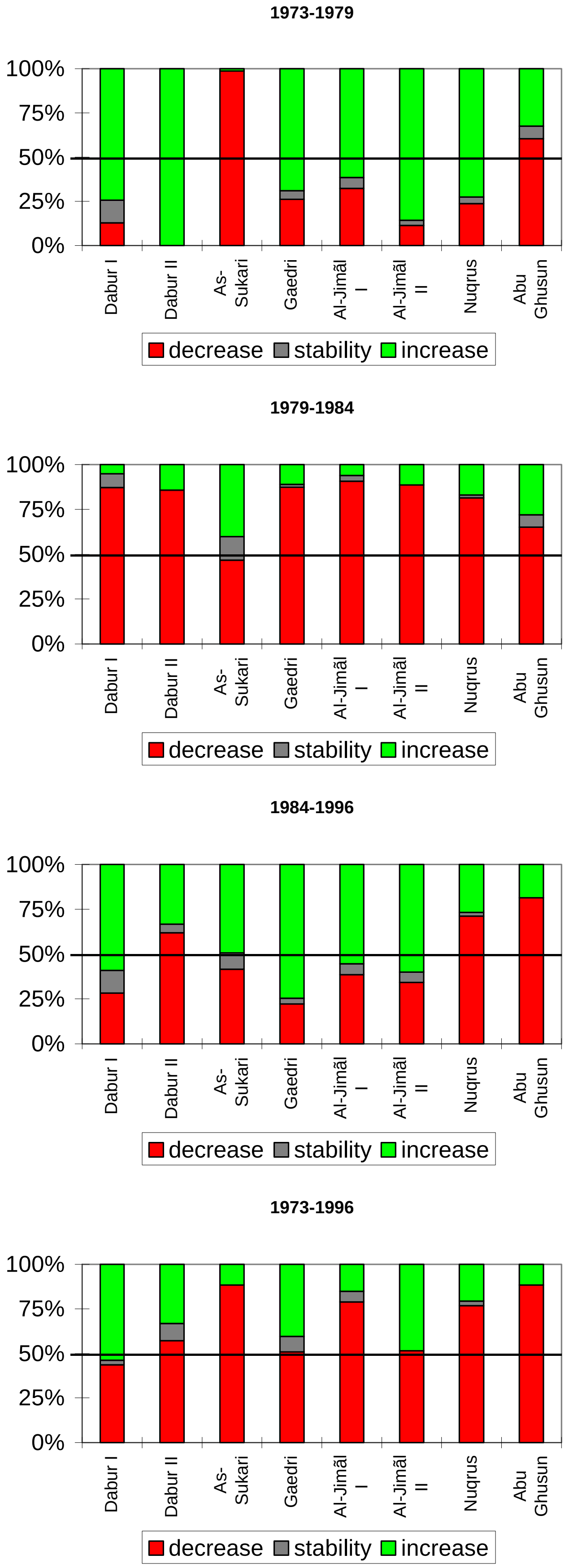


Figure 128 Changes for all sites and periods. Quantification is in accordance with the number of pixels in each group.

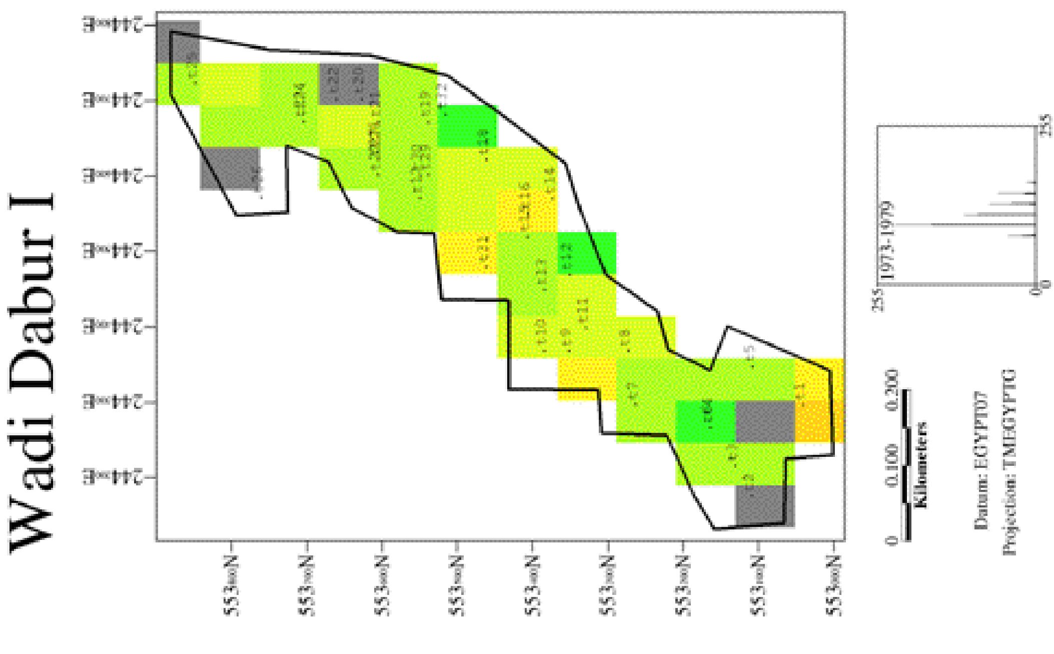
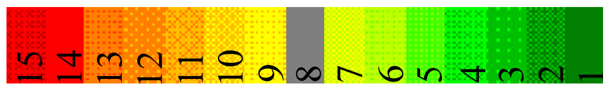


Figure 96 Change image 1973-1979, W. Dabur I



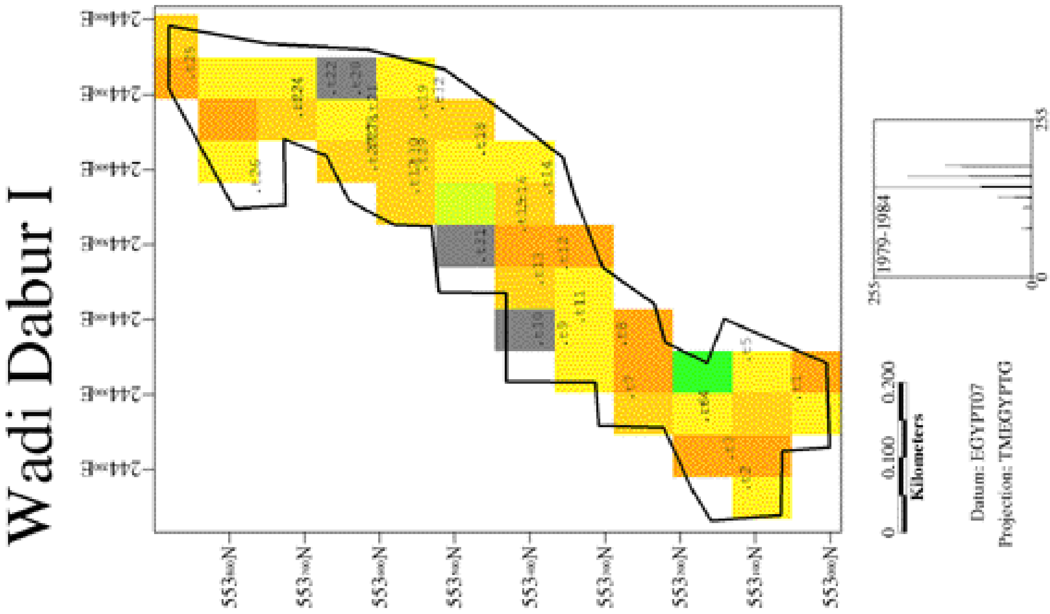


Figure 97 Change image 1979-1984, W. Dabur I

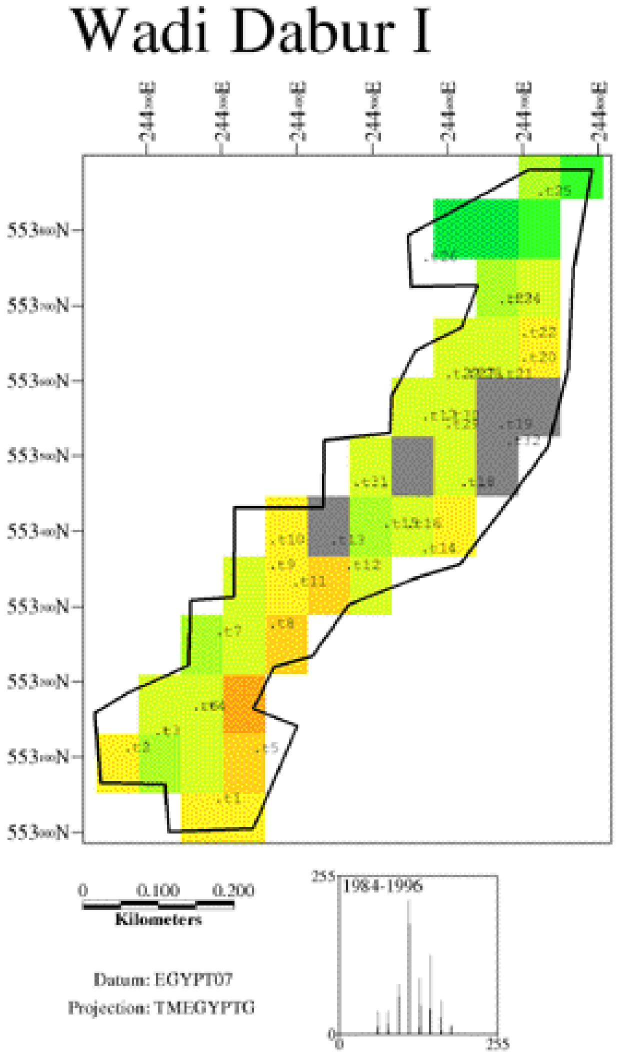
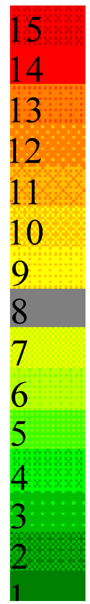


Figure 98 Change image 1984-1996, W. Dabur I



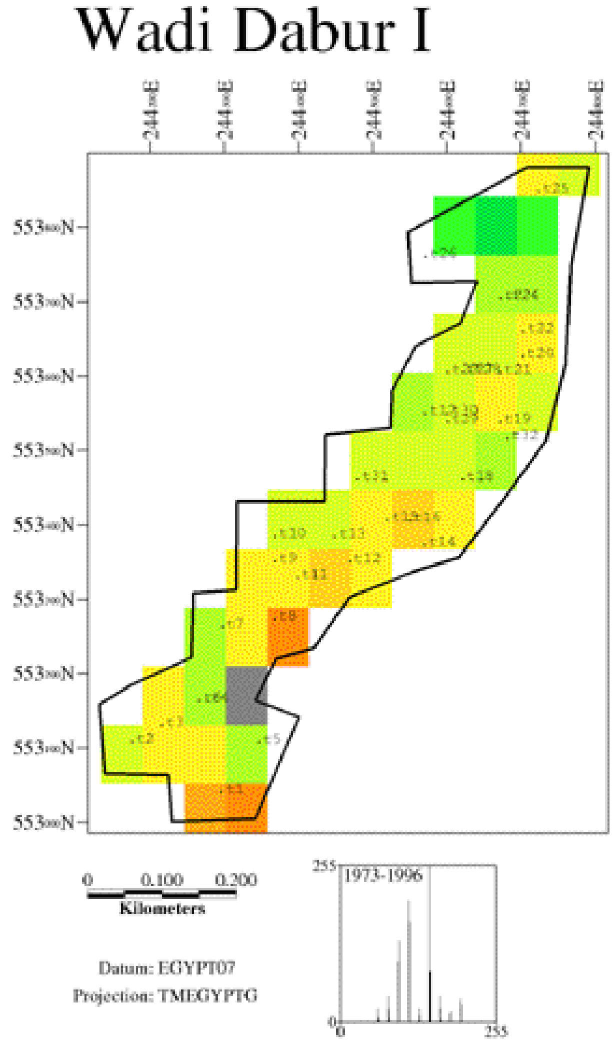


Figure 99 Change image 1973-1996, W. Dabur I

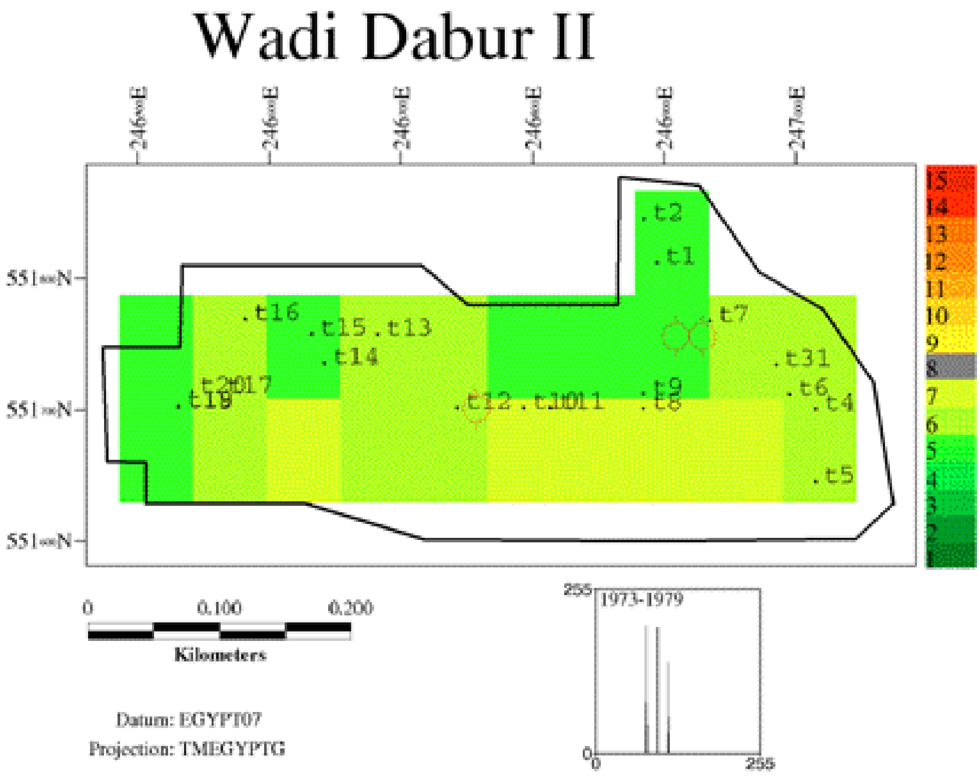


Figure 100 Change image 1973-1979, W. Dabur II

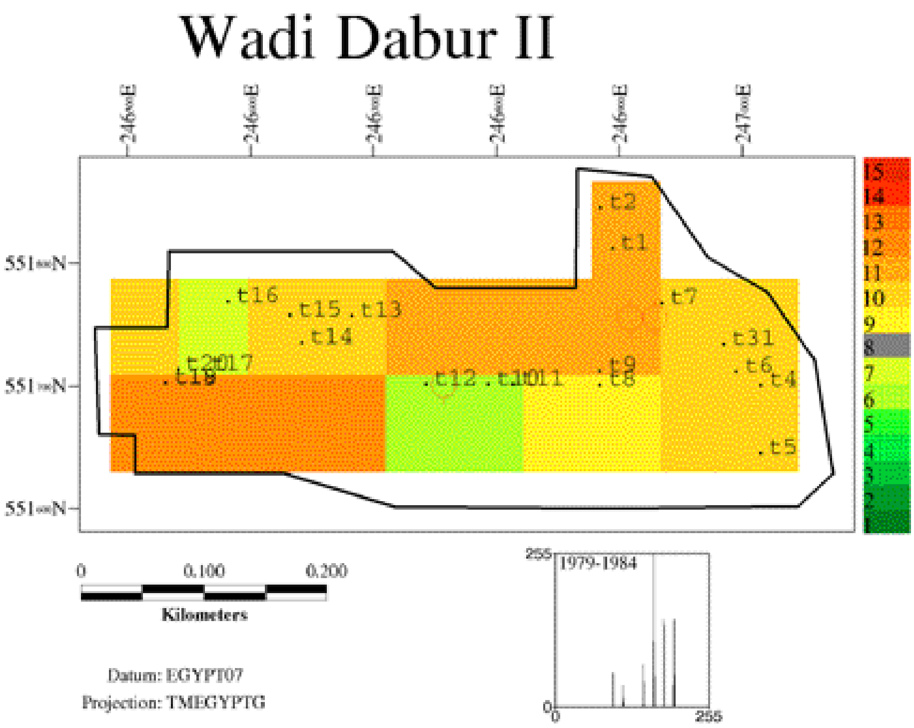


Figure 101 Change image 1979-1984, W. Dabur II

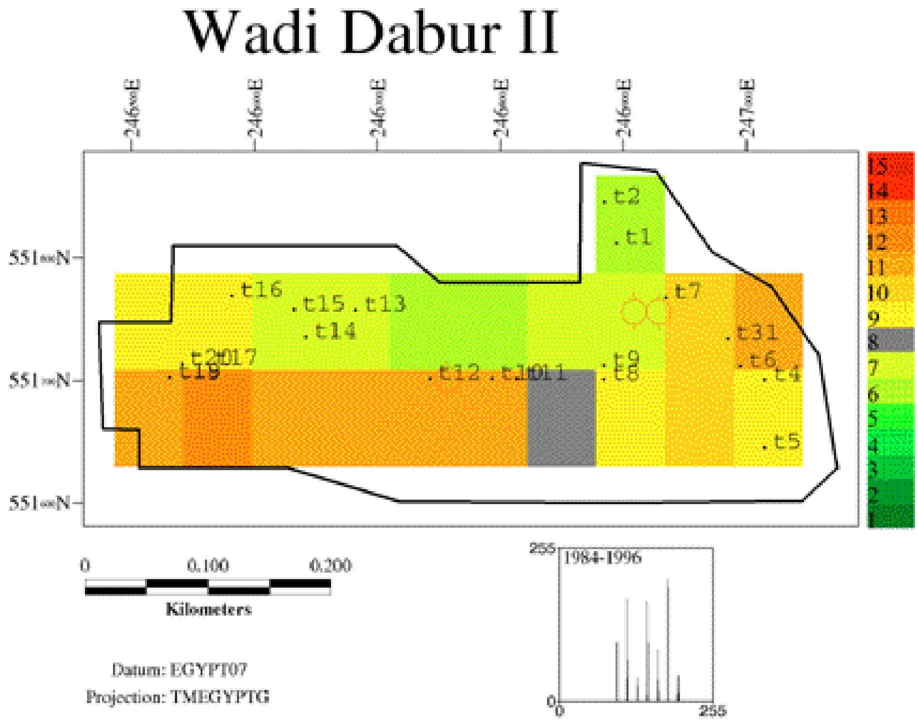


Figure 102 Change image 1984-1996, Wadi Dabur II

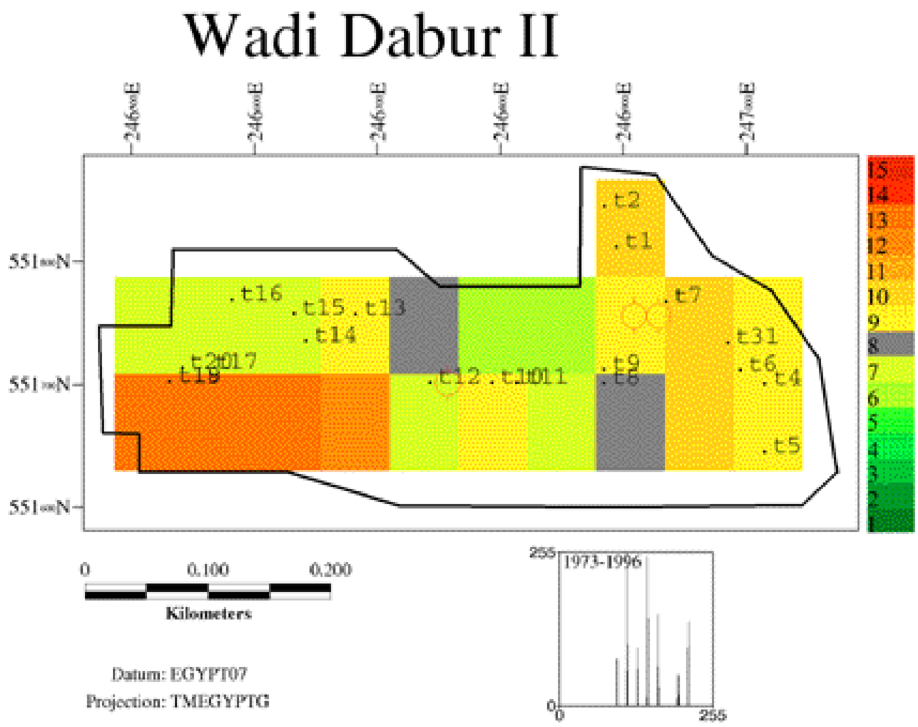


Figure 103 Change image 1973-1996, Wadi Dabur II

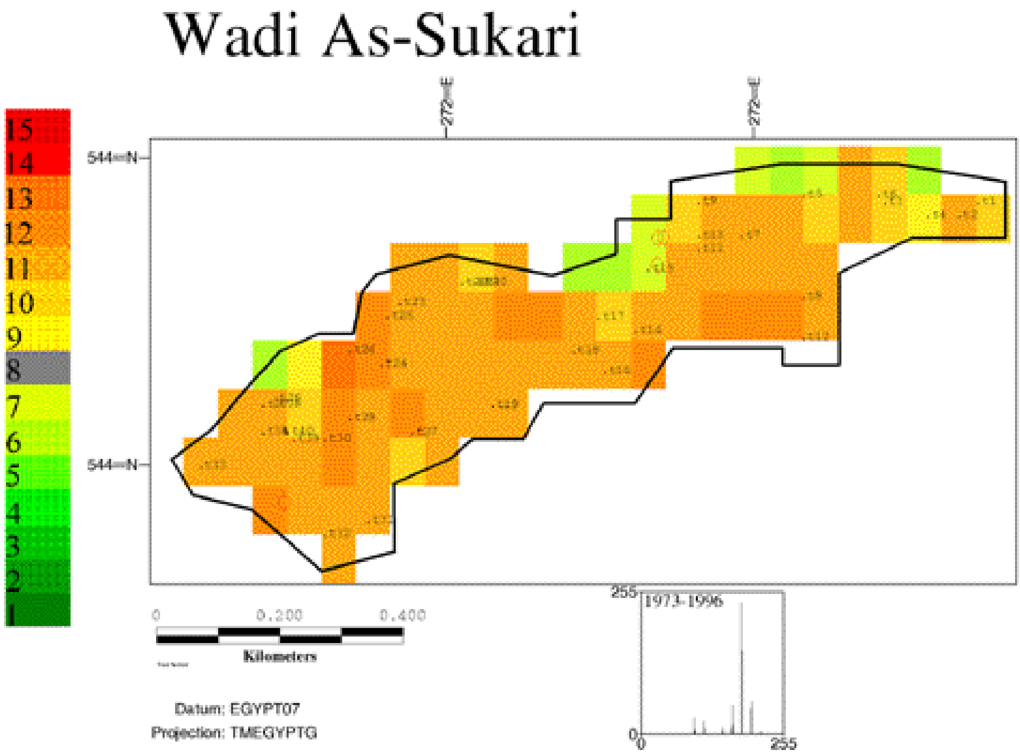


Figure 104 Change image 1973-1979, W. As-Sukari

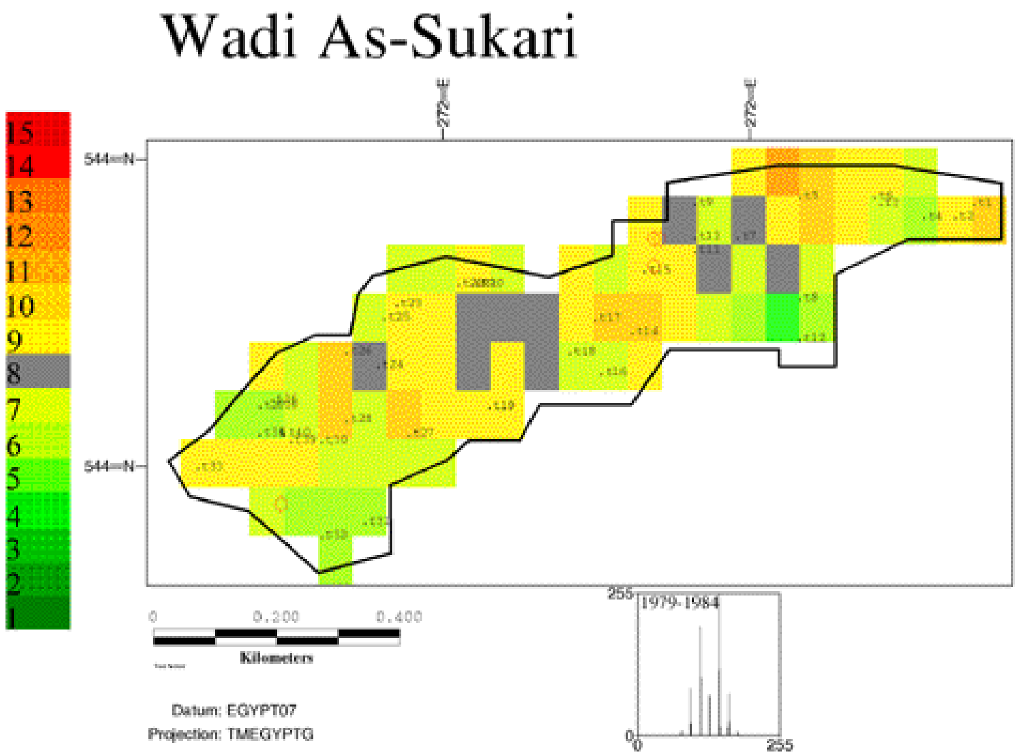


Figure 105 Change image 1979-1984, W. As-Sukari

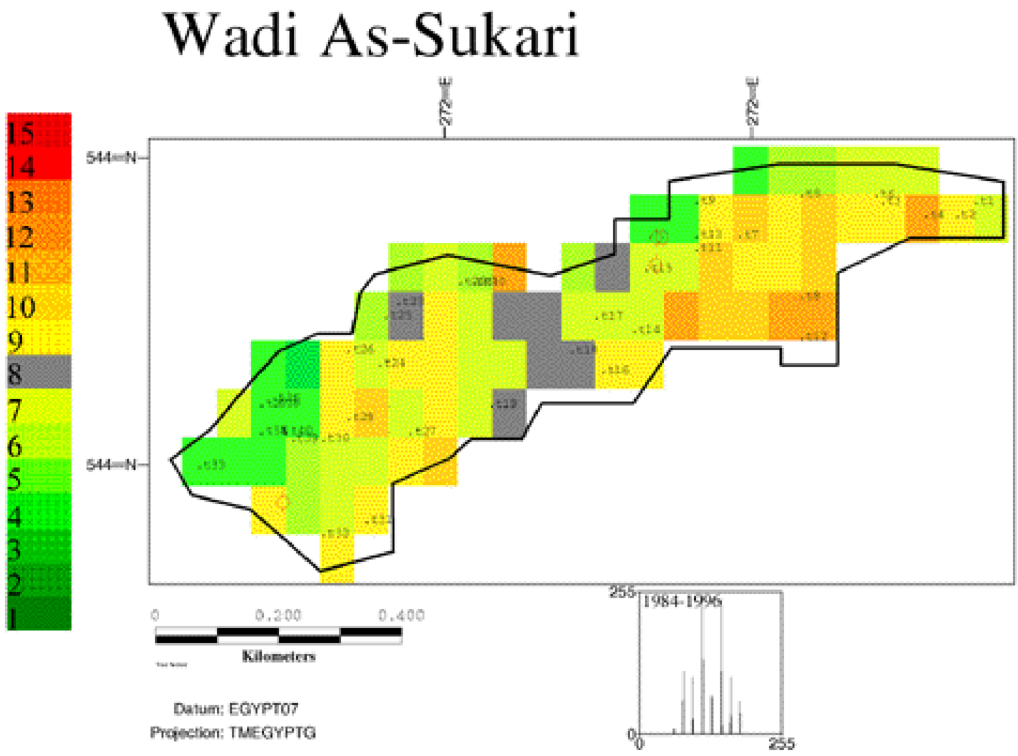


Figure 106 Change image 1984-1996, W. As-Sukari

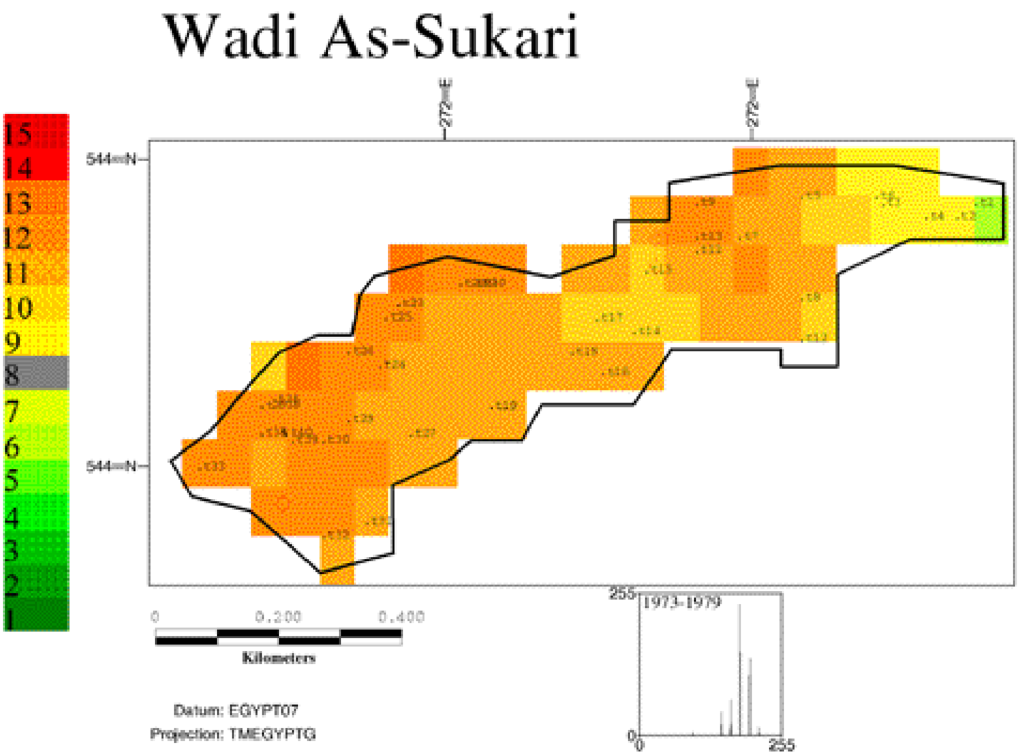


Figure 107 Change image 1973-1996, W. As-Sukari

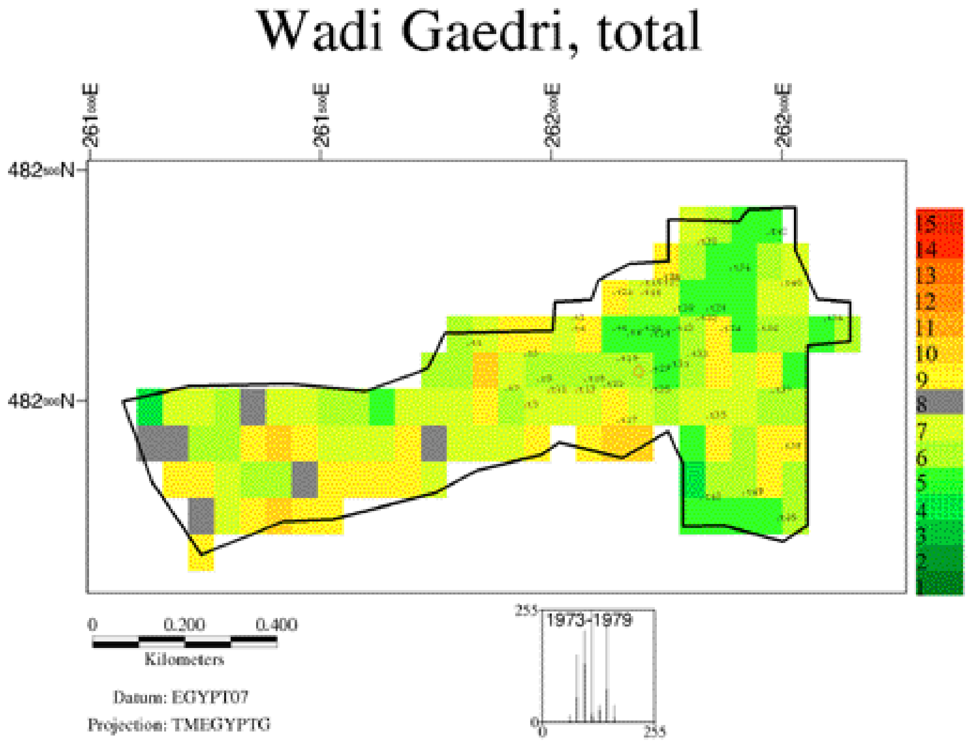


Figure 108 Change image W. Gaedri, total, 1973-1979

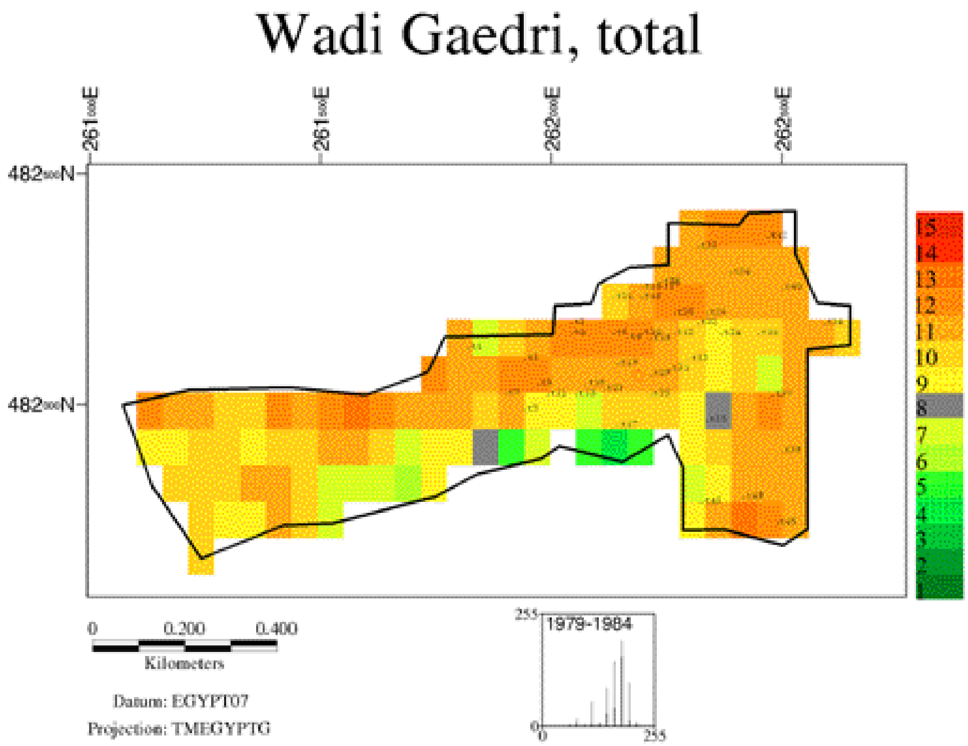


Figure 109 Change image W. Gaedri, total, 1979-1984

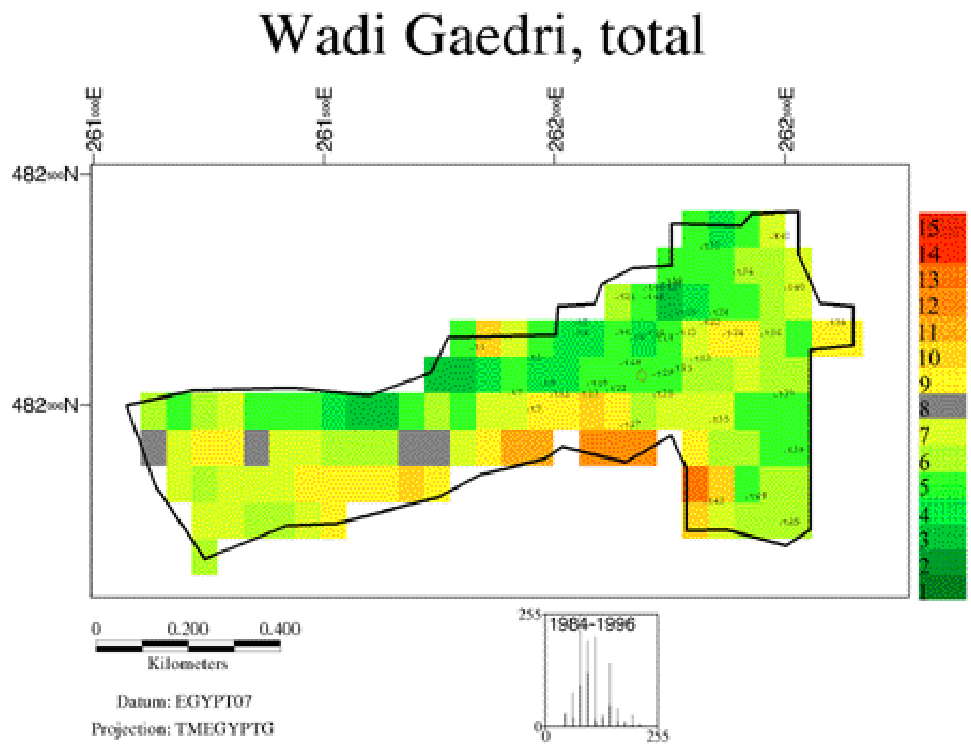


Figure 110 Change image W. Gaedri, total, 1984-1996

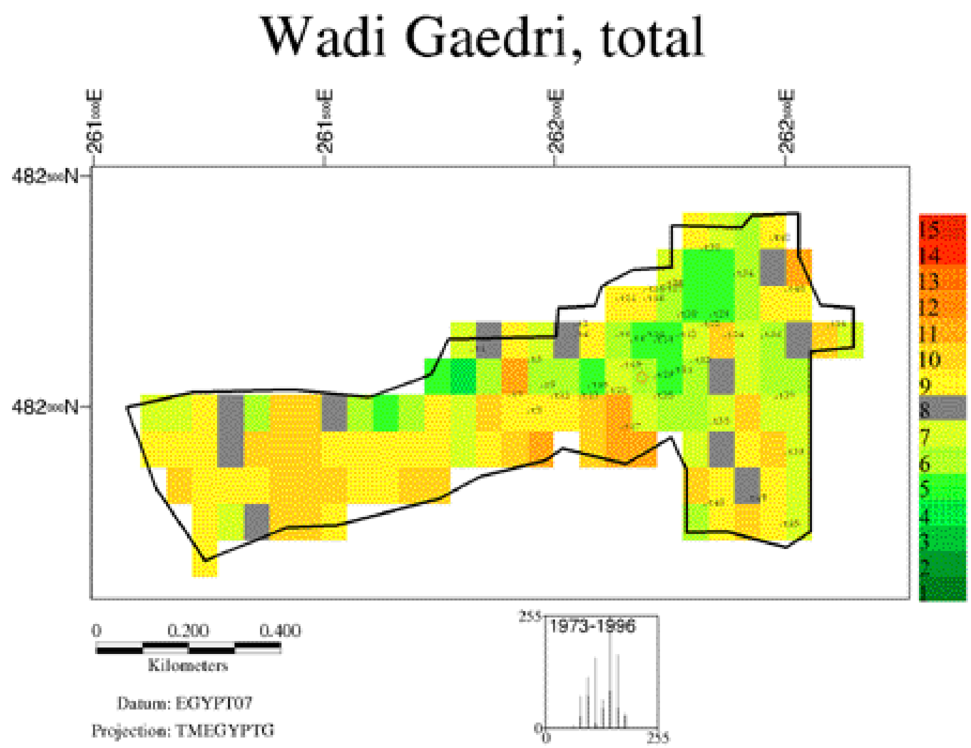
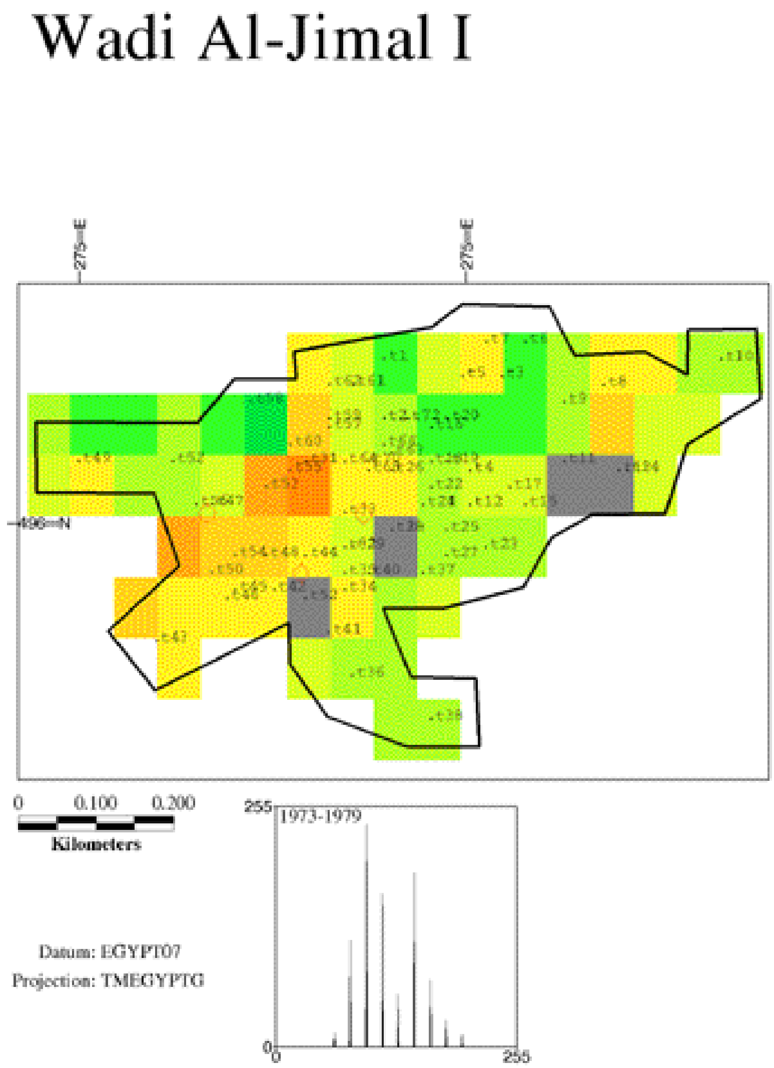
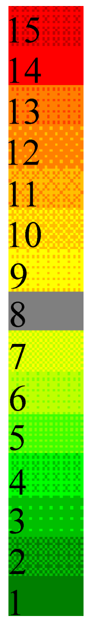


Figure 111 Change image W. Gaedri, total, 1973-1996





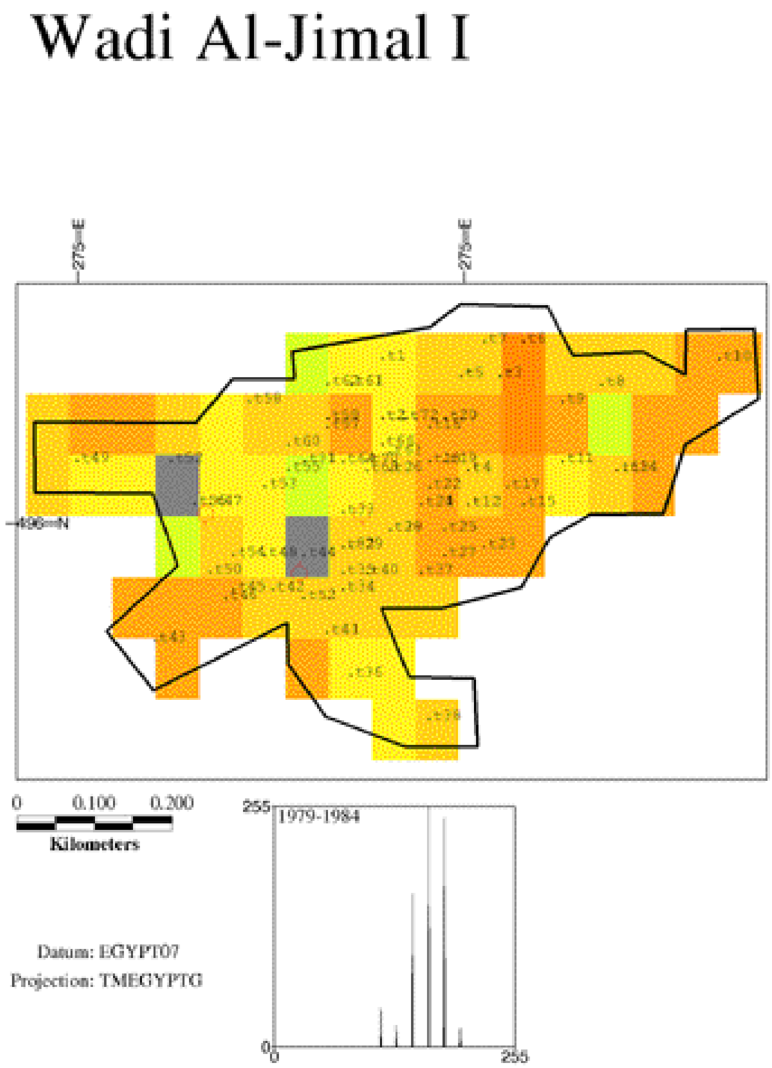
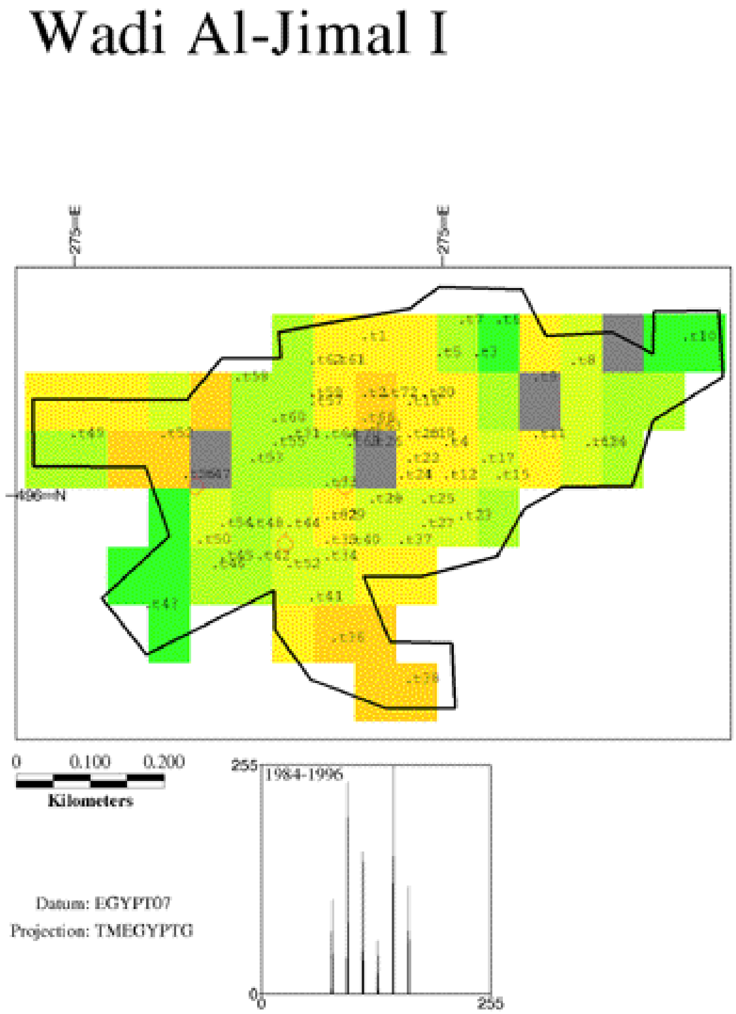
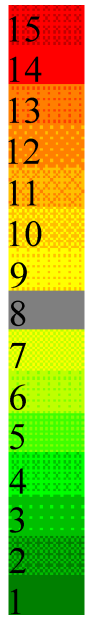


Figure 112 Change image W. Al-Jimâl, 1973-1979

Figure 113 Change image W. Al-Jimâl, 1979-1984





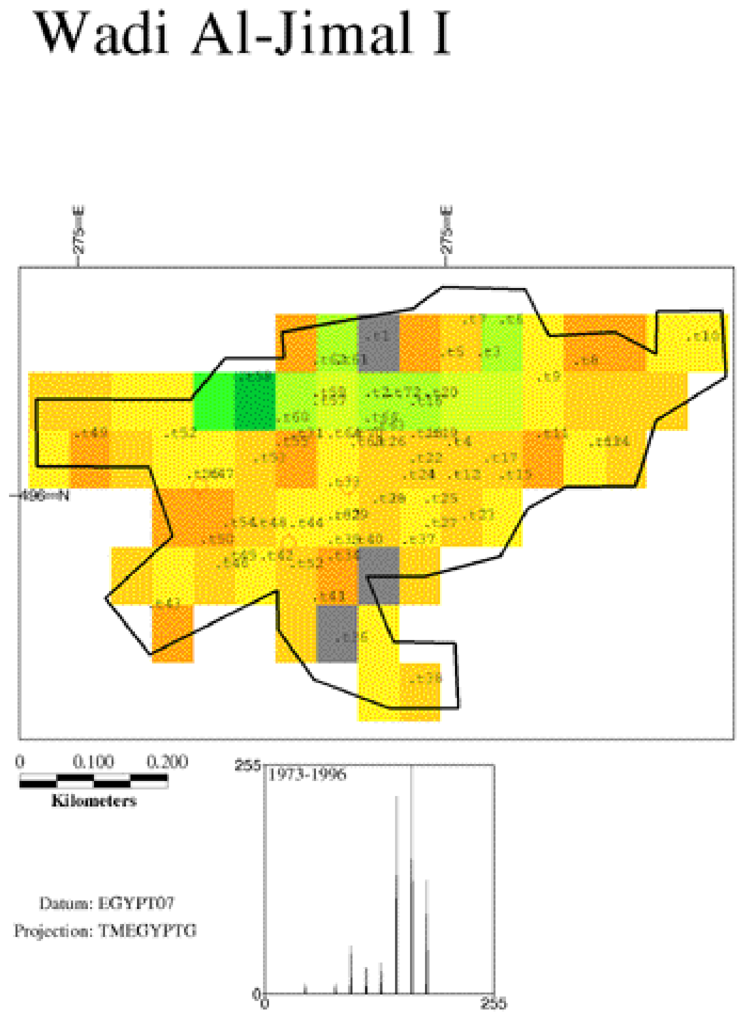


Figure 114 Change image W. Al-Jimâl, 1984-1996

Figure 115 Change image W. Al-Jimâl, 1973-1996

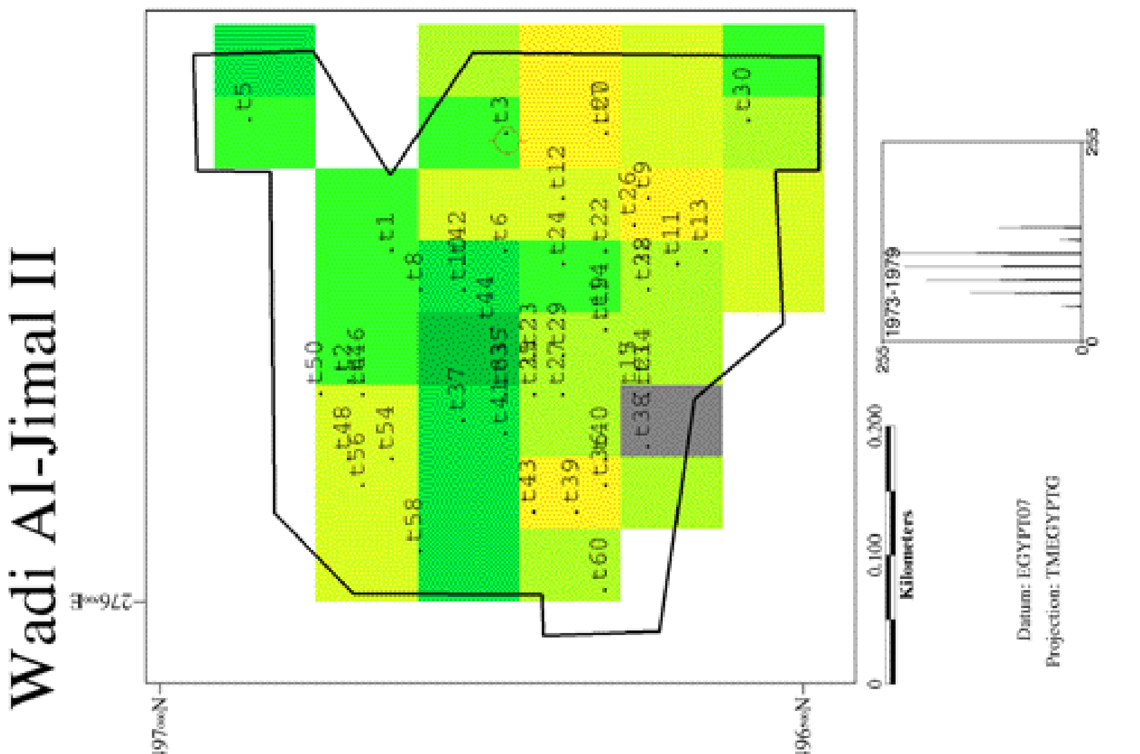
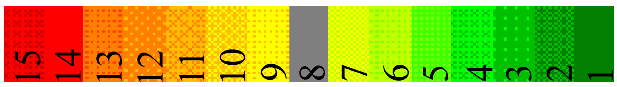


Figure 116 Change image W. Al-Jimâl II, 1973-1979



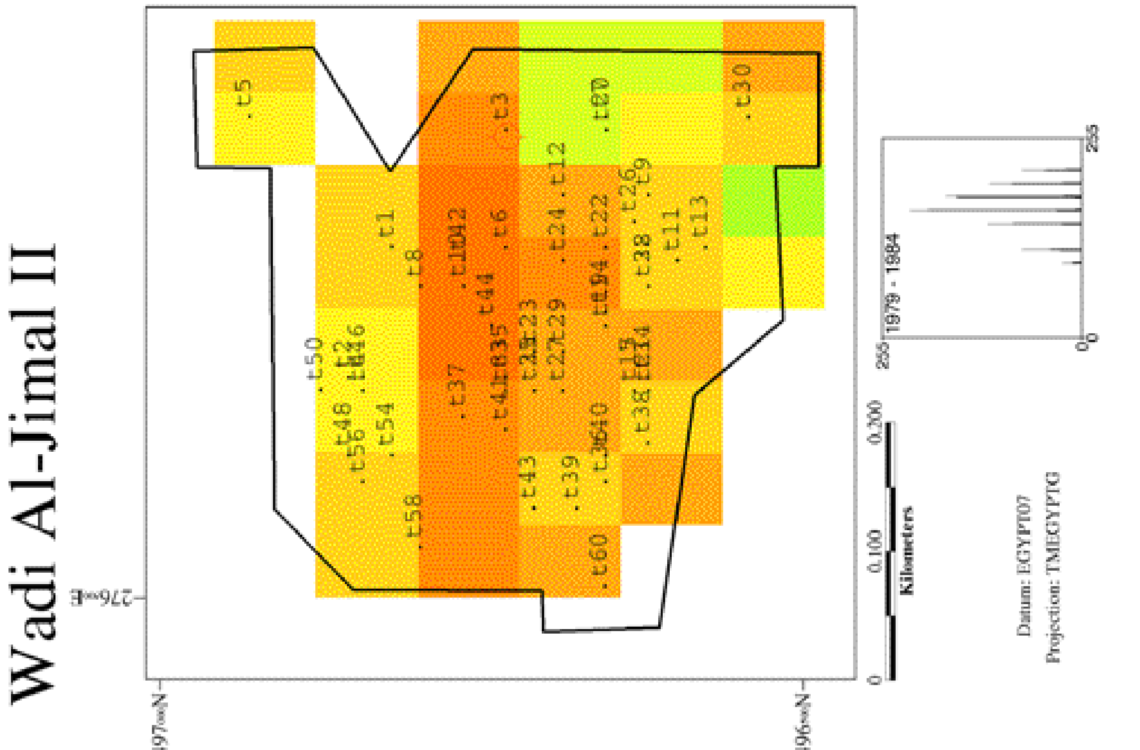


Figure 117 Change image W. Al-Jimâl II, 1979-1984

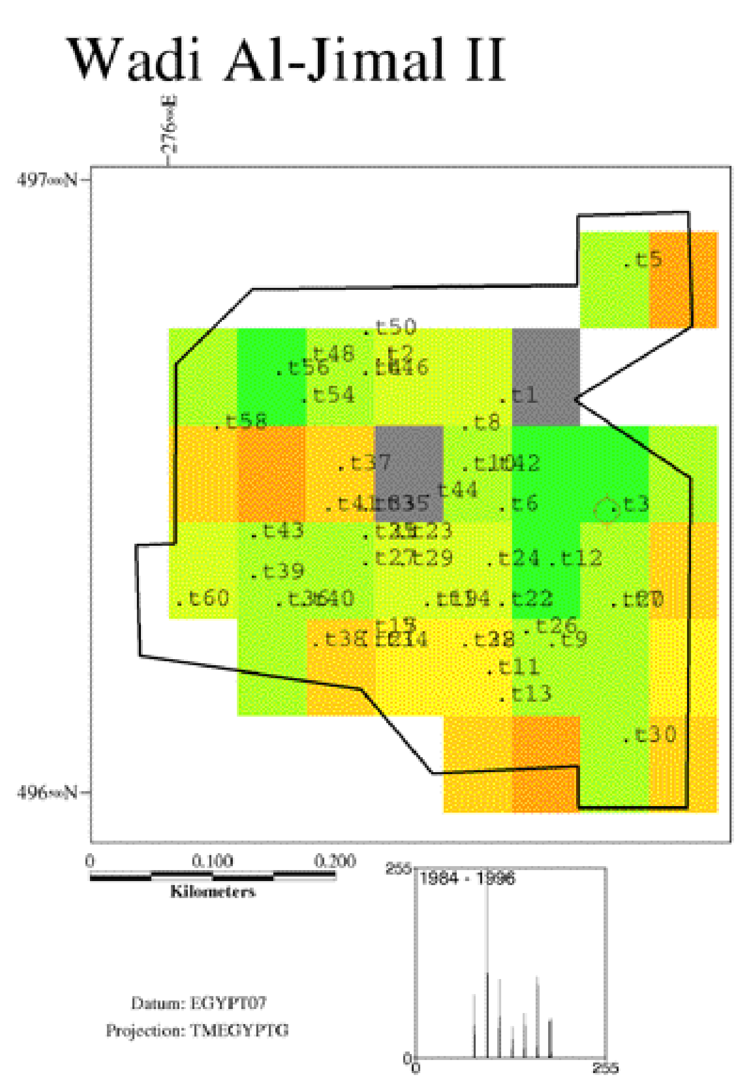
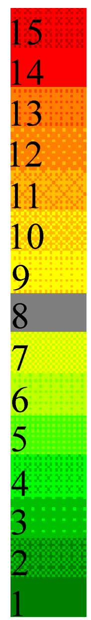


Figure 118 Change image W. Al-Jimâl II, 1984-1996



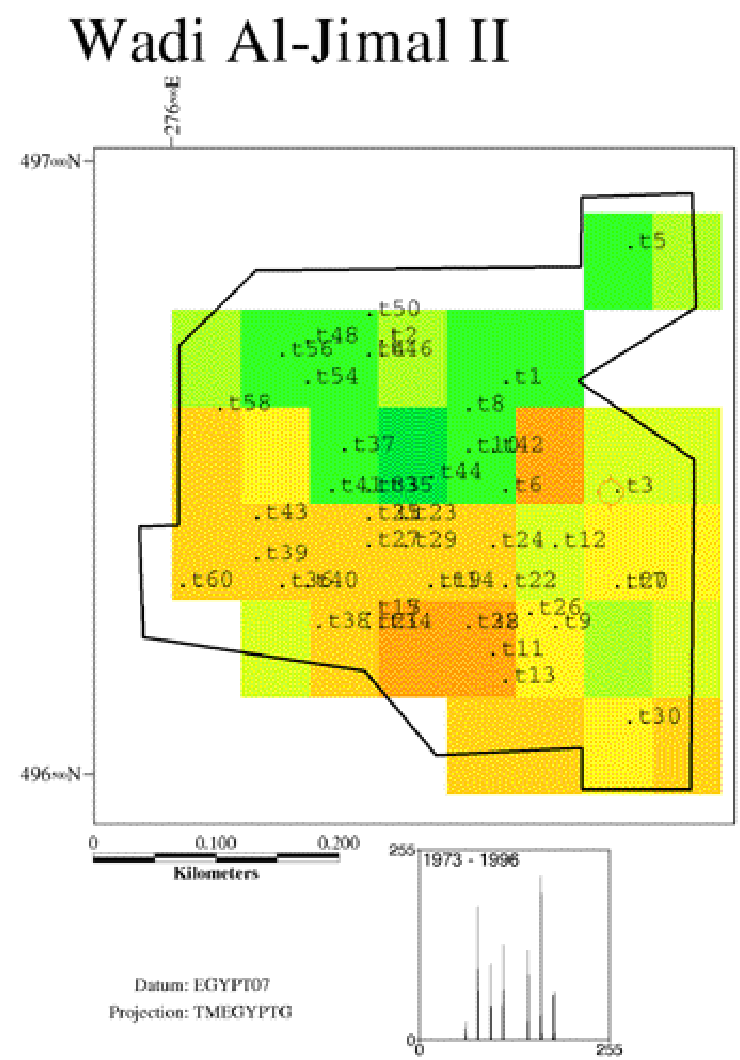


Figure 119 Change image W. Al-Jimâl II, 1973-1996

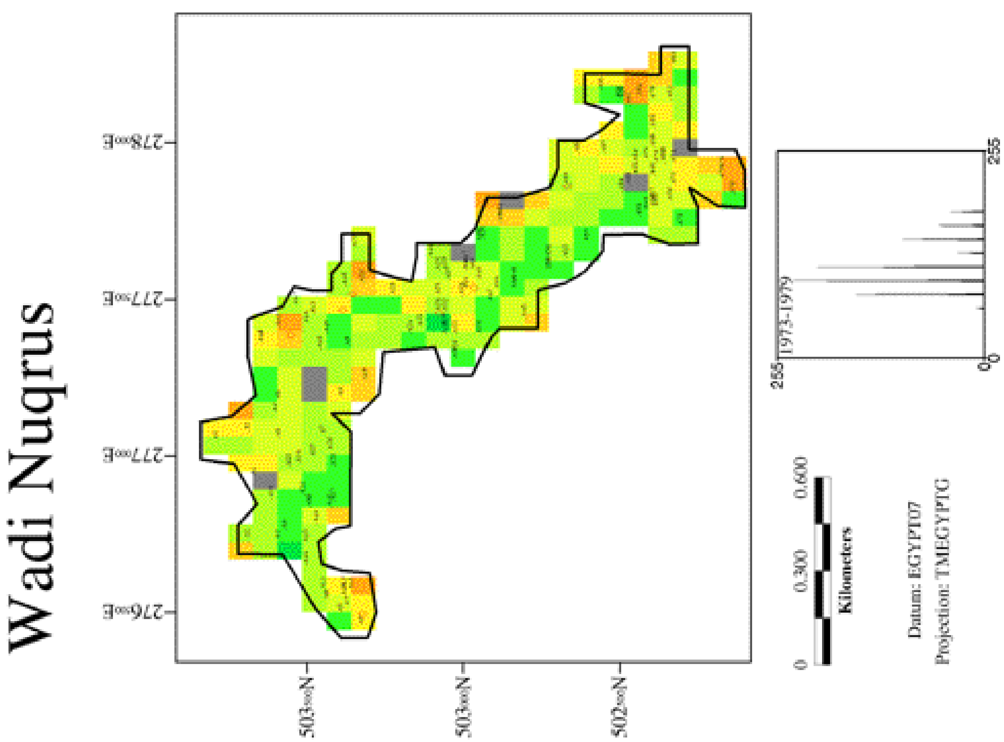
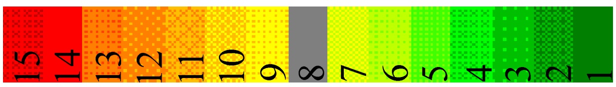


Figure 120 Change image W. Nuqrus, 1973-1979



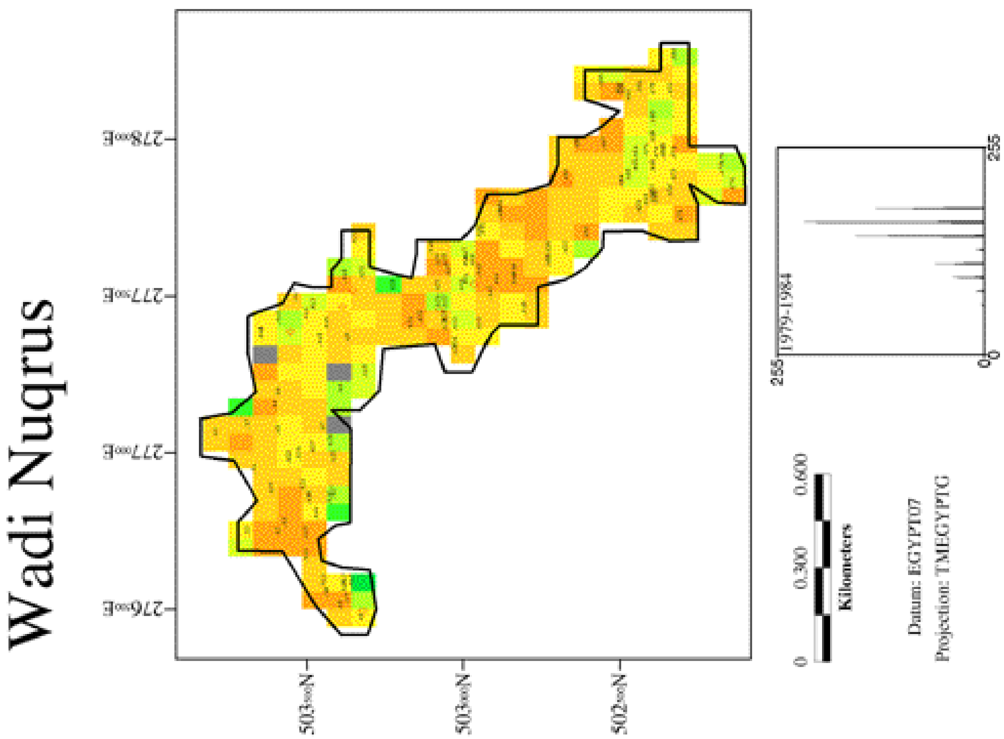


Figure 121 Change image W. Nuqrus, 1979-1984

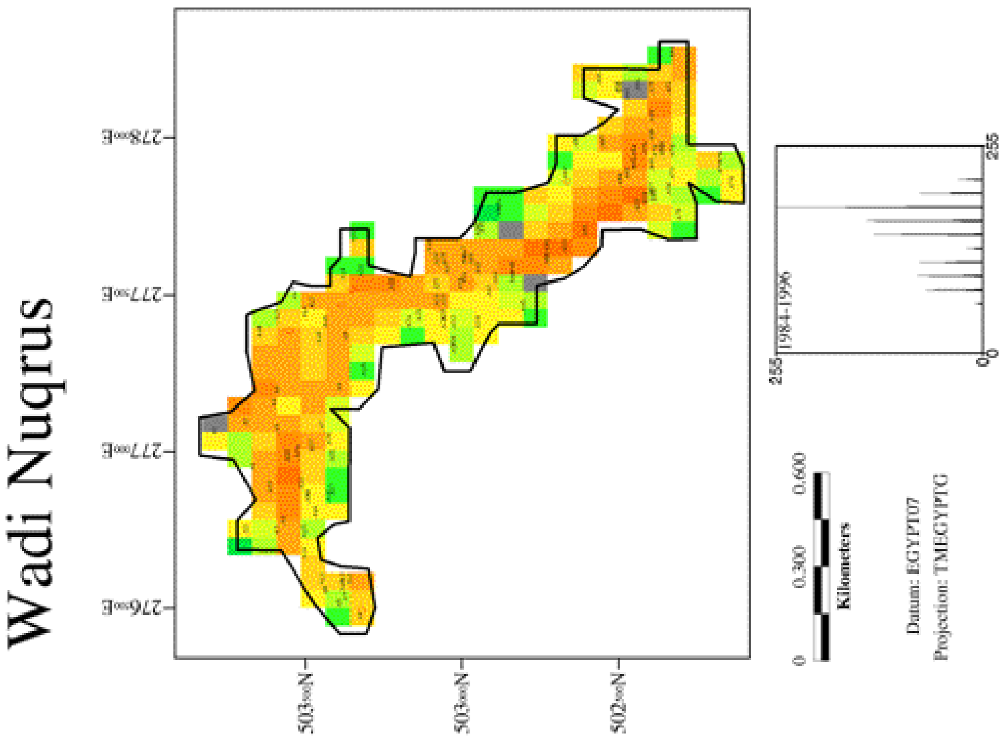
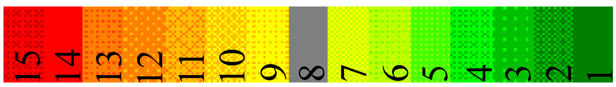


Figure 122 Change image W. Nuqrus, 1984-1996



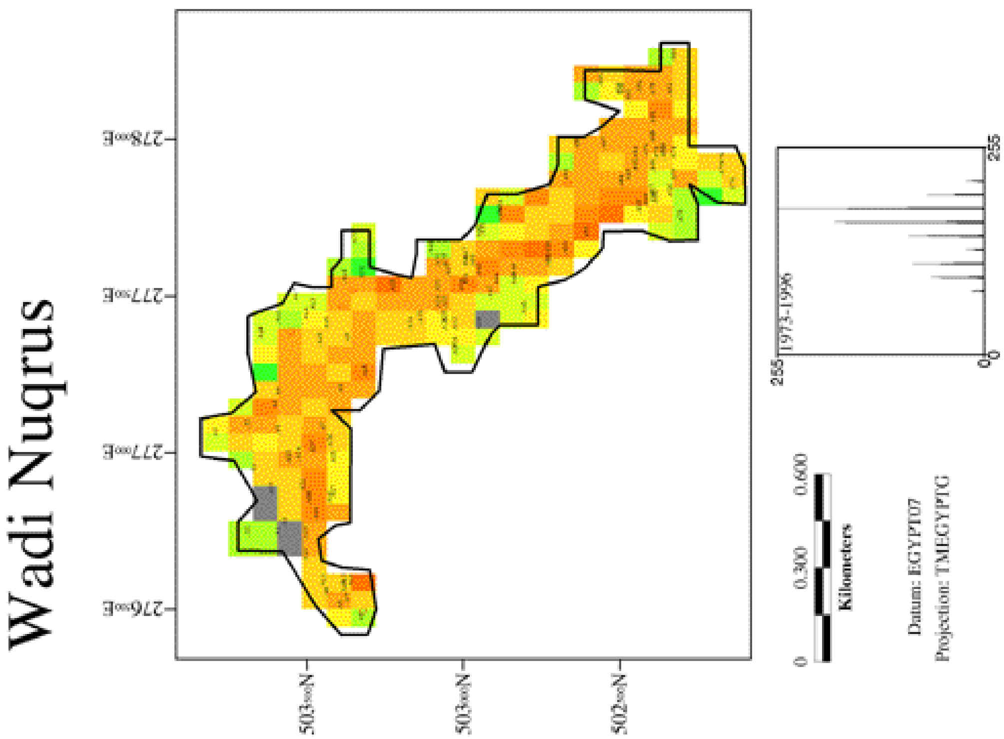


Figure 123 Change image W. Nuqrus, 1973-1996

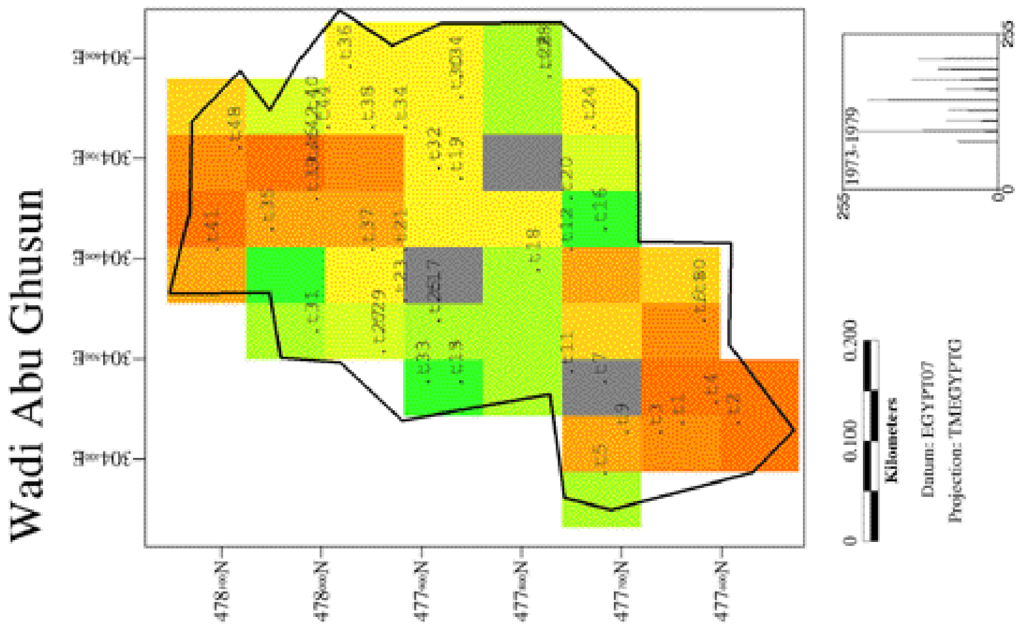
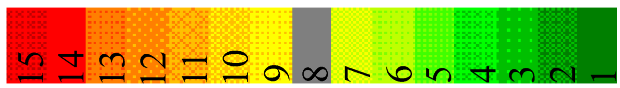


Figure 124 Change image W. Abu Ghusun, 1973-1979



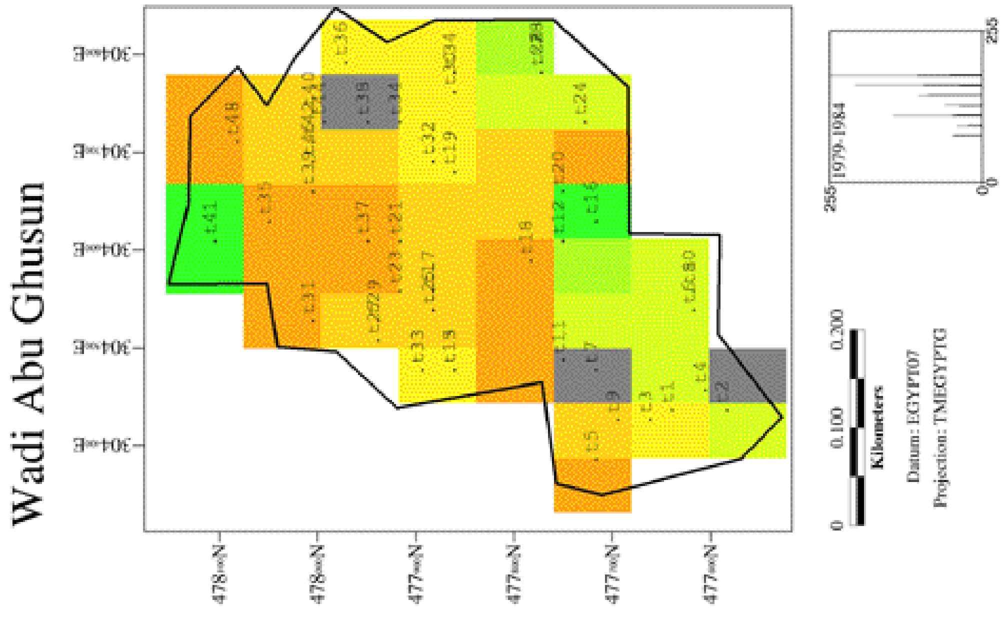


Figure 125 Change image W. Abu Ghusun, 1979-1984

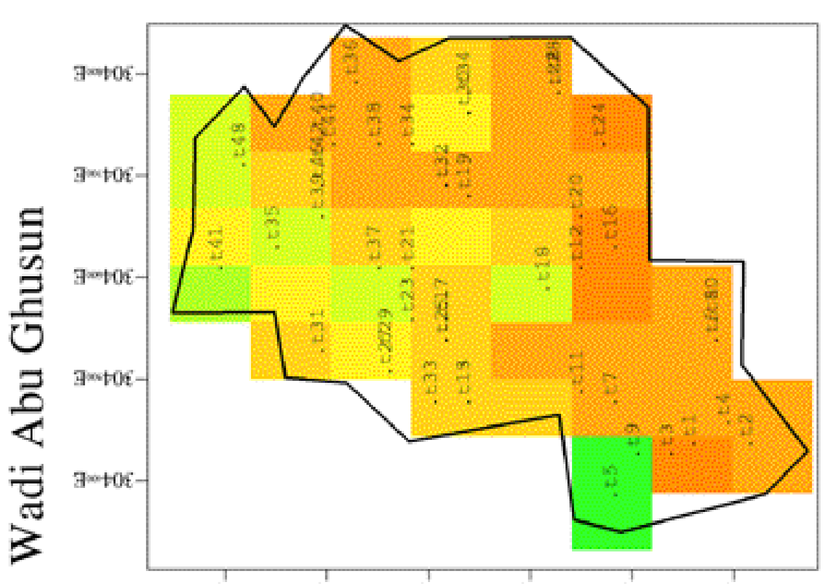
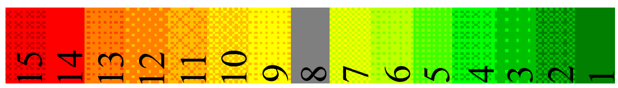


Figure 126 Change image W. Abu Ghusun, 1973-1996



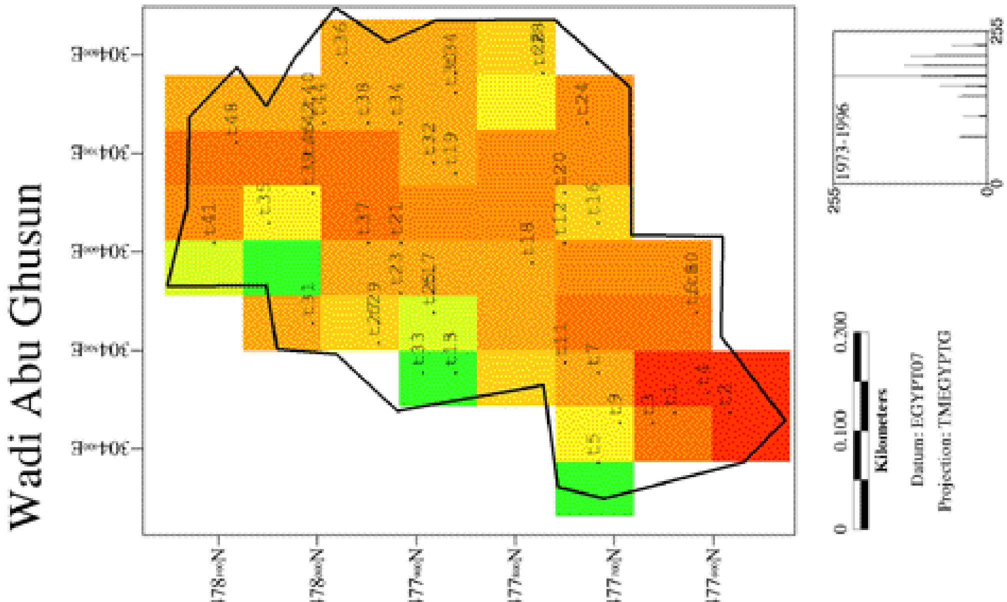


Figure 127 Change image W. Abu Ghusun, 1984-1996

Trends across periods

The eight possible combinations of increase and decrease are given in Table 44, 'display' value refers to histograms seen on change images (cf. p. 131). Cross-periodic change images are shown in Figs. 131-138.

The eight different trends are quantified in accordance with the number of pixels for each trend recorded at each site and are plotted for each site in Fig. 129.

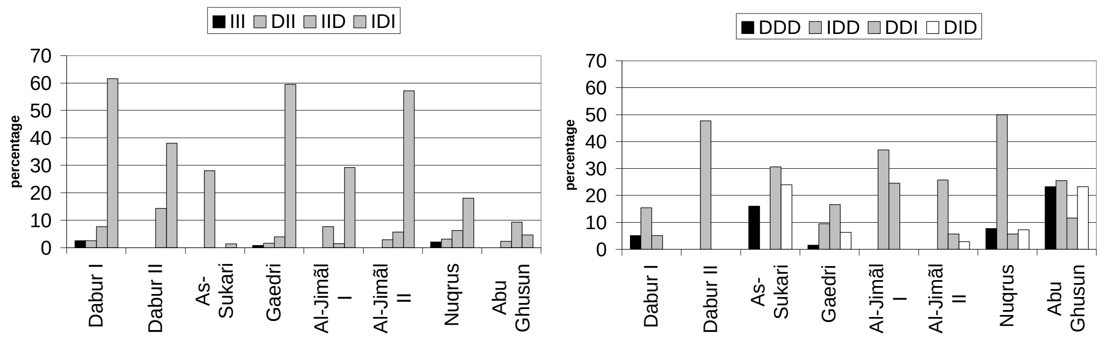
Pixels of increase for two or more consecutive periods are a minority at all sites (Table 45 and Fig. 129 a). Only Dabur I and Nuqrus have pixels that show increase for all three periods, and these are very few indeed (respectively 1 and 4). The cross-periodic trend IID is more abundant than DII for most sites, the exceptions being Al-Jimãl I and As-Sukari (Fig. 129).

The last cross-periodic trend dominated by increase, IDI, is, however, one of non-consecutive increase. In contrast to other cross-periodic trends dominated by increase this is a quite abundant one. At Dabur I, Al-Jimâl II and Gaedri a majority of pixels are, in fact, dominated by this trend (Fig. 129a). It should be noted, however, that this trend is not as great as might be inferred from a consideration of the sequence of trends at each site (cf. Fig. 95).

The remaining four cross-periodic trends have at least two periods of decrease. Four localities are dominated by these trends: As-Sukari, Nuqrus, Al-Jimãl I and Abu Ghusun (Fig. 129 b). More sites have pixels indicating three periods of decrease than of three with increase, and within these sites such pixels are also more numerous. The trend IDD is represented by more pixels than is DDI for most sites, the only exceptions being As-Sukari

Table 44 The eight possible cross-periodic trends

IP trend	1973-1979	1979-1984	1984-1996	Display value
III	Increase	Increase	Increase	1
DII	Decrease	Increase	Increase	50
IID	Increase	Increase	Decrease	100
IDI	Increase	Decrease	Increase	127
DID	Decrease	Increase	Decrease	Null
DDI	Decrease	Decrease	Increase	170
IDD	Increase	Decrease	Decrease	200
DDD	Decrease	Decrease	Decrease	255



a) b)

Figure 129 Cross-periodic trends for all sites, calculated according to the number of pixels in each trend. a) Trends dominated by Increase b) Trends dominated by Decrease

and Gaedri. The last trend dominated by decrease, DID, is not recorded or is relatively rare for most sites except As-Sukari and Abu Ghusun.

Cross-periodic trends compared to general trend

Although either increase or decrease dominates the trend for a given pixel, this is not necessarily the general trend (1973-1996) for that pixel. There is a greater percentage of pixels of increase for at least two periods (II) recording general decrease than there is of pixels of decrease for at least two periods (DD) recording general increase (Fig. 130). The

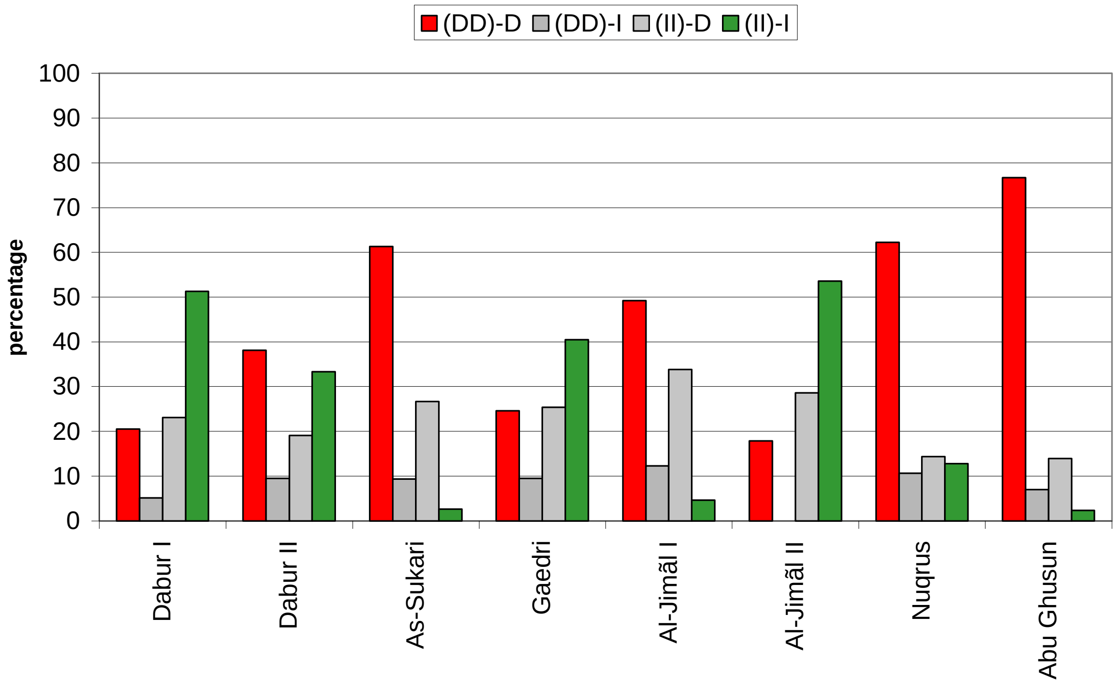


Figure 130 Distribution of cross-periodic trends dominated by either decrease or increase according to general trend for all sites. (DD)-D includes pixels with at least two periods of decrease and with decrease for the period as a whole, (DD)-I includes pixels with at least two periods of decrease and with increase for the period as a whole, (II)-D includes pixels with at least two periods of increase and with decrease for the period as a whole, (II)-I includes pixels with at least two periods of increase and with increase for the period as a whole.

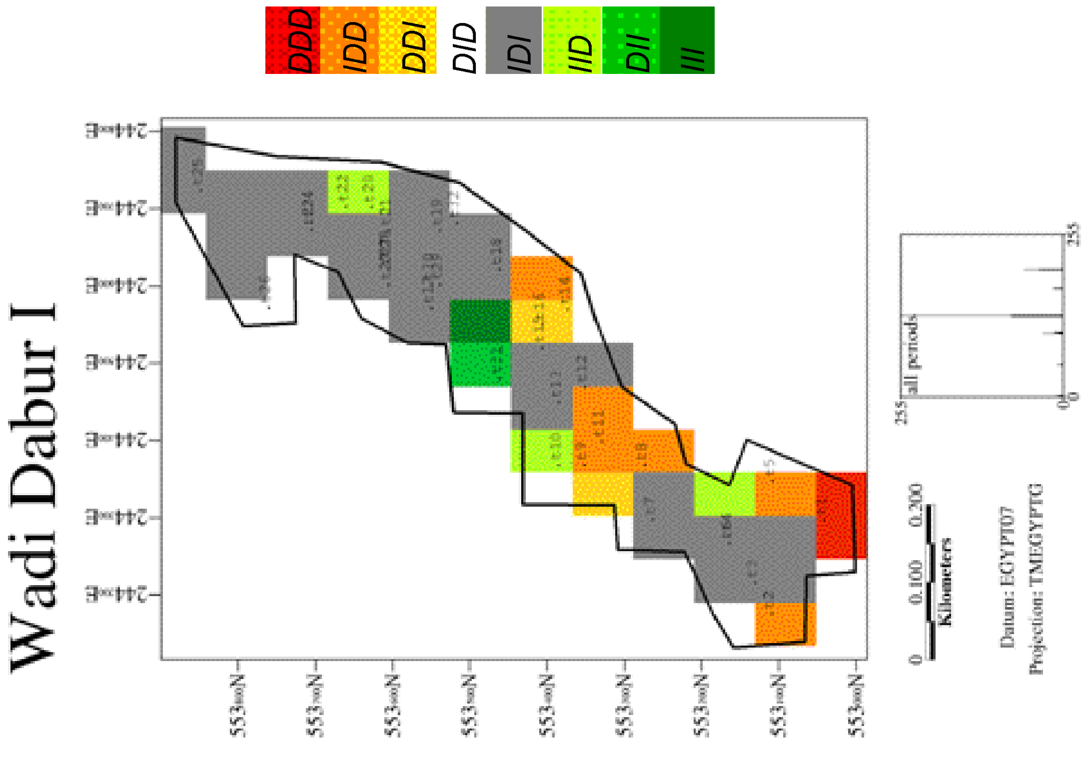


Figure 131 Trends across periods for W. Dabur I.

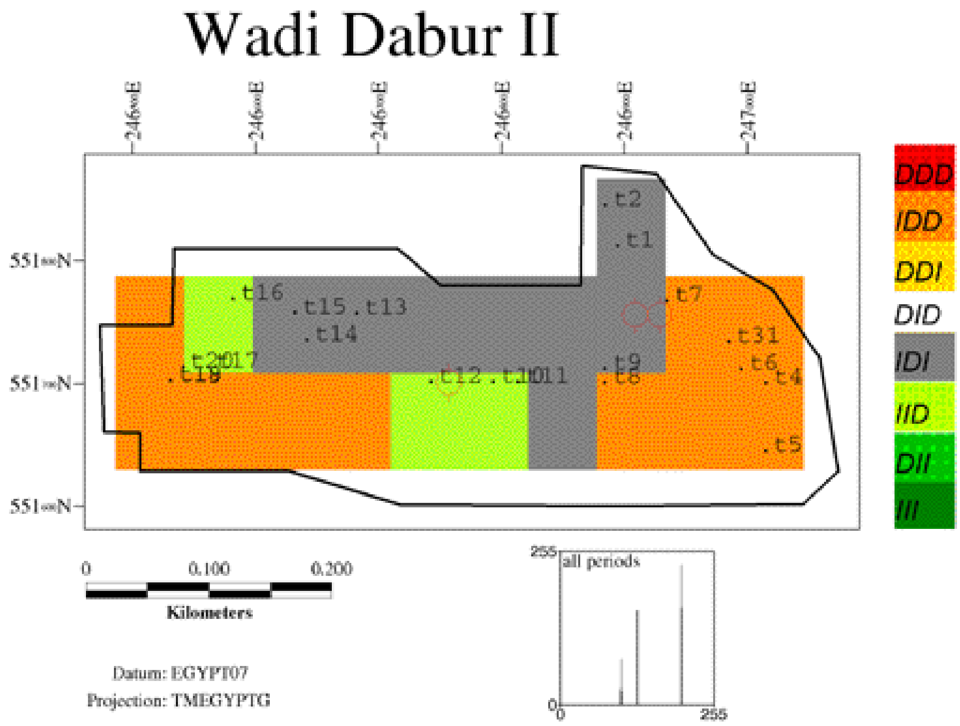


Figure 132 Trends across periods for W. Dabur II.

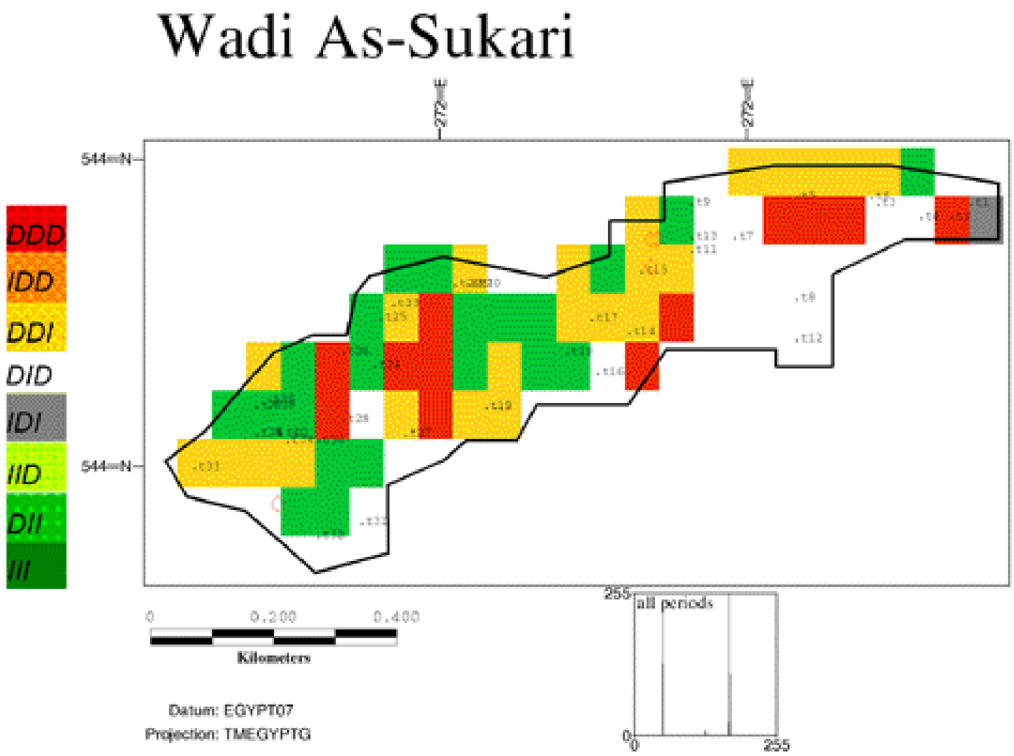


Figure 133 Trends across periods for W. As-Sukari.

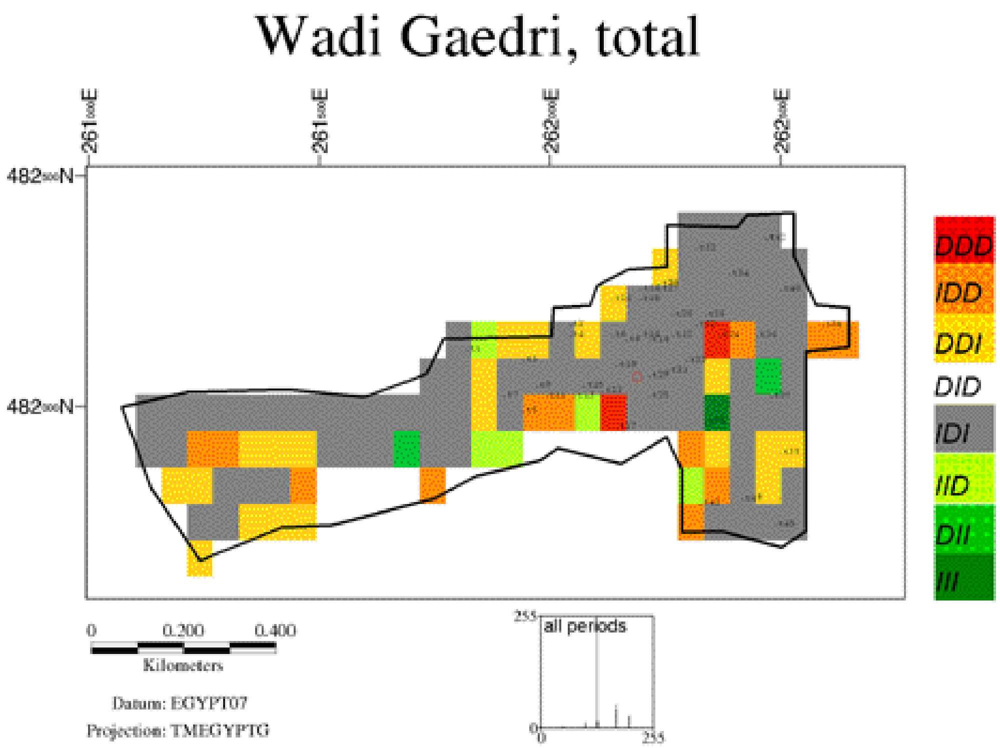


Figure 134 Trends across periods for W. Gaedri, total.

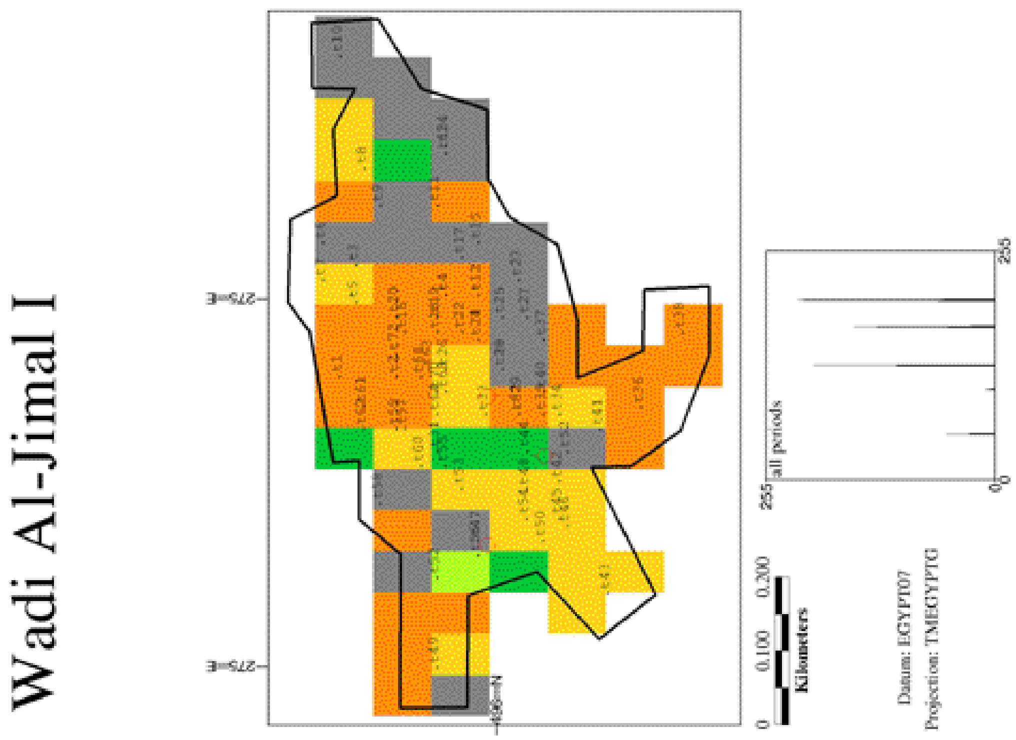


Figure 135 Trends across periods for W. Al-Jimâl I.

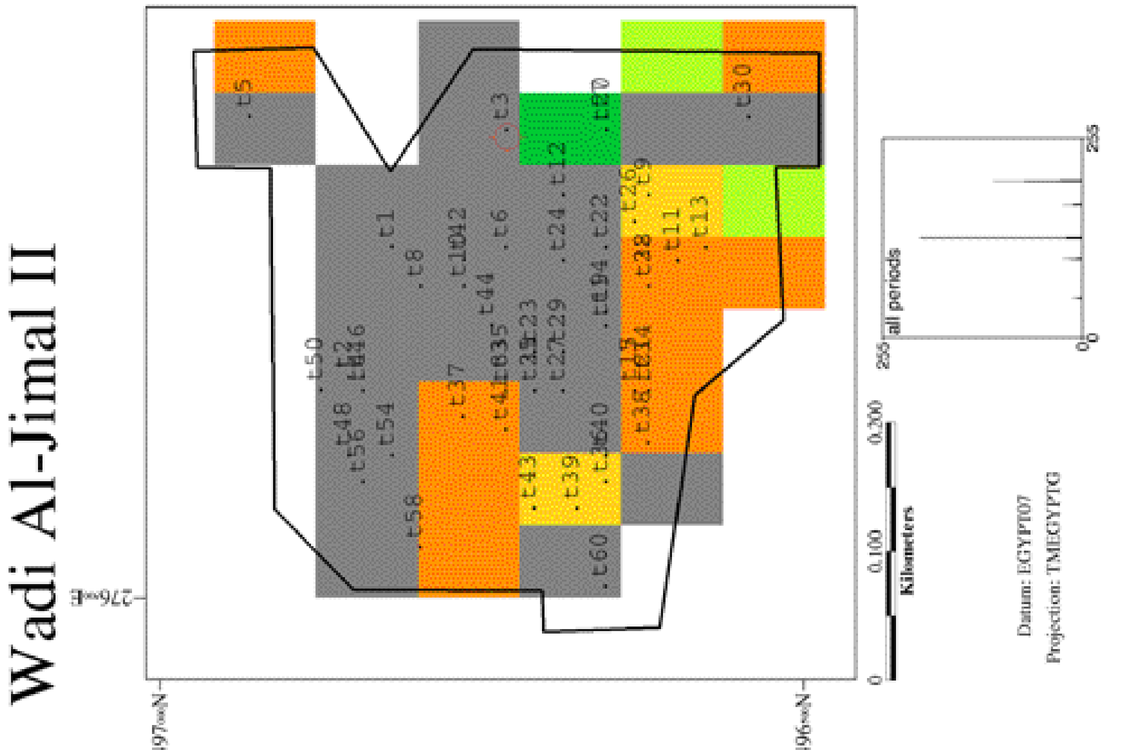


Figure 136 Trends across periods for W. Al-Jimâl II.

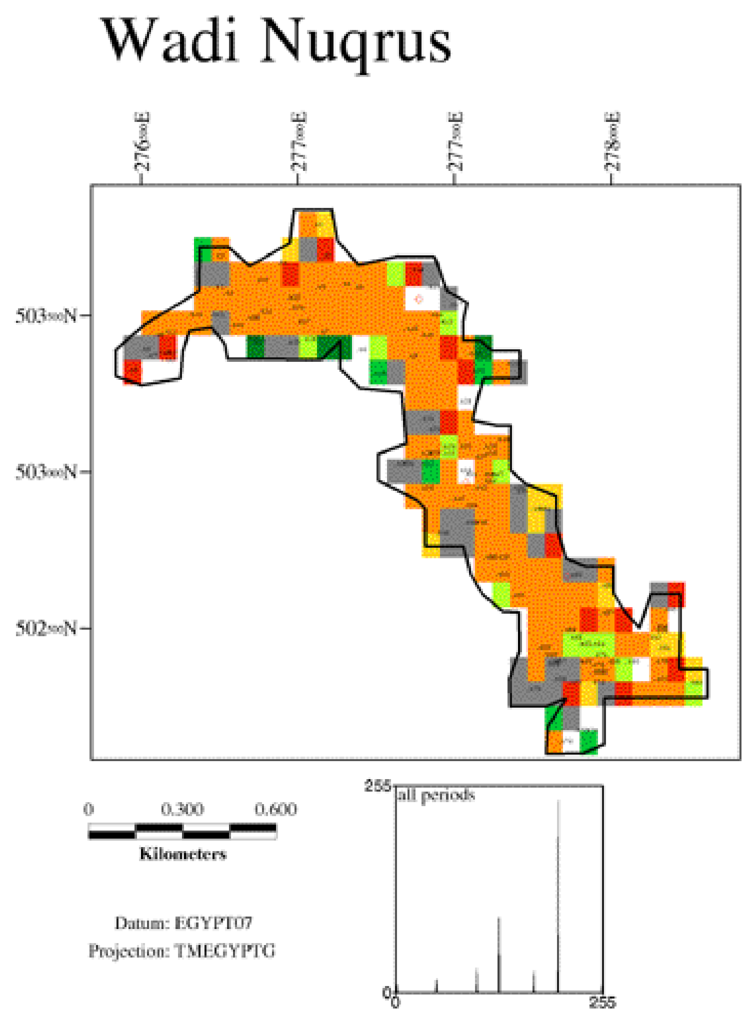


Figure 137 Trends across periods for W. Nuqrus.

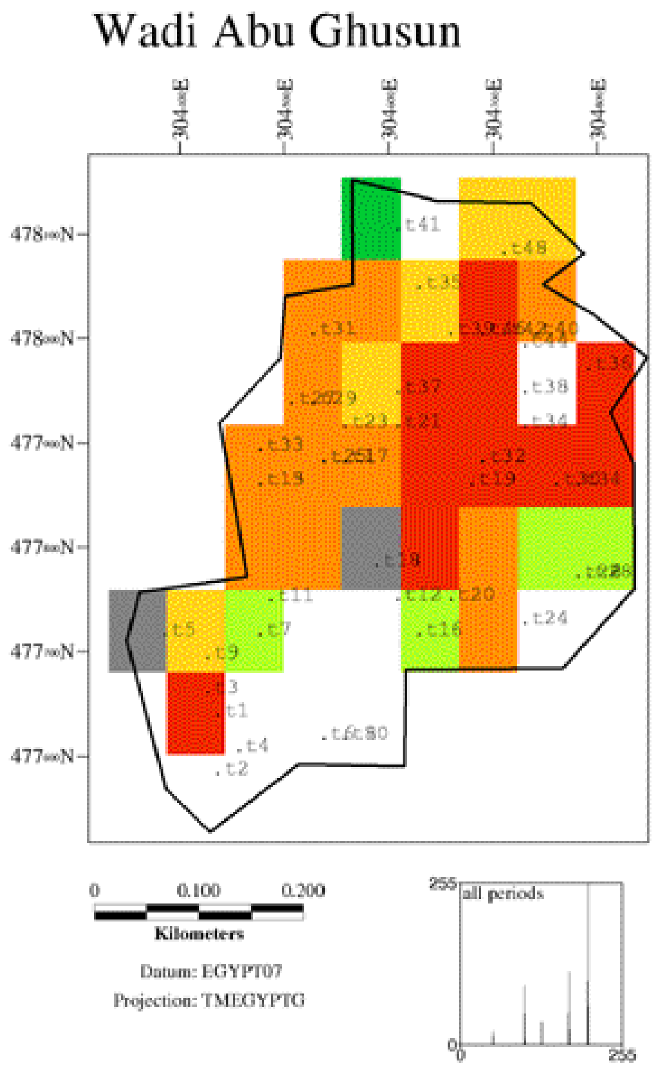


Figure 138 Trends across periods for W. Abu Ghusun.

distribution of pixels within each cross-periodic trend according to their general, *i.e.* the trend between 1973 and 1996, is given in Table 45.

The majority of pixels of general decrease, although recorded for at least two periods of increase, are of the IDI trend. The only exceptions are Abu Ghusun where this happens most often for pixels of the IID trend and As-Sukari where this happens most often for pixels of the DII trend, see Table 45.

Pixels of general increase, although dominated by periods of decrease, are most commonly found within the IDD trend. However, at Gaedri and As-Sukari such pixels are more frequent within the DDI trend.

Finally, it should be noted that Nuqrus shows two inexplicable switches between cross-periodic trends and the overall trend; both pixels of III and DDD show general D and I, respectively.

Table 45 Distribution of pixels within each cross-periodic trend according to general trend calculated as number of pixels

	Dabur I	Dabur II	As-Sukari	Gaedri	Al-Jimãl I	Al-Jimãl II	Nuqrus	Abu Ghusun
DDD-I	0	0	0	0	0	0	2	0
DDD-D	2	0	12	2	0	0	13	10
IDD-I	2	2	0	5	9	2	14	3
IDD-D	4	8	0	7	15	7	83	8
DDI-I	0	0	7	7	1	0	3	0
DDI-D	2	0	16	14	15	2	8	5
DID-I	0	0	0	0	0	0	2	0
DID-D	0	0	20	8	0	1	12	10
IDI-I	16	5	0	48	3	14	19	1
IDI-D	8	3	1	27	16	6	16	1
IID-I	2	2	0	1	0	1	1	0
IID-D	1	1	0	4	1	1	11	4
DII-I	1	0	2	1	0	0	3	1
DII-D	0	0	19	1	5	1	3	0
III-I	1	0	0	1	0	0	1	0
III-D	0	0	0	0	0	0	3	0

DISCUSSION

The broad objective of this study is to investigate temporal changes in wadi vegetation in the Eastern Desert of Egypt, based on satellite data. The interpretation of satellite data has two requirements: relevant reference data and an understanding of the relation between reference and digital data. The results achieved will therefore be discussed in three different parts: first field observations and related information, second spectral vegetation signatures, and third change images.

Field observations and related information

Field observations and related information, *e.g.* hydrological data such as catchment and slope, provide knowledge not only about sites studied but also about the desert landscape in general. In the following, this is discussed mainly from the point of view of 'change'.

Utilisation of arboreal resources in the cultural desert landscape

In general, field observations confirm that the area under study is a cultural landscape where each tree is an important resource, since it is normally utilised both for fodder and fuel. However, several observations, such as cut *Moringa peregrina*, heavy cutting (W. Al-Jimãl I and observations on individual trees), burnt trunks, large-scale charcoal production (W. Hulus) and reports by nomads in W. Gaedri, indicate an intensified utilisation of arboreal resources.

The charcoal production observed in the W. Hulus is not just an indication of an intensified utilisation of tree resources, it also gives an idea about the character and degree of change. The production technique corresponds to that of the *kamina* (Christensen 1998), which she refers to as the technique used for commercial production. The large number of sacks observed also emphasises the commercial character of this production. More than 11 sacks a month has been characterised as a high production for one producer (*op. cit.*), and in this case 20 sacks were observed.

Different studies relate the weight of charcoal produced to the number of trees needed, *i.e.* the number of trees cut (Christensen 1998, Olsson 1985). According to the estimates and observations described in Christensen (1998) and Olsson (1985), the twenty bags observed indicate an off-take of between 10 and 21 trees[60]. Several factors influence the reliability of such conversions, *e.g.* size of sacks, varying growth-form and size of individuals, estimation of ratios, *etc*.

Even though there remain several questions related to the conversion between charcoal produced and off-take of trees, the case observed in W. Hulus certainly highlights the considerable extent of the production there. Compared to estimated tree density (less than 4 trees/ha., cf. Fig.79) this production (potentially) causes change (cf. p. 15-18). This process of change is in semi-arid areas recognised as deforestation. Obviously, it seems forced to use a term related to 'forest' with reference to a desert environment. Nevertheless, the charcoal production observed in W. Hulus is in both causes and consequences compatible with the concept of 'deforestation'.

Gradients, sites and recorded variables

The hypothesis of the cultural character of this desert landscape was tentatively employed when sites were selected. A water gradient too was selected to represent the most important natural factor.

The results of this study show that there are differences among sites, both in degree of human interference and in relation to natural factors. They also show a certain expected correlation between variables selected and sites studied; but more evident still is, perhaps, the complexity of the gradients themselves and the interference between them.

The cultural gradient selected is one of traditional vs. non-traditional land-use. This gradient has, however, at least two dimensions, one temporal and one spatial, *e.g.* As-Sukari is both historically and at present situated close to an area of non-traditional land-use. However, the present location of sites along this gradient is difficult to assess, especially if they are not situated along direct routes of communications. There are at least two explanations for this, *viz.* the size of the area and the present scientific focus on the area. The area studied is large, and consequently it is difficult to obtain detailed knowledge about all of it. More important is the fact that little scientific interest has been shown in present social conditions in the study-area.

[60] Three sacks weigh 100 kg Christensen (1998). The conversion ratio between charcoal weight and dry weight is 1:4 (Christensen (1998) and as referred; hammer digernes, 1977) and between dry weight and wet weight it is 2:3 (Olsson (1985)- based on *Acacia tortilis* estimates). The conversion rate between wet weight

It is not possible exhaustively to capture a cultural gradient in the parameters measured in this study. Nevertheless, in terms of branch height (Figs. 69 and 70) and charcoal related observations (Table 27) most sites come out as expected. All sites assumed to be closer to the non-traditional end of the cultural gradient, *e.g.* Nuqrus, As-Sukari, Dabur I and Al-Jimãl I, show more signs of human interference than sites that, according to their location, should be further away from the non-traditional end of the cultural gradient, *e.g.* Dabur II, Al-Miyãh and Al-Jimãl II. This indicates that historical sites where non-traditional land-use has been common are located along important communication routes that are important today too.

The only exception to the expected pattern is the Gaedri site. It is not located as close to any known, important historical site influenced by non-traditional land-use as other sites are and does not lie on any direct currently used communication route. The same is true for the location in W. Hulus and this highlights the need for a better understanding and knowledge of spatial patterns of human life in this environment (cf. above).

Employing branch height as a cultural indicator seems to be useful. At Al-Jimãl I this variable is one important factor that distinguishes it from Al-Jimãl II, which, in terms of charcoal related observations is similar. However, low branch height is not necessarily the result of reduced browsing and/or cutting pressure. Younger, shorter individuals automatically have a low branch height. If there is a direct connection between this variable and height, it will be reflected in a similar distribution pattern for these two variables too. However, this is not the case for Dabur I, Al-Miyãh, or Al-Jimãl I.

In this study the gradient of water availability is measured by catchment and slope only. Important indicators like soil texture and depth are not included, nor are internal variations in slope (both longitudinally and laterally) at the sites; hence it is not an exhaustive gradient. Nevertheless, this gradient too explains some of the variation among sites.

Balanites aegyptiaca is known to have greater moisture requirements, to avoid freely drained sites, and to prefer those with deeper soils and gentler slopes Hall (1992). Some individuals were recorded in W. Gaedri (t45) and Nuqrus (t1, t10, t11, t24), and in both places they grew on the edge of the wadi where water flow is slower. However, the only localities dominated by *Balanites* are the W. Al-Jimãl localities, both of which have gentle

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and number of trees is based on average size of individuals: 200 kg (height 4.2). A large tree observed by Christensen (1998) weighed approximately 400 kg.

slopes. These latter two sites have large catchments that indicate good water conditions too. Thus, the interpretation of the name Wadi Al-Jimãl made by El-Sharkawi *et al.* (1982b) has to be questioned. According to him 'valley of camels' indicates the "extremely arid characteristics reflected on the vegetation which is only grazeable by camels". Rather than reflecting extreme conditions the vegetation seems to reflect favourable water conditions and to be valuable pasture for browsing. The 'negative' interpretation of the name is unreasonable. More probably this name indicates that it is a good valley for camels. Traditional naming of wadis indicates that their names are often related to their importance for nomads (Hobbs 1989).

Tree density and coverage seem to be well explained by a water gradient, but other factors seem to be influential too. Land-use activities, in particular charcoal production where whole individuals are removed, can obviously reduce both density and coverage. The estimates in this study were based on polygons outlined to include all registered trees and surrounding pixels (cf. p. 82), and also possible errors introduced by the method itself must be considered (see below).

Most striking for estimated density and coverage are their low magnitudes and their low variation between sites. Low magnitudes are expected for a hyper-arid area, and the low variation may indicate that the area selected is large enough to reflect a 'true' value. Unfortunately, it is difficult, even impossible to compare - and therefore confirm - these values with those from other studies because most studies conducted in the Eastern Desert have focused on plant sociology (El-Sharkawi and Fayed 1975, El-Sharkawi *et al.* 1982a, 1988, El-Sharkawi and Ramadan 1983, 1984, El-Sharkawi *et al.* 1982b, 1990, Kassas. 1952, 1953a, 1954, Kassas and El-Abyad 1962, Kassas and Girgis 1964, 1965, 1972, Kassas and Imam 1959, Kassas and Zahran 1962, 1965, Salama and Fayed 1989, 1990, Springuel *et al.* 1991, Zahran and Mashaly 1992, Zareh and Fargali 1991). Any derived coverages or densities are not comparable, either because of methodological differences or because no distinction has been made between arboreal species and less drought-resistant ones.

Other studies, mainly related to the use of remotely sensed data, involve a partly comparable methodology, *i.e.* they consider arboreal species only; but the areas they study are in the Sudan (Blomberg 1992, Cole 1989, Larsson 1993, Olsson 1985). Consequently these calculated densities and coverages are greater due to a more favourable climate, and consequently more favourable water conditions. Densities range between 2.1 trees/ha. (Cole 1989) and 520 trees/ha. (130/0.25 trees/ha., Olsson 1985) and coverages between 1.1% (Blomberg 1992) and 74.6% (Olsson 1985).

However, the field units, *i.e.* the bases for these estimations, vary among these studies from 0.12 to 25 ha. In the study of Cole (1989) there seems to be some bias because sparsest cover is at the largest site and *vice versa*. Olsson (1985) also samples data from aerial photos and then applies a larger sample unit (average of 9 ha.) than that of the maximum of 0.25 ha. used during field-work. Densities and coverages derived from aerial photos reach a maximum of 109 trees/ha and 27.9% respectively. Although the variation seen in the current study is negligible in comparison, estimates for Nuqrus in particular seem to be affected by a large polygon, *i.e.* area (84 ha.). Gaedri, As-Sukari and Al-Jimãl I are also sites of a somewhat larger area than the remaining ones; but their densities and coverages are well explained by other factors.

Gaedri has a relatively larger coverage than density due to a majority of large individuals. As-Sukari is of comparable size to Gaedri, so its lower estimates cannot be explained as an area effect. Rather they can be related to poorer water conditions. This impression, that water conditions are relevant, is strengthened by the Dabur localities. Both sites are relatively small; and, if there were a size effect, values higher than those for other small sites would be expected. However, density and coverage are low for both sites, and water conditions are poor. Also the W. Al-Jimãl sites admit of such an explanation because their high estimates can be related to their good water conditions.

Although even a simplified water gradient seems to explain the slight variations in density and coverage among sites, influence from cultural factors should not be forgotten. As shown by Cole (1989), there was a marked difference in estimated density between 1960 and 1989. A site could have a reduction of between 100 and 13%, and this was principally due to human activities[61]. Springuel and Abdel (1994) too relates present tree growth to historical activities, *i.e.* mining since Pharaonic times. Presently observed densities and coverages may, therefore, be less than actually could have been supported by the environment itself. Perhaps it is not just the arid conditions that explains the low estimates, and perhaps a greater variation existed among these sites earlier. Low estimates at Nuqrus

[61] These activities include charcoal and firewood production for market, land settlement, and intensification of land use.

could just as well be caused by past and present cultural activity, not by its large area alone. As-Sukari falls nicely into this explanation too. However, Al-Jimâl I and Abu Ghusun, which are similar as regards past pressure and seem to be similar as regards present pressure to, at least, Nuqrus, have in this case higher estimates than expected. Dabur I, which seems to be the site of least influence, has lower estimates than expected, at least compared to Dabur II. In this case, sites are ambiguous along their gradients, and therefore it is difficult to isolate sites and factors.

The individual trunk size of trees seems to be the variable least affected by present cultural influence. There is a clear connection between, and a rapid effect of, removal of branches and crown diameter. Moreover, removal of top branches influences the height of an individual. Cutting and browsing (which may appear similar to twig biting) may produce a similar effect to pruning, *i.e.* an increased vigour of the tree that results in an increased growth (Bergström 1992, DuToit *et al.* 1990). Therefore, influence on trunk size is possible. However, this is a positive feedback loop limited by growth ratio which anyway is most limited by growth conditions at the site. In addition, the distribution of trunk sizes is more different from that of other variables, *i.e.* branch height, height and crown size (cf. Fig. 76).

Moreover, trunk size seems to be the most interesting variable that has a bearing on understanding change. As an indicator of total thickness growth it is not only related to growth conditions but also to age. Small trees either grow under poor conditions or are young. Total distribution, especially by its gaps, can be related to both cultural influence and regeneration. The current study was not designed to go into the population dynamics of desert trees, but a few points relevant for interpreting change will be made.

1. Very small/young trees are rare or absent at all the sites studied.
2. Some very large trees (appearing as outliers) are seen at many sites, and some sites are dominated by large trees.

The first point is related to regeneration. Successful regeneration is recognised and/or observed as rare by many authors (Christensen 1998, Kenneni and van der Maarel 1990, Obeid and Seif El Din 1971, Seif El Din and Obeid 1971, Springuel and Abdel 1994). Different factors are mentioned as explanations: rainfall is rarely sufficient, long dry periods, browsing and grazing. Rare success is suggested to result in stands with trees of the same age (Greenway and Vesey-Fitzgerald 1969, Hughes 1988). The lack of small individuals observed at sites studied – and this is the general impression for the study area too - seems therefore to confirm that regeneration is rare and poor.

The second point is related to growth ratio and age. Two different views are found in the literature. Some authors argue that desert trees grow fast and do not become very old (Gourley 1995, Springuel and Abdel 1994); others argue that growth is slow and that trees may reach a considerable age (Kenneni and van der Maarel 1990, Wyant and Reid 1992). The latter view is in accordance with the observations made by nomads (nomadic statements in Hobbs 1989, Springuel and Abdel 1994).

Both Wyant and Reid (1992) and Gourley (1995) relate growth rings to known age. The study of Gourley (1995) is, however, based on the growth of trees in botanical gardens, *i.e.* the trees have been removed from their natural conditions, and grow under conditions where irrigation probably increases the water available to them. Wyant and Reid (1992) base their study on trees that were growing in their natural environment, and they find a significant linear relationship between ring-count and age. However, this is not a one to one relationship, but rather one that suggests a relation between the frequency of missing rings and the frequency of very dry years or droughts (in their study area, South Turkana, Kenya, three years in each decade are estimated to be very dry). Applying their results and taking into consideration the erratic and rare rainfall in our study area, the largest individual at the Nuqrus site could be at least 400 years old[62].

In the study of Hobbs (1989) his informants convey a respect for old trees. This fact can explain that large trees are seen in the landscape. That only a few large trees are present is perhaps due to other trees of the same age group having already been removed a long time ago, before they were considered as “antiquities”. Therefore, the large trees observed today may be relicts from earlier generations.

For each tree a positive correlation between trunk size and age obviously obtains. However, in a comparison of several trees it is not necessarily the case that a large tree is

[62]It is indicated that an individual grows 10 cm in diameter in 27.5 years (*op. cit.*). This gives an annual increase in trunk diameter of 0.36 and an average width of growth rings of 0.26 cm (10 years gives only 7 growth rings). The growth rings can be even thinner in the much drier study area. The largest tree in Nuqrus has according to these estimates approximately 200 growth rings (=(1/0.26)*0.5 trunk diamter). According to rainfall data (18 years only), rain falls every second year; and two consecutive years of rainfall occur less than every fourth year, which indicates an age between 400 and 800 years. If the trunk was measured at its base as it is in their study, an even greater age would have been indicated.

older than a smaller tree. Poor growth conditions may restrict growth sufficiently to give an old tree a smaller trunk than that of a younger or similarly-aged tree that grows under better conditions. The effect growth conditions can have on trunk size increases over time and can therefore be greater for the older trees, *i.e.* two trees of different sizes can be of the same age. Consequently, it is not obvious which trees that are similarly-aged. The variation in trunk size within sites does not therefore automatically contradict a theory that suggests that regeneration is rare. The variation in trunk size can represent a few generations of trees, if not only one. If trees rarely regenerate, it seems probable too that the life-time of survivors is longer.

These complex relations between water, age, culture and distribution of trunk size within sites make it difficult to interpret trunk size in terms of one variable only. However, trees are generally smaller at the Dabur sites, and this may indicate that water conditions, at least at these sites, are more important for size than are other factors.

Spectral vegetation signatures

The part of this study that focuses on spectral vegetation signatures is related to the second objective of the thesis, *viz.* To extract vegetation information and hence to discover at what level vegetation change may be interpreted.

There is evidence that vegetation also gives significantly different spectral signatures in this hyper-arid area of very low vegetation cover. The vegetation information is best reflected by the Red band. Thus the trend seen in other arid, but less arid, areas is observable here too (cf. p. 38).

Field registrations were made at a very detailed level to allow highly detailed interpretations of digital data. However, it is now clear that the methods chosen cannot establish a relation between vegetation cover and spectral data, either at the level of stations or at a pixel level.

Vegetation cover vs. Vegetation reflectance

The failure to establish a quantitative relationship between vegetation cover and reflectance leaves one question, *viz.* why?

The main problem was inadequate positioning accuracy so that it became impossible to link field and digital data, a process required for the completion of correlation and regression analysis.

Inadequate positioning accuracy was suggested in the first test between presence and absence groups. This test was based on pixels with TM resolution, and it revealed no significant differences among groups tested (cf. Fig. 92). The trend found in the test based on neighbour pixels confirms that low positioning accuracy influences the ability to distinguish between pixels with and without trees. At least, it confirms that inadequate positioning accuracy introduces a greater obstacle than does low spectral contribution from correctly positioned trees.

Differences can, however, be exaggerated in this test because the number of units in the presence group decreases as a more restricted selection of pixels is adopted. If such testing is to be extended, the selection of groups should be improved.

The Walsh test proves that there exist differences between pixels with and without vegetation, *i.e.* trees, although this is confirmed for only one of the pixels tested; there is no significant difference present for the other four pixels tested. However, no precautions were taken to reduce position errors in this test, and probably this explains why only one of four trees tested gave a significant difference.

At least three factors influence positioning accuracy, *viz.* GPS measurements, transformation of positions, and rectification.

Transformation of positions is a purely mathematical operation, and any errors introduced are not very great. The RMS error from rectification is small too, *i.e.* about 7 m, (rectification is further discussed below). GPS measurements seem, therefore, to be the main source of error.

Field registrations were based on GPS point mapping because it is the method that permits the highest resolution and therefore the best integration with raster data (cf. Integrating dryland vegetation data with spatial raster data, p. 20.). The accuracy to be expected from GPS positions is well known and was considered in advance of and during field-work. At that time it was planned to work on a MSS resolution only (cf. p. 52). Lower resolution tolerates lower accuracy, and consequently conditions seemed to be optimal. A reduced SA further improved conditions. This is seen in flat and open areas, and even at a TM resolution accuracy seems to be good (Fig. 25). The sites are, however, situated in wadis surrounded by mountains of varying heights. Multipathing, caused by shadowing, delays the satellite signal and therefore reduces its accuracy. This is perhaps the main cause of the insufficient positioning within the sites studied.

Other methods could have given greater accuracy, but they are neither time efficient nor practical to carry out (cf. p.22). Olsson (1985) does not describe her field positioning method, and it is therefore assumed that she used map and compass readings. One of her conclusions is that there is a problem locating field units, *i.e.* quadrates. The control and backup method for this study (cf. p. 75) too has problems locating trees accurately because at least one point has to be accurately known - and there isn't any. In addition, errors will increase for each measurement because every one relies on, and therefore includes, the errors of the previous position.

Although the method selected introduces a limit on the level of detail that can be attained, it still seems to be the best of the currently available and practical methods. Future, improved technologies, *e.g.* DGPS, may reduce these problems, but the problem of multipathing is inherent in the GPS method.

Factors influencing vegetation signatures

Both Larsson (1993) and Olsson (1985) derived a quantitative relation between vegetation cover and reflectance based on field methods basically similar to those used in this study (or even methods that seem to be less accurate, cf. above: Olsson 1985). There is, however, one main difference between their study areas and ours, *viz.* the sparser vegetation cover in our study area.

Nevertheless, this study confirms that even with this sparse vegetation cover differences in spectral signatures over vegetation and non-vegetation can be registered (cf. above). The Walsh test indicates a difference between pixels tested and surrounding ones of about 5 DNs. Differences are seen in individual pixels on the test site too; there the greatest differences reach as much as 40 DNs (compared to the general background level). This value is notable from a change perspective; perhaps it is an indication of what coverages were once present (cf. p. 62-63).

On the other hand, although significant differences exist, this is an area where digital vegetation monitoring by MSS and TM data are close to their practical limits. As seen in results both from study sites and the test area, this fact is linked not only to a sparse cover but perhaps more importantly to the subsequent and increasing influence of other factors. Factors recognised in the course of the current study are resampling, resolution, and variation in background reflectance. These are interlinked to varying degrees.

The effect of resampling is seen especially in the test area. A moving grid (cf. p. 123) influences both the ability to link field and digital data and the ability to detect change (cf. below).

One part of the resampling process is the calculation of new pixel values. Apparently, resampling to a lower resolution for heterogene and scattered vegetation gives, until a certain resolution (cf. below), a reduction in cover within a pixel. Lower values are, therefore, to be expected after resampling. However, the fact that a recalculated value is based on several surrounding pixels makes the output more similar to the original, surrounding background. Therefore, an amplified reduction in content of vegetation information may follow resampling too. To visualise this, consider an area with a scarce and scattered vegetation cover of trees. If one considers one specific tree and a very high resolution; *i.e.* units smaller than the size of the tree-crown, then vegetation cover within one pixel will be hundred percent. It will remain hundred percent until the resolution becomes lower than the size of the crown. From then on coverage will decrease, and consequently influence from the background will increase. The vegetation coverage will again increase slightly when the resolution includes more than one tree only. The vegetation cover will therefore oscillate towards a specific value at which point the resolution has reached a level that captures the variability of the vegetation pattern.

In the current study, vegetated pixels could be differentiated from surrounding pixels only when spatial resolution was high (TM) and when different steps were taken to normalise/reduce background variation too, *i.e.* steps such as calculating classification and vegetation indices and using data from one (dense) site only. The ability to distinguish between pixels with and without vegetation increases with higher resolution because differences introduced by vegetation become more distinct compared to general background reflection and therefore become easier to detect.

Reducing spatial resolution is equivalent to working at even lower coverages (cf. above). At the locality level, cover is even below 1% and not greater than 2%; and at this level no consistent relation was found between spectral indicators selected and actual vegetation cover. Spatial comparison based on single bands requires a stable background, and evidently there was no stable background at sites selected. However, no consistent relation is found after normalising background either. In fact, there seems to be no relation at all (Figs. 89 and 90). This is seen in Olsson's (1985) study too, where vegetation indices are about constant below a vegetation cover of 16%. For the single bands, however, she finds a large scatter for such low coverages. She relates this scatter primarily to a localising problem, yet still she claims that selected field units are representative of larger areas. The scatter is still present when field units are selected and positioned from aerial photos, a method which she regards as more accurate. Therefore, it seems likely that background variations too introduce scatter.

In the current study, there is no localising problem at the locality level. Rather, variations in background reflectance seem to be greater than any deviations introduced by vegetation cover. Apparently, reflectance from vegetation cover is too low to influence the mean for the site significantly. This is also the case even if the background is normalised by either VI or PVI. Elvidge and Lyon (1985) recognise the latter to be very efficient in semiarid and arid environments, but at as sparse coverages as dealt with in this study this does not seem to be true. The main problem is probably to be sought in the fact that there is not one constant soil line (Jasinski and Eagleson 1989, Pickup *et al.* (1993), which the PVI relies upon, nor is the IR reflection as theoretically expected.

Change analysis

The change analysis is based on a subtraction between red bands of the years compared. Also Chavez and MacKinnon (1994) recognised that calibrated single bands, in particular the Red one, is the most efficient input to a change analysis where the focus is on vegetation in arid and semi-arid environments. In this study a subsequent classification of pixels according to the magnitude of their change was performed to facilitate the interpretation. Another set of images was made where the per pixel, cross-periodic trends were visualised. Plots of the total distribution of pixels showing periodic trends and cross-periodic trends for sites were also made.

Change images have to be interpreted from three points of view: one natural, one cultural and one methodological. Considering these three factors is of the utmost importance if one is to distinguish between change and variation. While all three may introduce variation, only the first two can disclose changes.

In the following the results from the change analysis are first discussed in a natural and cultural framework. Methodologial aspects of the change analysis are discussed in a final section. All factors that are recognised to influence the change analysis are, together with their effects and control factors, summed up in Table 46.

Table 46 Factors that influence the change analysis, together with their effects and control factors.

Category	Variables	Change	Trend	Indicator
Natural	Rainfall	Regeneration/ growth of arboreal perennial vegetation	+	Catchment and slope, field data
		Flood - destruction of arboreal perennial vegetation	-	Catchment and slope, field data
	Lack of rainfall	Arboreal death - only for very severe and long droughts	-	Catchment and slope, field data, rainfall data
Cultural	Traditional land-use	Browsing of seedlings/young individuals		
	Non-traditional land-use	Removal of per. arboreal veg, *e.g.* charcoal production	-	Field-observations and land-use gradient
		Severe browsing and lopping	-	Field-observations and land-use gradient
Category	**Variables**	**Variation**	**Trend**	**Control factor**
Natural	Rainfall	Ephemeral growth	+	Acquisition date
		Arboreal greenness performance	+	Acquisition date
	Lack of rainfall	Ephemeral withering	-	Acquisition date
		Arboreal greenness performance	-	Acquisition date
Cultural	Traditional land-use	Browsing	-	Comment: severity increase with length of dry period
		Lopping	-	Field-observations
Technical	Illumination and angles (cf. Fig. 9.)	Spectral properties of features	+/-	Acquisition date and system characteristics
	Spatial resolution	Detection of features; background and vegetation	+/-	
	Grid placement	Small spatial differences between pixels compared	+/-	Detectable along edges
	Resampling	Smoothing of differences	+/-	
	Rectification	Moving features	+/-	RMS
	Radiometric resolution	Interpretation of DNs	+/-	Max difference is 4
	Radiometric calibration	Change thresholds	+/-	R^2
	Striping		+/-	Only 73-image

Change and variation in a natural and cultural framework

The ability to distinguish change from variation and therefore to interpret change is basically restricted by the pixel. "What's in a pixel" is a question raised by Cracknell (1998) and this is, indeed, a very pertinent question for this study, even when technically induced errors are excluded. The limits set by resolution are absolute; and even if there are several different trends within one pixel only the most dominant trend will be reflected. In practice, this means that within a pixel of increase, decrease too may occur, and *vice versa*. Accurate field registrations could have excluded some possible combinations of increase and decrease; however, at the pixel level their lower than expected accuracies make these registrations of limited help. Nevertheless, both selection of periods and pattern of across-periodic and general trends give important indications for drawing a distinction between variation and change.

An attempt to define change was made in the theory chapter (cf. p. 15). This definition questions whether decrease or increase in only one period can be defined as a change. Cross-periodic trends too are of importance when change images are interpreted. Even for the whole period, covering 23 years, inter-periodic trends have to be considered in order to conclude whether a general increase or decrease is only part of a pattern of variation or belongs to a pattern where one trend is, or has been, prevalent. However, to conclude that a change has occurred the particular trend has also to be seen in relation to the periods selected.

The periods selected correlate with the main meteorological periods in Northern Africa since 1973 (cf. p. 77). The two periods, 1973-1979 and 1984-1996, are in terms of water availability more favourable than the dry period between 1979 and 1984. The entire period, 1973-1996, is bracketed by a year after a severe drought (1973) and a year (1996) following a period of several rather good years. Increase and decrease may have different interpretations within these periods.

Decrease in arboreal vegetation in the wadi ecosystem is caused mainly by land-use activities, *i.e.* primarily lopping, browsing and charcoal production. None of these activities is restricted to “bad” or “good” periods; but their effects may become more severe during dry periods (cf. p. 62).

Two other factors may give decrease, *viz.* droughts and floods. However, compared to the cultural factors that give decrease, droughts and floods are less frequent. Arboreal trees are drought-enduring species, and established individuals are unable to withstand a drought in exceptional cases only. Floods may uproot and kill trees; however, uprooted, dead trees were rarely observed during field-work. Nevertheless, there were observed uprooted trees that were still alive.

Increase in arboreal vegetation reflectance is mainly related to three factors, all natural: regeneration, growth, and denser foliage. Excluding cultural influence, both (successful) regeneration and growth represent a long term increase. Because arboreal species are drought-enduring species, growth is not restricted to "good" periods. However, as referred to earlier (cf. p. 196), growth increases in good periods; while regeneration seems to be restricted to consecutive years of rainfall. Variation in foliage is, however, positively correlated with meteorological conditions; *i.e.* an increase due to denser foliage is expected to be followed by a decrease in the next dry period.

Factors that may produce change (cf. p. 15-18) appear first of all as decrease on a change image. Therefore, it is pixels of (several periods of) decrease, not outweighed by increase, that indicate where changes probably have occurred.

At first glance, if one considers trends for separate periods only, it seems as if variation, not change, dominates most of the sites. The majority of pixels correlate with the meteorological conditions recorded for the periods in question; hence the observed trends may be explained as variation in leaf density. Christensen (1998) holds that increased leaf density in favourable periods is the main explanation for increase in vegetation cover. In areas where ground water is close to the surface, Krzywinski (1993b) associates increase with photosynthetic activity in the perennial grass *Panicum turgidum*. This species was not present on any of the sites selected, either in its photosynthetically active or in its dry state. Nevertheless, it is a less drought-resistant species than trees, and normally it is such species, in addition to ephemeral species, that explain most of the variation in desert ecosystems. During field-work all such species were rarely observed in a photosynthetically active state (Figs. 38-46). However, it has to be mentioned that there was rain in January 1979, *i.e.* a short time before the 1979-acquisition date. Also 1977 was a "good" year; and if these rains also affected the sites studied, this may explain some of the increase and subsequent decrease in vegetation cover. Whether these rains extended further north is unsure, and clearly this erratic rain combined with the paucity of meteorological stations in the study area is a disadvantage for the interpretation of a satellite based study.

On the other hand, it is not the majority trend for separate periods that gives the best indication of where a change has occurred. Even for sites and pixels where correlation with periods is dominant, several other characteristics indicate that decrease becomes more common. During periods when reduced leaf density cannot explain decrease, this trend is also observed, and it becomes more stronger in the last period, *i.e.* between 1984 and 1996. This more dominant character of the trend toward decrease during the last period can be interpreted as reflecting an ecosystem where cultural pressure has increased. This interpretation is supported by the dominant role of the trend toward decrease during the period as a whole as well.

If one studies cross-periodic trends, the impression that the ecosystem is changing becomes stronger.

The cross-periodic trend of IDI is less marked than suggested by the trends in separate periods, *i.e.* many of the pixels correlate meteorologically only with either one or two of the periods. Many IDI pixels show a general decrease. Such a trend of IDI-D is related to a decrease which is not outweighed by the subsequent increase, *e.g.* one of several trees within a pixel is removed, or trees have not recovered after lopping and/or browsing, and the subsequent growth and/or denser foliage cannot outweigh the decrease in cover. Hence, this pattern of IDI-D can indicate a greater cultural pressure and may indicate change; but only the future trend can confirm a change.

Pixels that depart from a meteorologically induced trend are more often dominated by a general decrease than by a general increase. Moreover, the majority of these pixels show decrease for more than one period (Table 45). Only a very small percentage of such (DD) pixels shows a general increase. Hence, the majority of pixels that depart from a meteorologically induced trend probably do indicate change.

Change images seem, therefore, to confirm the impression of a generally changing ecosystem. Moreover, they do reflect some of the expected and observed differences and trends among sites studied:

Gaedri is perhaps the most informative site when it comes to telling anything about the reliability of change images because this is the only site where historical reference data are also available. Some of the pixels in the western part of the locality show decrease for several periods and show a general decrease as well, *i.e.* they indicate change. If one considers the general change image only, a majority of the western pixels show decrease.

Observations made at Gaedri indicated that this was a locality where cultural activities were very influential. According to that observation, the IDI-I trend is perhaps more marked than expected. However, for other localities the distribution of trends gives meaning when compared with field observations. Al-Jimâl II and Dabur I were both localities where a weaker cultural pressure was indicated. This is reflected by a very abundant IDI trend.

Both As-Sukari and Abu Ghusun were dominated by decrease in the first period. Considering their geographical location this is an explicable pattern. Both sites were subject to great pressure in the succeeding periods as well; however, at As-Sukari increase becomes more abundant. This increase can be related either to differences in water availability at the site or to differences in land-use practice; *e.g.* differences in the degree and amount of lopping and browsing compared to the level of charcoal production. Because both catchment and slope are poorer at As-Sukari, the latter only may give an increase as observed.

Dabur I, Al-Jimâl I and Nuqrus all have geographical locations that suggest a greater cultural influence, and this was confirmed by field observations. Pixels indicating a greater probability of change are also very abundant for these sites.

Methodological aspects

Main trends and patterns for sites can be explained as change and/or variation caused by natural and cultural factors. However, methodological factors have to be considered too. Ideally, these factors are neutral and therefore negligible in the interpretation of change images. Change images do, however, yield some contradictory results which indicate that other factors also influence the results, *e.g.* trends like DDD-I and III-D, and reflected increase towards 1996 even in places where no vegetation was observed during field work.

There exist several different methods of digital change analysis (Singh 1989, Mas 1999). Most of these methods require that the data be spatially and radiometricly comparable, and for the method selected in this study it is a major requirement. To reduce further the influence of errors, resulting change images are normally thresholded, *i.e.* all pixels that are distributed around zero and are between certain values, are not considered to represent change. However, as indicated by the Walsh test, one tree introduces only small differences in pixel value compared to the value of pixels with no vegetation. Therefore, in order to avoid actual changes being removed as variations caused by technical factors, no thresholding was done in this study.

Spatial comparability

A major source of spatial errors is the rectification process. The RMS error describes the difference between actual and output coordinates and therefore indicates the magnitude of the spatial error introduced by this procedure.

For the TM image the RMS error is well below the resolution; recalculated as meters the error amounts to approximately 7.5 meters. Normally, a RMS error below 0.5-1.0 pixel is taken as an indication of a satisfactory geometric correction (Chavez and Mac Kinnon 1994, Cracknell 1998, Guirguis *et al.* 1996, Helldén 1988, Jensen *et al.* 1995, Townshend *et al.* 1992). This small difference between an old and a new grid also assures that no significant errors are introduced by the resampling procedure.

GPS measurements were used to assess the rectification. This can be questioned because the magnitude of the errors involved is not known; however, only the best available positions, *i.e.* positions from flat areas, were used in these tests and a good general fit would not have been found if these GPS measurements had been highly inaccurate.

For the relative rectification of MSS images it was difficult to find good positions and to locate them accurately. This was due to the lower resolution of MSS images and to differences among their grids. Notwithstanding, average RMS errors are below 0.5 for all three images.

A RMS error below the recommended threshold is not, however, a guarantee that there will be no errors introduced by spatial differences between the data-sets compared. In this study, spatial differences seem to be caused in particular by the resampling from TM to MSS resolution as well as by differences among original image grids or by a combination of these two factors. In a change image this can be seen especially along its edges, *i.e.* the transitions between wadi beds and surrounding mountains. This zone is one of very great heterogeneity in ground features, and consequently small differences between grids can introduce great differences in pixel values. On change images, pixels that represent such artificial changes may be distinct from other pixels either because they exhibit an opposite trend or are of relatively great magnitudes. This is, for instance, seen at both Dabur sites, at Al-Jimâl II, and at Nuqrus.

On the TM image from Dabur I dark pixels are present in the northern part of the site, see Fig. 45. On both the resampled TM-images (Appendix 5), these are seen as three dark pixels in a row; while on derived change images, they are traced as three pixels of great increase in “vegetation” (class 4 and 5). In this case, resampling to MSS resolution has changed the appearance of the darker mountains: a larger area is dark, and it extends more to the south because a new pixel size and therefore a new grid is introduced. Similar dark features are not present on any of the historical scenes. This is attributable to grid placement combined with the spatial resolution of these images: if only a small part of a feature is inside the IFOV, the spectral influence is less than if a larger part is inside.

Along the southern edge of the Dabur II site there is a great decrease (class 11-13) for the three periods 1979-1984, 1984-1996 and 1973-1996. This is caused by the varying influence of mountains on the pixels in historical scenes. On the 1996 images, however, this influence seems to be nearly absent, *i.e.* pixels are brighter and on a change image consequently represent a decrease.

In the northern part of the Al-Jimâl II-site, a horizontal row of pixels shows great changes between 1973 and 1979 (class 12-13) and between 1979 and 1984 (3-4). This is linked to the 1979 image where the dark pixels extend further south than in any other years. The grid of the image has overlapped the mountainous terrain differently, and consequently another row of pixels is highly influenced by the darker mountains.

The contradictory trends (DDD-I and III-D) observed for a few pixels on the Nuqrus site are introduced by the resampling from TM to MSS resolution, *i.e.* there are differences in grids between the TM_{79} and $TM_{81.5}$ data-sets. The comparison between 1984 and 1996 is based upon the $TM_{81.5}$ image, while that between 1973 and 1996 is based upon the TM_{79} image. Due to differences in grids it is not the same pixel that represents 1996 in both the resampled TM images from which change images are derived, hence these contradictory trends become possible. These few pixels are all related to edges.

Radiometric comparability

Radiometric correction too is a prerequisite for a successfull change analysis. The change analysis is based on the Red band which is the band with the best calibration in all the images. Nevertheless, between 10 and 18% of the variation in the MSS images cannot be explained by the reference image. As already discussed, much of this variation can be related to changes and variations caused by natural and cultural factors. On the other hand, variations that are not explicable by natural or cultural factors are still present. For instance, several of the sites had areas of continous pixels without any arboreal vegetation, *e.g.* Dabur II, Gaedri west and As-Sukari. Even so these pixels do show an increase towards 1996; and in these areas ephemeral and shrub vegetation was absent or dry as well (Figs. 38-46). The expected trend is, therefore, no change or decrease, not the observed increase (classes 6 and 7). Together with the two lowest classes of decrease, *i.e.* 9 and 10, these classes are the most frequent land-cover classes. Most of the desert landscape is, however, not subject to change; and these classes therefore probably include the most pixels of no change as well. It would appear that this inherent variation is not removed by the calibration process. As already mentioned, some of the expected changes have low values, and consequently they overlap with the classes that for the most part represent no change. This is a major challenge, and perhaps an obstacle, to digital change analysis in hyper-arid areas.

It is a disadvantage of the selected calibration method that the calculation of slope uses the covariance of the input images, *i.e.* any errors in the rectification process will also affect the accuracy of this calibration. There are other relative methods which do not rely upon covariance or other variables that depend on the accuracy of the rectification (Yuan, D. and Elvidge 1996). However, these methods have their own weaknesses. For instance, a haze correction corrects for simple atmospheric errors only (Pickup *et al.* 1993). According to Yuan and Elvidge (1996), methods employing low percentages of the image data, extracted from atypical cover types, *i.e.* dark set - bright set normalisation and pseudo-invariant normalisation, do not perform well because, for the most part, they work well only for the small image area defined in the normalisation procedure. Rather, variables employed in the normalisation should be derived from a larger subset of the image; however, areas of apparent change have to be excluded (*op. cit.*). The method selected follows this advice.

Other factors influencing comparability of data

MSS data have not been taken down since 1994, and consequently long-term change analysis has to compare different data-types.

One of the differences between MSS and TM data is their spatial resolution. Although the TM image is resampled to MSS resolution, some of the changes observed seem to arise out of differences in the original resolution.

At all localities there are bright areas caused by high reflection from sandy areas. These bright areas are fingerprints from torrents. (If water-flow is slower, there is rather a deposition process that leaves dark silt.) These sandy areas are seen on all the panorama images, to some extent on the TM-image, and to a lesser extent on the resampled TM-images. Their presence seems to be a question of resolution rather than of ground truth. Decrease or increase in pixels within these areas is, therefore, not necessarily related to vegetation.

At the Nuqrus site, bright areas appear on both the panorama images and on the TM-image. They do not, however, appear on any of the historical scenes (MSS scenes with lower resolution); and derived change images show sharp decreases in “vegetation” (class 13) for these areas. On the panorama image it can also be seen that trees grow along the edges of these patches; however, no arboreal vegetation was growing at that time within these bright, sandy spots. If this is the normal, main channel, it is likely that no trees have had an opportunity to establish themselves in this unstable area. On the other hand, one cannot exclude the possibility that arboreal vegetation has been growing there. Although arboreal death seems only rarely to be caused by torrents, it is not unlikely that torrents do damage trees; and such damage might be an incentive to remove that tree for charcoal production. The recorded decrease can, therefore, be a combination of resampling from higher resolution and an actual decrease in vegetation coverage.

Radiometric resolution constitutes another difference between TM and MSS data. The actual difference is fourfold, *i.e.* one DN in a raw MSS image is divided into 4 DNs in a TM-image. In theory, some pixels may therefore show artificial differences of up to four DNs. A calibration stretches the digital data of MSS images, and these artificial differences are reduced, but they still represent an artificial variation. This variation is dealt with in the chosen classification scheme. All the classes applied in the change analysis cover a range larger than or equal to four steps. Hence, except for border-line cases, variations introduced by differences in radiometric resolution are negligible.

Differences in illumination and angles (cf. Fig. 9) introduce variations in all images, independently of data type. As far as possible these variables are controlled by the selection of the acquisition date. According to Olsson (1985), the varying size of the shadow cast by vegetation is a problem even for images from the same season. The images employed in this study range in acquisition date between the end of February and mid-April (see Table

15). In terms of shadowing effect, they can be ranged in decreasing order as follows: 1973, 1996, 1984, 1979. If this is a problem, it is expected that the 1973 image should be darker over vegetation than any of the other years. Lack of historical reference data makes it impossible to estimate the ground truth. But when one considers the localities, other variables evidently cause greater variations and/or changes because the trends observed cannot be attributed to a shadowing effect alone.

A final factor that introduces variation, *i.e.* striping, is relevant to the 1973 image only. It affects every sixth line and is due to calibration errors in some of the detectors (Colwell 1983). In this study no de-striping was done because the methods available do not correct for the actual difference, they only derive new values from the pixels of those scanlines that are not affected by striping (Lillesand and Kiefer 1994). This is not, however, a great problem for any of the selected localities, for no differences are systematically related to every sixth line.

CONCLUSION

- Have there really been temporal changes in the arboreal vegetation cover of the areas studied and to what factors are possible changes to be attributed?

Both field observations and satellite images indicate that the desert cultural landscape is changing. The changes are mainly the consequence of a process that in less arid areas is called 'deforestation', *i.e.* a process caused by land-use activities. Very few, if any, signs of recovery, *i.e.* successful regeneration, were observed during fieldwork.

Change images suggest that decrease in vegetation cover has become a more common and dominant trend during the period studied. An interpretation based on cross-periodic trends also confirms that a majority of pixels that do not correlate with a meteorologically induced trend are pixels that probably register change, *i.e.* the removal of arboreal species.

- At what level is it possible to extract vegetation information from optical satellite images and hence to interpret change?

The method selected for change analysis gives results that are explicable and compatible with field observations. Even so it has not been possible to achieve as detailed an interpretation as had been intended. An absolute interpretation of spectral vegetation reflectance and therefore of changes was not possible. On the other hand, there is evidence that vegetation introduces significantly different spectral signatures, in particular in the Red band. The ability to recognise vegetation and changes in it, is, however, reduced as heterogeneity at pixel- and locality- level increases. Another obvious problem is the overlap in magnitude between small, but important changes and the "inherent" variation in digital data that the calibration does not remove.

Improved methods, both for extracting vegetation information and detecting changes, and also better technology seem to be prerequisites if a more detailed interpretation of change is to be achieved and if it is to become possible to realise the full potential of remote sensing in hyper-arid areas.

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APPENDICES

Appendix 1: Conversion of GPS positions

The formulas for conversion of positions are seen below (The Geographer's Craft Project, Department of Geography, The University of Texas at Austin. All commercial rights reserved. Copyright 1998 Peter H. Dana. http://www.utexas.edu/depts/grg/gcraft/notes/datum/datum.html).

Coordinate Conversion: Cartesian (ECEF X, Y, Z) and Geodetic (Latitude, Longitude, and Height)

Direct Solution for Latitude, Longitude, and Height from X, Y, Z

This conversion is not exact and provides centimeter accuracy for heights < 1,000 km
(See Bowring, B. 1976. Transformation from spatial to geographical coordinates.
Survey Review, XXIII: pg. 323-327)

$$\phi = \operatorname{atan}\left(\frac{Z + e'^2 b \sin^3\theta}{p - e^2 a \cos^3\theta}\right)$$

$$\lambda = \operatorname{atan2}(Y, X)$$

$$h = \frac{p}{\cos(\phi)} - N(\phi)$$

where:

ϕ, λ, h = geodetic latitude, longitude, and height above ellipsoid

X, Y, Z = Earth Centered Earth Fixed Cartesian coordinates

and:

$$p = \sqrt{X^2 + Y^2} \qquad \theta = \operatorname{atan}\left(\frac{Za}{pb}\right) \qquad e'^2 = \frac{a^2 - b^2}{b^2}$$

$N(\phi) = a / \sqrt{1 - e^2 \sin^2\phi}$ = radius of curvature in prime vertical

a = semi - major earth axis (ellipsoid equatorial radius)

b = semi - minor earth axis (ellipsoid polar radius)

$f = \frac{a - b}{a}$ = flattening

$e^2 = 2f - f^2$ = eccentricity squared

Coordinate Conversion
Geodetic Latitude, Longitude, and Height to ECEF, X, Y, Z

$$X = (N + h)\cos\phi\cos\lambda$$

$$Y = (N + h)\cos\phi\sin\lambda$$

$$Z = [N(1 - e^2) + h]\sin\phi$$

where:

ϕ, λ, h = geodetic latitude, longitude, and height above ellipsoid

X, Y, Z = Earth Centered Earth Fixed Cartesian Coordinates

and:

$N(\phi) = a / \sqrt{1 - e^2 \sin^2\phi}$ = radius of curvature in prime vertical

a = semi - major earth axis (ellipsoid equatorial radius)

b = semi - minor earth axis (ellipsoid polar radius)

$f = \frac{a - b}{a}$ = flattening

$e^2 = 2f - f^2$ = eccentricity squared

Peter H. Dana 8/3/96

According to these formulas a program, prog2.f, was written Thorkildsen (1998) to convert GPS positions from WGS84 to Helmert07. The source code is given below:

```
program prog
implicit none
CHARACTER(LEN=20) FIL
double precision fp,fl,tp,tl,fx,fy,tx,ty,fz,tz
double precision fa,fb,ff,fe2,N,dxab,dyab,dzab
double precision ta,tb,tf,te2,tem2,p,th
double precision dtor,rtod,PI
PARAMETER (PI=3.14159265358979312D0)
integer i

dtor=PI/180.d0
rtod=1/dtor
open(30,file='file_names')

! WGS84
fa=6378137.0d0
fb=6356752.314245170d0
ff=(fa-fb)/fa
fe2=2.0d0*ff-ff*ff

!WGS84 -> Helmert
dxab=130.d0
dyab=-110.d0
dzab=13.d0

! Helmert
ta=6378200.d0
tb=6356818.16962789d0
tf=(ta-tb)/ta
te2=2.d0*tf-tf*tf
tem2=(ta*ta-tb*tb)/(tb*tb)

write(*,'(A,4F21.11)')'Helme',ta,tb,tf,te2
write(*,'(A,4F21.11)')'WGS84',fa,fb,ff,fe2

write(*,*)'WGS84 -> Helmert'
write(*,'(A,F6.1)')'deltaX=',dxab
write(*,'(A,F6.1)')'deltaY=',dyab
write(*,'(A,F6.1)')'deltaZ=',dzab

do while(.true.)
  read(30,1100,end=121)FIL
  open(unit=10,file=TRIM(FIL))
  open(unit=20,file=TRIM(FIL)//'.new')
  i=0
  do while(.true.)
   read(10,*,end=120)fl,fp
   fp = dtor*fp
   fl = dtor*fl
   i=i+1
   N=fa/sqrt(1.d0-fe2*sin(fp)**2.d0)
   fx=N*cos(fp)*cos(fl)
   fy=N*cos(fp)*sin(fl)
   fz=N*(1.d0-fe2)*sin(fp)

   tx=fx+dxab
   ty=fy+dyab
   tz=fz+dzab

   p=sqrt(tx*tx+ty*ty)
   th=atan(tz*ta/(p*tb))
   tp=atan((tz+tem2*tb*sin(th)**3.d0)/(p-te2*ta*cos(th)**3.d0))
   tl=atan2(ty,tx)
   N=ta/sqrt(1.d0-te2*sin(tp)**2.d0)
   th=p/cos(tp)-N
   tp = rtod*tp
   tl = rtod*tl
   write(20,*)tl,tp,th
   write(*,'(2F10.6)')rtod*fl-tl,rtod*fp-tp
  end do
  120 write(*,*)'End of file: ',TRIM(fil),', number of pos=',i
  close(10)
  close(20)
end do
```

```
121 write(*,*)'The End'
1100 FORMAT(A20)
end program prog
```

Appendix 2: Reading raw image formats

Image formats

Each image format usually has two data-types: the image-data itself and the image-information data. There are three main methods of organising image data, image information, however, can be more randomly placed.

Image data consist of rows/scanlines and columns of pixels, *i.e.* the main unit of raster data. Normally, there are also several layers of data that correspond to the different channels/bandwidths. The formats organise pixels and layers in different ways.

The three main formats for writing image data are:

- BIL, **B**and **I**nterleaved by **L**ayer: For each scanline pixels from every channel is consecutively written, e.g. $Scanline_{1-n}$: C_1P_{1-n}, $C_2P_{1-n,}$ $C_3P_{1-n,}$ C_4P_{1-n}
- BSQ, **B**and **S**e**Q**uential: Every channel is written in one file. Both columns and scanlines are continuously ordered, e.g. $Scanline_{1-n}$: C_nP_{1-n}
- BIP, **B**and **I**nterleaved by **P**ixel: The corresponding pixel from different channels is written one after another, e.g. $Scanline_1$: C_1P_1, C_2P_1, C_3P_1, C_4P_1, C_1P_N, C_2P_N, C_3P_N, C_4P_N, C_1P_{N+1}, C_2P_{N+1}, C_3P_{N+1}, C_4P_{N+1}. Total length of one scanline is four times the length of each channel.

Image information can occur in one file or in the same file as the image-data, than either in the start or end of the file.

Reading procedures

Images that were received on exabyte tape were read from the tape-station by following commands:

```
dd if=/dev/rmt0.5 of=<filename> bs=<number of horizontal bytes>
```

Use conversion command if needed (to read header information)

```
conv=ascii
conv=ebdc
```

Rewinding the tape:

```
mt -f /dev/rmt0.5 rewind
(writing 0.4 in the reading command (not 0.5) automatically rewinds the tape.
```

Skipping files to read the next file:

```
 mt -f /dev/rmt0.5 fsf 1
```

BIP2 – from raw format to a compatible format

The 1973 data-set is written as a BIP2. It is a BIP format, but two consecutive pixels from each channel is written successively, *e.g.* P1B1, P2B1, P1B2, P2B2, P1B3, P2B3, P1B4, P2B4, P3B1, P4B1 and so on.

There is a total of 5 files.

File 1-4 are similar:

```
1 record         40 bytes long
1 record        624 bytes long
2340 records   3296 bytes long
end of file >>> totally 3242 records long
```

Record one and two consist of header information and the image data are in the last 2340 records. Each of these four files is one fourth of the total image. Also in the start of every image record there are 56 bytes of information, hence the image data itself is 3240 bytes. Every channel for each fourth of the image is thus 810 bytes.

```
File 5:
1 record       2048 bytes long
1 record       268  bytes long
1 record       222  bytes long
1 record       160  bytes long
1 record       144  bytes long
1 record       76   bytes long
```

```
1 record       324  bytes long
1 record       480  bytes long
end of file 5 >>> 8 total records.
```

Selecting two and two pixels from the image data is done by the program rmss1 (Hamre 1997).

Program interface:

```
rmss1version 1.1, 14-MAR-1997
conv. MSS BIP2 Tenneco!form rawdata to FLAT out-file.

enter in-filename (NO quotes):
file1_186_43_73oct.dat

Enter by/rec(EROS-old:3296, BIE:3248):
3296
In-file opened with   3296 by/rec!

Enter number of bytes in header:
664

Enter out-filename (NO quotes):
ch4_1b.dat
Out-file opened! (ch4_1b.dat)

enter out-rec.size in bytes(=pixels/line!):
810

No conversion U to T!  Ua must be odd!
Conv.'i4' x-pixels from  Ua! Ua:
1
Convert npy lines from line dVa, aggr=nmy! dVa,npy,nmy:
1,2340,1

Enter selected channel (4,...7):
4
list each ln out-line for check.  ln:
100

Starting conversion of data...
in-line no=   100,  out-line no=   100,  offset=330264
in-line no=   200,  out-line no=   200,  offset=659864
in-line no=   300,  out-line no=   300,  offset=989464
in-line no=   400,  out-line no=   400,  offset=1319064
in-line no=   500,  out-line no=   500,  offset=1648664
in-line no=   600,  out-line no=   600,  offset=1978264
in-line no=   700,  out-line no=   700,  offset=2307864
in-line no=   800,  out-line no=   800,  offset=2637464
in-line no=   900,  out-line no=   900,  offset=2967064
in-line no=  1000,  out-line no=  1000,  offset=3296664
in-line no=  1100,  out-line no=  1100,  offset=3626264
in-line no=  1200,  out-line no=  1200,  offset=3955864
in-line no=  1300,  out-line no=  1300,  offset=4285464
in-line no=  1400,  out-line no=  1400,  offset=4615064
in-line no=  1500,  out-line no=  1500,  offset=4944664
in-line no=  1600,  out-line no=  1600,  offset=5274264
in-line no=  1700,  out-line no=  1700,  offset=5603864
in-line no=  1800,  out-line no=  1800,  offset=5933464
in-line no=  1900,  out-line no=  1900,  offset=6263064
in-line no=  2000,  out-line no=  2000,  offset=6592664
in-line no=  2100,  out-line no=  2100,  offset=6922264
in-line no=  2200,  out-line no=  2200,  offset=7251864
in-line no=  2300,  out-line no=  2300,  offset=7581464

Finished!
```

Program source code:

```
#define PROG_ID      "rmss1"
#define PROG_VERSION "version 1.1, 14-MAR-1997"

/*
** C version of:
** MSS tape read.   BIP2(Band interl. by pixel-2) format (Eros).
** Convert data in direct, raw-data byte-image file.  21.feb.88 kk.
** 3296 by/rec(EROS-old) and 3248 by/rec(BIE).
** Revised 14.Feb.90.
**         12.Mar.97 TH Output file is "flat", i.e. contains only pixel values.
**         14.Mar.97 TH Corrected bug in conversion, jump 2x4 bytes.
```

```
**
** Compile: cc -o rmss1 rmss1.c
*/
#include<stdio.h>

#define BUFSIZE 3296

main (argc,argv)
      int argc;
      unsigned char argv;
{
      unsigned char InBuf[BUFSIZE],OutBuf[BUFSIZE];
      unsigned char Filename[256];
      unsigned char AuxStr[81];
      int irby;
      int idv,npx,npy,nmy;
      int ich;
      int iout,iin;
      int iy,iv,iua,ln;
      long Offset,HdrSize;
      FILE  *InFile,*OutFile;

      printf("%s%s\n", PROG_ID, PROG_VERSION);

      printf("conv. MSS BIP2 Tenneco!form rawdata to FLAT out-file.\n\n");

      printf("enter in-filename (NO quotes):\n");
      gets(Filename);

      printf("\n");
      printf("Enter by/rec(EROS-old:3296, BIE:3248):\n");
      gets(AuxStr);
      irby=(int)atoi(AuxStr);

      InFile=fopen(Filename,"rb");
      if (InFile==NULL)
      {
        fprintf(stderr,"%d: could not open file %s\n\n",
                PROG_ID,Filename); fflush(stderr);
        exit(1);
      }
      printf("In-file opened with %6d by/rec!\n",irby);

      printf("\n");
      printf("Enter number of bytes in header:\n");
      gets(AuxStr);
      HdrSize=(long)atoi(AuxStr);

      printf("\n");
      printf("Enter out-filename (NO quotes):\n");
      gets(Filename);
      OutFile=fopen(Filename,"wb");
      if (InFile==NULL)
      {
        fprintf(stderr,"%d: could not open file %s\n\n",
                PROG_ID,Filename); fflush(stderr);
        exit(1);
      }
      printf("Out-file opened! (%s)\n\n",Filename);

      printf("enter out-rec.size in bytes(=pixels/line!):\n");
      gets(AuxStr);
      npx=(int)atoi(AuxStr);

      printf("\n");
      printf("No conversion U to T!  Ua must be odd!\n");
      printf("Conv.'i4' x-pixels from  Ua! Ua:\n");
      gets(AuxStr);
      iua=(int)atoi(AuxStr);

      if((iua%2) != 1)
      {
        fprintf(stderr,"U-start pixel must be odd!"); fflush(stderr);
        exit(1);
      }

      printf("Convert npy lines from line dVa, aggr=nmy! dVa,npy,nmy:\n");
```

```
        gets(AuxStr);
        sscanf(AuxStr,"%d,%d,%d",&idv,&npy,&nmy);
        printf("\n");
        printf("Enter selected channel (4,...7):\n");
        gets(AuxStr);
        ich=(int)atoi(AuxStr);

        printf("list each ln out-line for check.  ln:\n");
        gets(AuxStr);
        ln=(int)atoi(AuxStr);

        /*
        ** Main loop:
        */
        printf("\nStarting conversion of data...\n");
        for (iy=1; iy<=npy; iy++)
        {
            iv=idv+(iy-1)*nmy;
            Offset=HdrSize+irby*iv;
            fseek(InFile,Offset,0);
            fread(InBuf,sizeof(unsigned char),irby,InFile);
            if((iy%ln) == 0)
               printf("in-line no=%6d,  out-line no=%6d,  offset=%ld\n",iv,iy,Offset);
            /* Move bytes for selected channel to output buffer */
            for (iout=0,iin=(ich-4)*2; iout<npx; iout+=2,iin+=8)
            {
                OutBuf[iout]=InBuf[iin];
                OutBuf[iout+1]=InBuf[iin+1];
            }
            /* Write one image line to output file */
            fwrite(OutBuf,sizeof(unsigned char),npx,OutFile);
        }
        printf("\nFinished!\n\n");

        exit(0);
}
```

Output from this procedure is totally 16 files, *i.e.* four for each channel.

Combining these files to one is done in Erdas Imagine and ERMapper:

1) Via the import/export dialog in Erdas, import the four files from one channel as generic binary BSQ

-4 layers

-2340 rows

-810 columns

2) Export this *.img-file as generic binary BIL

-1 layer

This file is then actually a BSQ file where the four parts of the selected channel is connected into one part.

3) Combine the four channels into one file by the cat command

-cat <filename - outfile> >> < filename - channel n+1

4) Import this *.dat-file into ERMApper as generic binary

-Total number of rows 2340

-Total; number of columns 3240

BIL – from raw format to a compatible format

The 1979 image is in a BIL format. Images are processed by ESA. Shortly this format consists of three files where the two first are information data. The third file consists manly of image-data. This ESA BIL format places the ancillary data differently in the blue band and the other bands. The blue channel (channel 1) is preceded by 2 counter bytes and by 178 bytes of ancillary data. The other channels are only preceded by 2 counter bytes, while the ancillary data are placed after the image data. Hence, there is a spatial inconsistency between the blue channel and the other channels.

Counter and ancillary bytes have been removed by using the RLE-command RLETORAW. This command is used together with the RLEFLIP command that turns the image. In praxis the –l and –p flags remove bytes respectively in front of and after a row of data. These flags vary for the different channels.

```
rawtorle -w 3780 -h 2286 -n 1 -l<number of bytes skipped in front of the wanted channel> -p
<number of bytes skipped after the wanted channel> <filename> | rleflip -v | rleflip -v |
rletoraw -o <out filname>
```

Counter (c) and ancillary (a) data is then removed by adding their length to the number of bytes that precedes or follows the channel of interest:

```
channel 1:  l= c+a  (180)                   p= 3(c+a)+3w (11340)
channel 2:  l= (c+a)+w+a  (3782)            p= 2(c+a)+2w+a (7738)
channel 3:  l= 2(c+a)+2w+a  (7562)          p= (c+a)+w+a (3958)
channel 4:  l= 3(c+a)+3w+a  (11342)         p= a (178)
where w is the width of image data (3600)
```

This gives the following set of commands:

Channel 1:

```
rawtorle -w 3600 -h 2286 -n 1 -l 180 -p 11340 file3* | rleflip -v | rleflip -v | rletoraw -o
kanal1_79.dat
```

Channel 2:

```
rawtorle -w 3600 -h 2286 -n 1 -l 3782 -p 7738 file3* | rleflip -v | rleflip -v |rletoraw -o
kanal2_79.dat
```

Channel 3:

```
rawtorle -w 3600 -h 2286 -n 1 -l 7562 -p 3958 file3* | rleflip -v | rleflip -v | rletoraw -o
kanal3_79.dat
```

Channel 4:

```
rawtorle -w 3600 -h 2286 -n 1 -l 11342 -p 178 file3* | rleflip -v | rleflip -v |
rletoraw -o kanal4_79.dat
```

This gives four files where each file corresponds to one channel written in BSQ format. These files are then combined (cat-command) and imported.

BSQ

Both 1984 and 1996 images are received in BSQ-format. They are combined into one file (cat command) before they are imported into ERMapper.

Appendix 3: GCPs and RMS errors for historical scenes

GCPs for 1973 dataset:

```
# Total number of GCPs: 16
# Number turned on    : 14
# Warp order          : 0
# GCP TO map projection details:
#      Map Projection : TMEGYPTG
#          Datum      : EGYPT07
#          Rotation   : 0.000
#
#      Point  On Locked      Cell-X    Cell-Y            To-X            To-Y
        "26" Yes    Yes     406.500   250.500  247528.2859000  580280.9855000
        "27" Yes    Yes     302.000   599.000  235013.0000000  554175.0000000
        "28" Yes    Yes     829.404   466.595  267463.3416000  559295.4427000
        "29" Yes    Yes    1450.000   799.995  296453.0000000  527266.0000000
        "30"  No    Yes     924.500  1052.500  261806.3512000  512751.6698000
        "31" Yes    Yes     646.500  1300.500  241348.5634000  496207.3136000
        "32"  No    Yes    1290.901  1293.999  278070.4221000  490399.0923000
        "33" Yes    Yes     613.500  1771.500  230622.6419000  459878.1437000
        "34" Yes    Yes    1759.881  1965.056  292104.2208000  433516.5308000
        "35" Yes    Yes    2275.500  1693.500  326549.2066000  449631.0322000
        "36" Yes    Yes    1504.999  1454.021  287278.1025000  475845.8276000
        "37" Yes    Yes     893.000  1704.000  247738.2124000  462376.8846000
        "38" Yes    Yes     429.500   981.500  235061.6193000  523138.0892000
        "39" Yes    Yes    1068.500  2205.500  248248.5967000  421582.4693000
        "40" Yes    Yes    2550.000  1894.000  338357.6138000  431285.5156000
        "41" Yes    Yes     817.500  1230.503  252377.6485000  499980.9878000

# RMS error report:
#                -----ACTUAL-----    ---POLYNOMIAL---
```

```
#       Point    Cell-X    Cell-Y    Cell-X    Cell-Y      RMS
#        "26"   406.500   250.500   406.636   250.506   0.1362
#        "27"   302.000   599.000   302.134   599.080   0.1558
#        "28"   829.404   466.595   829.139   466.808   0.3401
#        "29"  1450.000   799.995  1449.733   800.002   0.2671
#        "30"   924.500  1052.500   924.083  1052.788   0.5072 OFF
#        "31"   646.500  1300.500   646.334  1300.379   0.2053
#        "32"  1290.901  1293.999  1290.191  1293.768   0.7463 OFF
#        "33"   613.500  1771.500   613.883  1771.202   0.4851
#        "34"  1759.881  1965.056  1759.944  1965.286   0.2387
#        "35"  2275.500  1693.500  2275.641  1693.198   0.3333
#        "36"  1504.999  1454.021  1505.228  1453.608   0.4729
#        "37"   893.000  1704.000   892.673  1703.928   0.3354
#        "38"   429.500   981.500   429.965   981.691   0.5027
#        "39"  1068.500  2205.500  1068.231  2205.874   0.4603
#        "40"  2550.000  1894.000  2550.113  1894.259   0.2825
#        "41"   817.500  1230.503   817.130  1230.350   0.4009
#
# Average RMS error :  0.330
#   Total RMS error :  4.616
# Note: Total and average RMS errors do not include OFF points
# End of GCP details
```

GCPs for 1979 dataset:

```
# Total number of GCPs: 16
# Number turned on    : 16
# Warp order          : 0
# GCP TO map projection details:
#      Map Projection : TMEGYPTG
#          Datum      : EGYPT07
#          Rotation   : 0.000
#
#      Point  On Locked      Cell-X    Cell-Y            To-X            To-Y
        "26" Yes    Yes     421.500   127.500  247502.7220000  580278.4660000
        "28" Yes    Yes     825.413   347.564  267328.1320000  559105.3900000
        "30" Yes    Yes     864.500   929.500  261629.0090000  513026.1860000
        "27" Yes    Yes     283.500   476.500  234987.3370000  554151.6600000
        "29" Yes    Yes    1421.500   681.500  296421.4770000  527207.1080000
        "38" Yes    Yes     377.500   860.500  235063.7090000  523079.5300000
        "31" Yes    Yes     565.459  1179.509  241331.8400000  496171.9170000
        "32" Yes    Yes    1220.500  1174.500  278384.6440000  490322.4260000
        "36" Yes    Yes    1417.500  1335.500  287335.1490000  475795.3170000
        "37" Yes    Yes     776.503  1584.500  247737.2450000  462321.5030000
        "33" Yes    Yes     488.500  1650.500  230620.9680000  459847.9130000
        "39" Yes    Yes     883.496  2085.500  247014.5810000  421818.3510000
        "34" Yes    Yes    1624.500  1846.500  292062.5730000  433564.0370000
        "40" Yes    Yes    2424.547  1778.448  338189.8700000  431331.4510000
        "35" Yes    Yes    2170.500  1576.500  326608.0130000  449628.9760000
        "41" Yes    Yes     743.500  1110.500  252343.1590000  499927.2450000

# RMS error report:
#                -----ACTUAL-----    ---POLYNOMIAL---
#       Point    Cell-X    Cell-Y    Cell-X    Cell-Y      RMS
#        "26"   421.500   127.500   421.597   127.857   0.3697
#        "28"   825.413   347.564   825.663   348.022   0.5218
#        "30"   864.500   929.500   864.451   929.016   0.4861
#        "27"   283.500   476.500   283.820   476.637   0.3484
#        "29"  1421.500   681.500  1421.079   681.327   0.4556
#        "38"   377.500   860.500   377.425   860.241   0.2694
#        "31"   565.459  1179.509   565.215  1179.500   0.2440
#        "32"  1220.500  1174.500  1220.236  1174.487   0.2647
#        "36"  1417.500  1335.500  1417.414  1335.245   0.2689
#        "37"   776.503  1584.500   775.989  1584.221   0.5845
#        "33"   488.500  1650.500   488.780  1650.461   0.2829
#        "39"   883.496  2085.500   883.855  2085.971   0.5927
#        "34"  1624.500  1846.500  1624.205  1846.975   0.5591
#        "40"  2424.547  1778.448  2424.646  1778.370   0.1265
#        "35"  2170.500  1576.500  2170.985  1576.531   0.4863
#        "41"   743.500  1110.500   743.556  1110.160   0.3451
#
# Average RMS error :  0.388
#   Total RMS error :  6.206
# End of GCP details
```

GCPs for 1984 dataset:

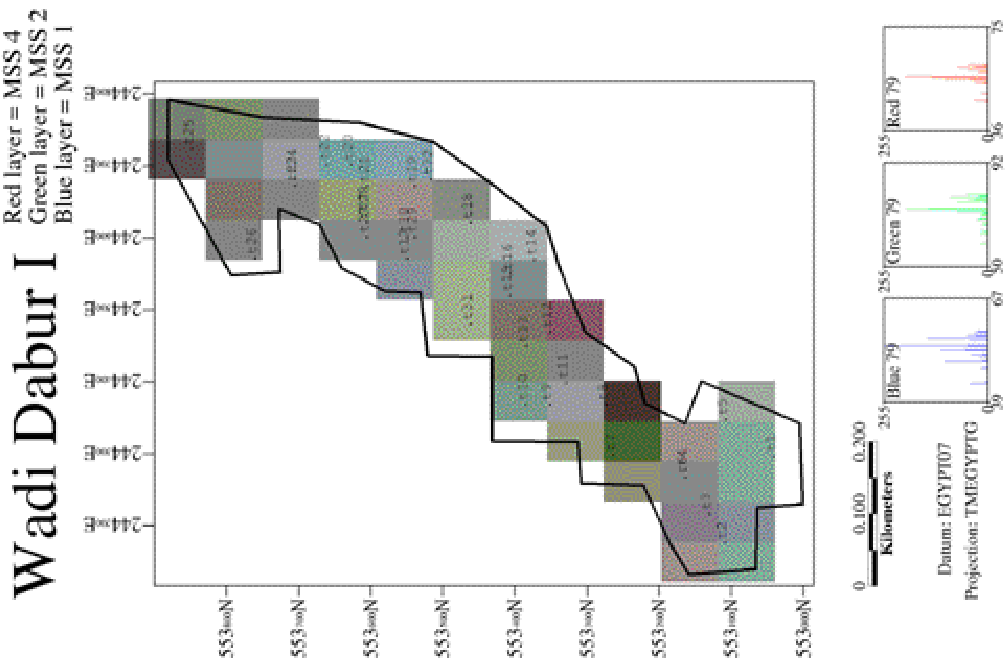
```
# Total number of GCPs: 15
# Number turned on    : 15
# Warp order          : 0
# GCP TO map projection details:
#      Map Projection : TMEGYPTG
#          Datum      : EGYPT07
#          Rotation   : 0.000
#
#      Point  On Locked      Cell-X    Cell-Y            To-X             To-Y
        "26" Yes    Yes     486.500   275.500  247529.8652000  580278.8327000
        "27" Yes    Yes     339.500   763.500  234988.2951000  554150.6577000
        "28" Yes    Yes     889.500   584.500  267389.7556000  559432.0881000
        "29" Yes    Yes    1484.500  1065.500  296487.5489000  527240.6519000
        "30" Yes    Yes     916.500  1405.500  261640.8309000  513048.9660000
        "31" Yes    Yes     615.500  1750.500  241739.6355000  496279.6830000
        "32" Yes    Yes    1265.500  1755.500  278098.7364000  490342.5466000
        "33" Yes    Yes     521.500  2411.500  230603.5794000  459918.1917000
        "34" Yes    Yes    1665.500  2704.500  292136.1598000  433520.3293000
        "35" Yes    Yes    2224.500  2337.500  326729.0332000  449298.0643000
        "36" Yes    Yes    1465.500  1982.500  287307.6702000  475848.7867000
        "37" Yes    Yes     813.422  2323.314  247742.9932000  462351.7889000
        "38" Yes    Yes     425.500  1302.497  235046.4227000  523129.6992000
        "39" Yes    Yes     505.500  2941.500  225010.8555000  430298.1206000
        "40" Yes    Yes    2483.394  2630.616  338667.1668000  430549.9408000

# RMS error report:
#               -----ACTUAL-----    ---POLYNOMIAL---
#       Point    Cell-X    Cell-Y    Cell-X    Cell-Y       RMS
#        "26"   486.500   275.500   486.471   275.940    0.4411
#        "27"   339.500   763.500   339.682   763.492    0.1818
#        "28"   889.500   584.500   889.424   584.495    0.0764
#        "29"  1484.500  1065.500  1484.327  1065.193    0.3528
#        "30"   916.500  1405.500   916.422  1405.522    0.0809
#        "31"   615.500  1750.500   615.831  1750.360    0.3594
#        "32"  1265.500  1755.500  1265.231  1755.537    0.2714
#        "33"   521.500  2411.500   521.559  2411.850    0.3544
#        "34"  1665.500  2704.500  1665.381  2704.566    0.1359
#        "35"  2224.500  2337.500  2224.519  2337.375    0.1261
#        "36"  1465.500  1982.500  1465.307  1982.448    0.2003
#        "37"   813.422  2323.314   813.343  2323.420    0.1319
#        "38"   425.500  1302.497   425.702  1302.081    0.4628
#        "39"   505.500  2941.500   505.341  2941.329    0.2338
#        "40"  2483.394  2630.616  2483.777  2630.821    0.4346
#
# Average RMS error :  0.256
#   Total RMS error :  3.844
# End of GCP details
```

Appendix 4: Recorded species

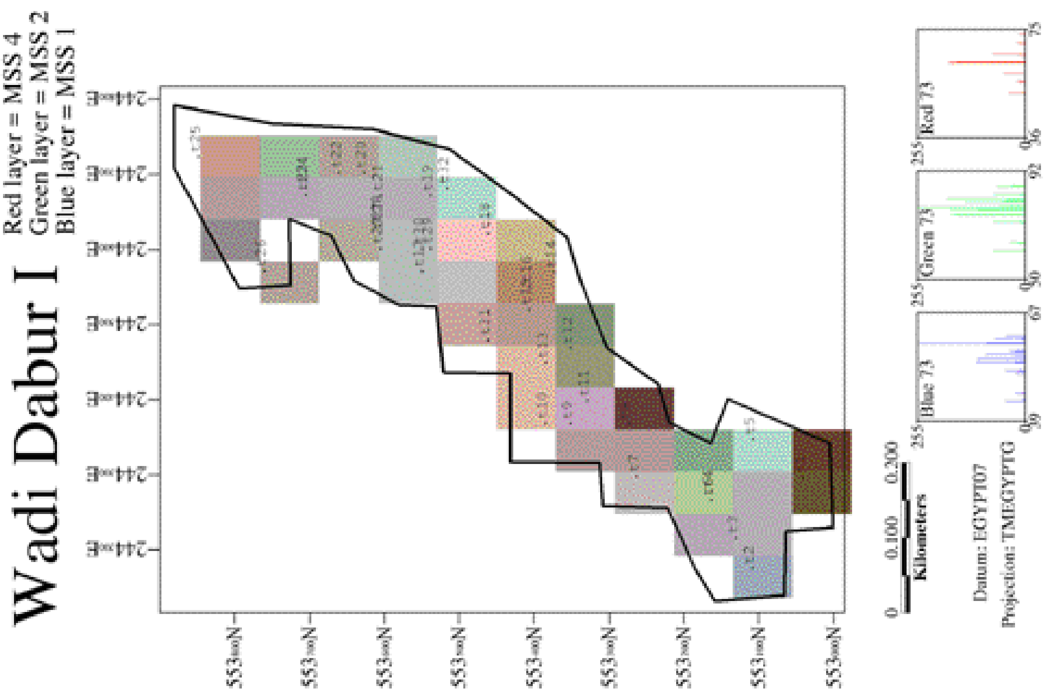
Species
Acacia ehrenbergiania
Acacia tortilis
Aerva javanica
Anthrochnemon glaucum
Avicennia marina
Balanites aegyptiaca
Belpharis ciliaris
Bergularia tomentosa
Calligonum polygonoides
Calotropis procera
Capparis decidua
Cassia italica
Cassia senna
Chrozophora plicata
Citrullus colocynthis
Cleome arabica
Cleome chrysantha
Cleome droserifolia
Coaulata monocantha
Cocculus pendulus
Cynodon dactylon
Fagonia arabica
Fagonia indica
Fagonia mollis
Farsetia aegyptiaca
Francoeuria crispa
Kickxia aegyptiaca
Lavendula stricta
Leptadenia pyrotechnica
Lycium shawii
Monsonia densiflora
Moringa peregrina
Ochradenus baccatus
Ochradenus baccatus
Paronychia sinaica
Pterantus dichotomus
pulicaria undulata
Reseda pruinosa
Reseda stenostachya
Salvadora persica
Solenostemma argel
Solenostemma argel
Tamarix aphylla
Trichodesma baccatus
vild sorghum
Zilla spinosa
Zizyphus spina-christi
Zygophyllum coccineum

Appendix 5: Historical data and resampled 1996 data for sites

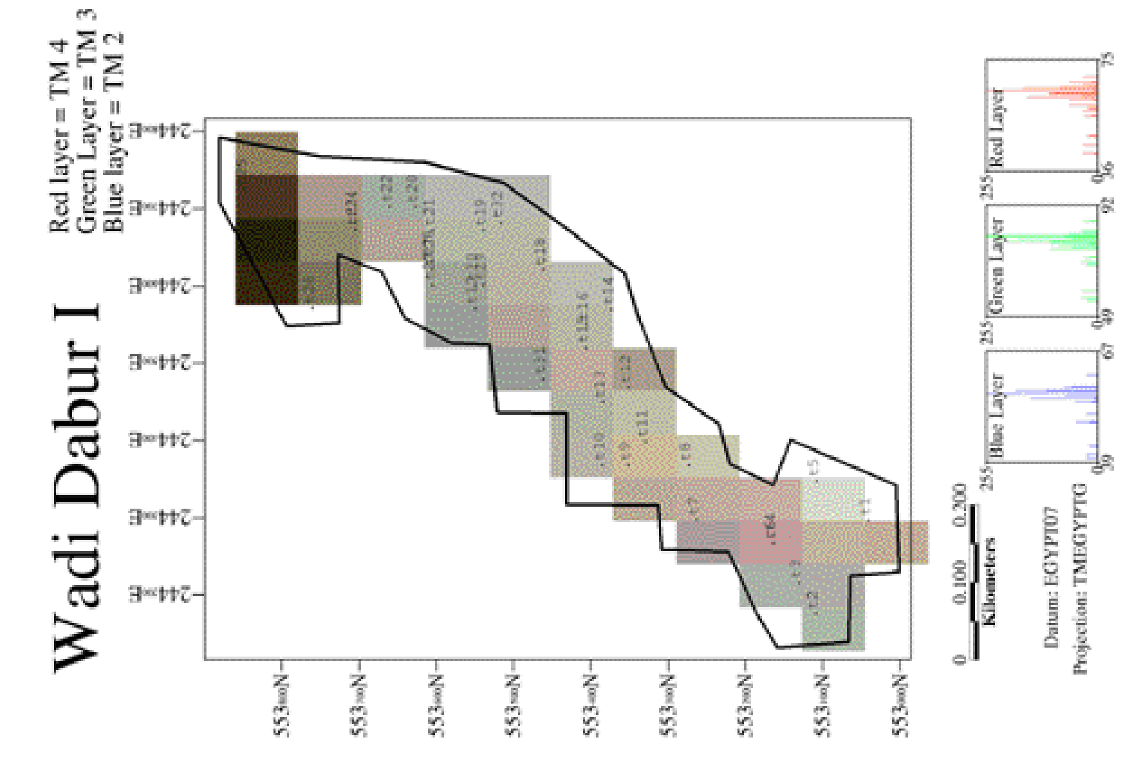
On the following pages are the historical data and the resampled 1996 data from all sites presented. These images are RGB colour composites from which the Red band is basis for the change analysis.


Wadi Dabur I
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
0 0.100 0.200
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG
Blue 79
Green 79
Red 79

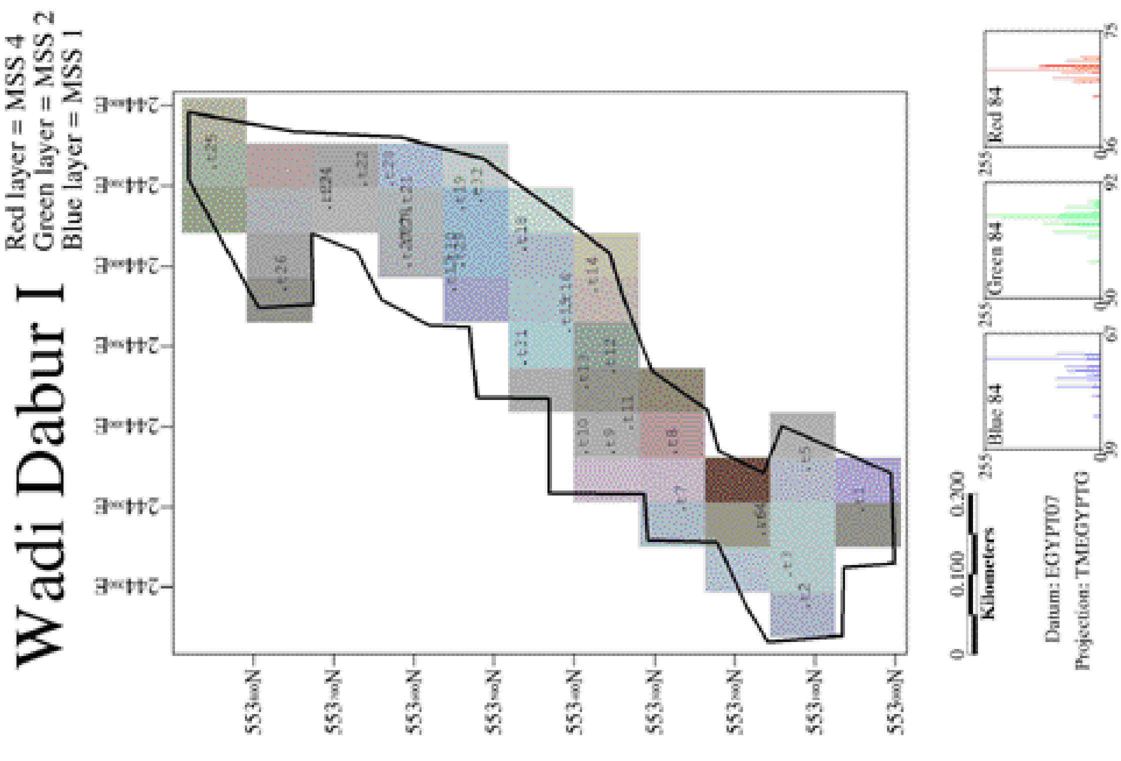
1979


Wadi Dabur I
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
0 0.100 0.200
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG
Blue 73
Green 73
Red 73

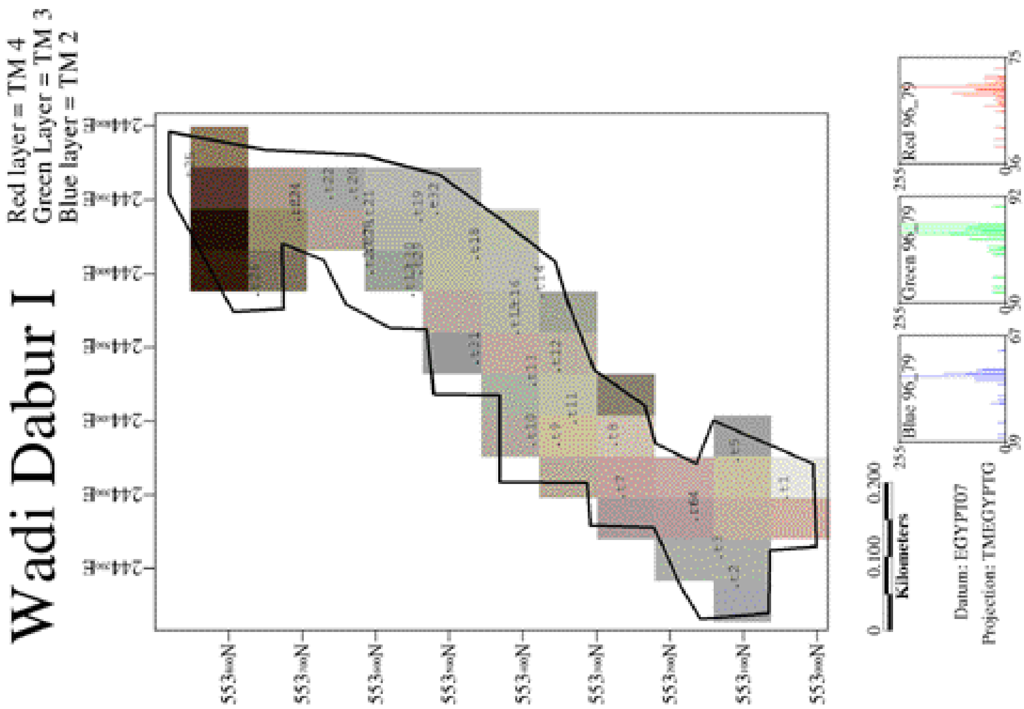
1973



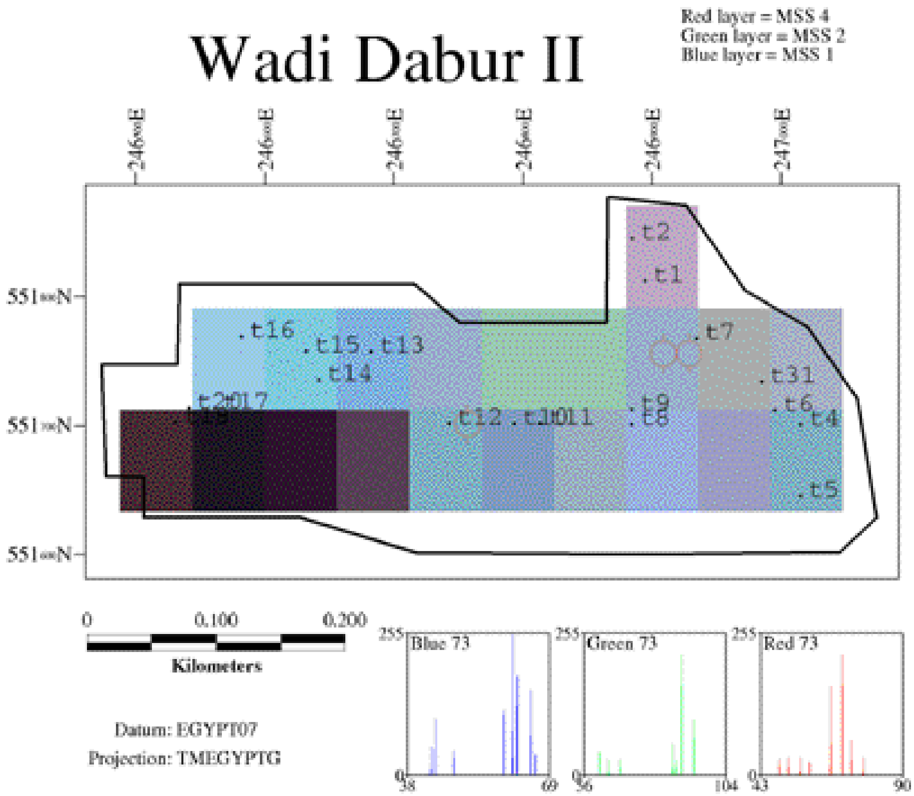
1996 81.5 m



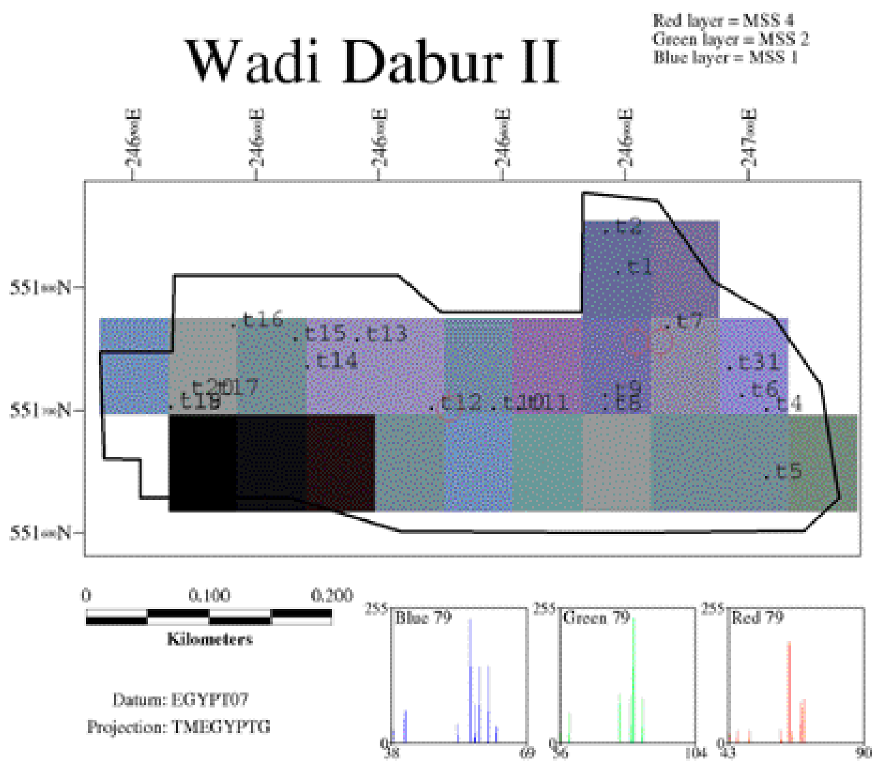
1984



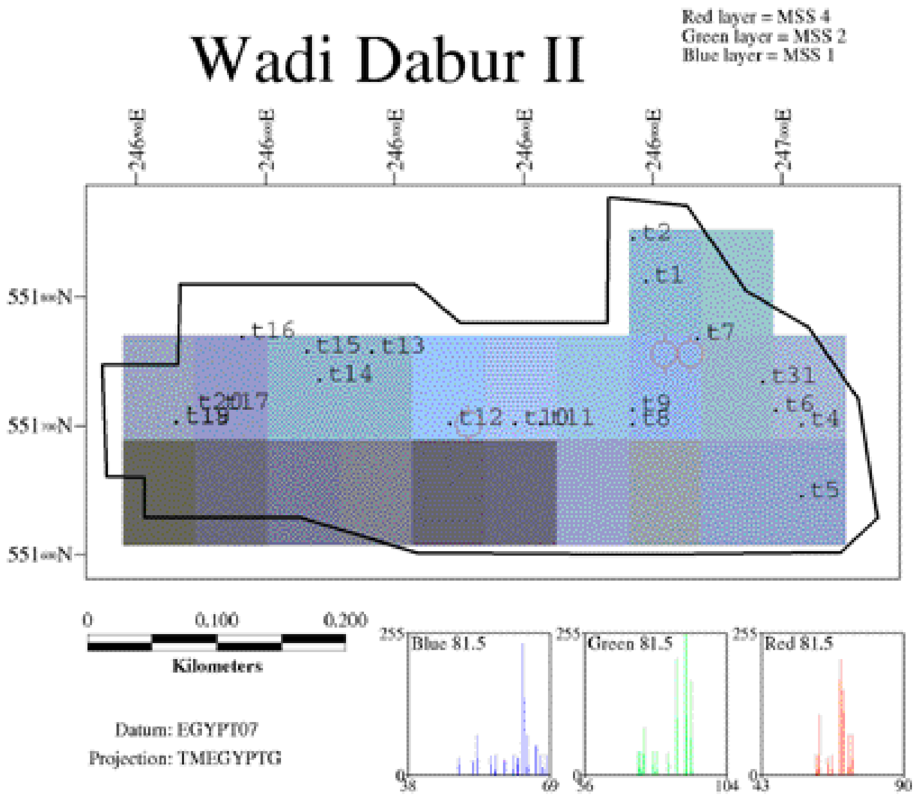
1996 79 m



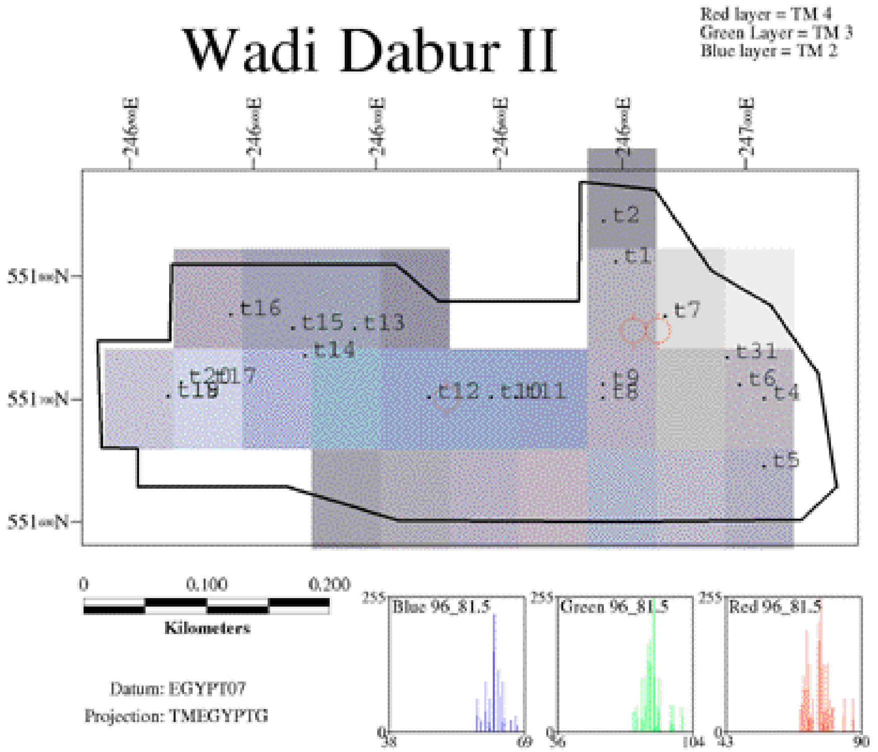
1973


Wadi Dabur II
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
.t2
.t1
.t16
.t15 .t13
.t14
.t7
.t31
.t6
.t4
.t5
0
0.100
0.200
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG
Blue 79
Green 79
Red 79

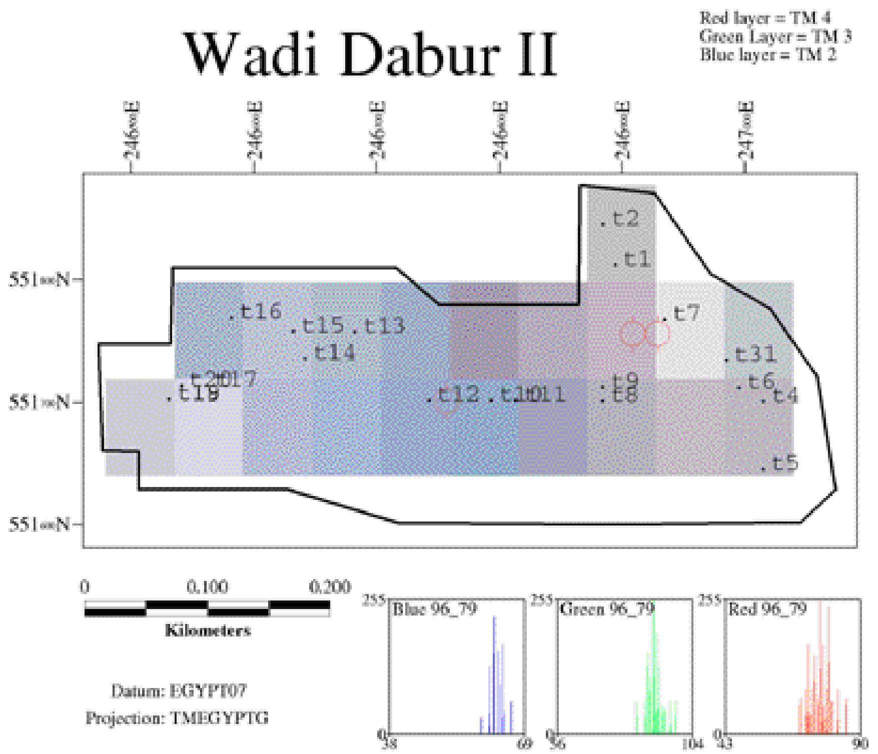
1979


Wadi Dabur II
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
.t2
.t1
.t16
.t15 .t13
.t14
.t7
.t31
.t6
.t4
.t5
0
0.100
0.200
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG
Blue 81.5
Green 81.5
Red 81.5

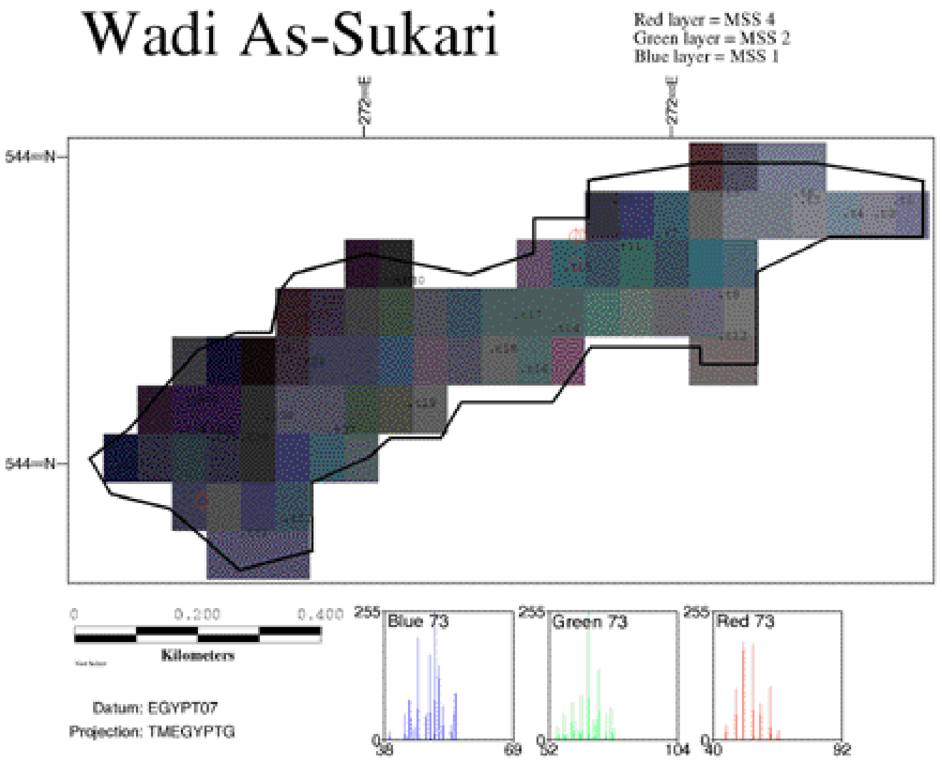
1984



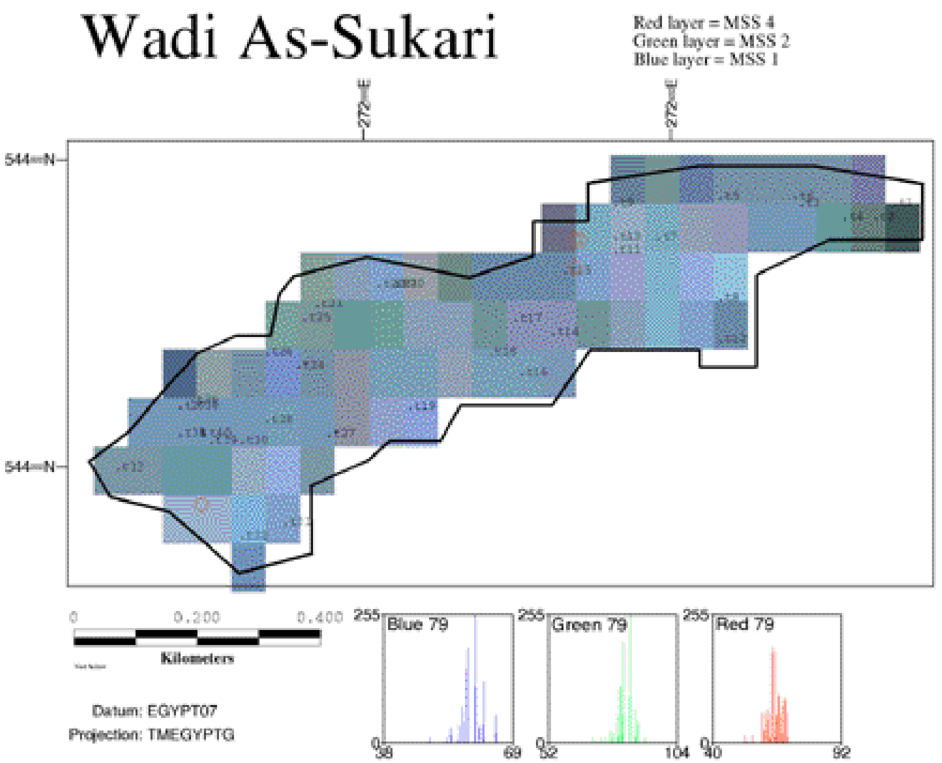
1996 81.5 m



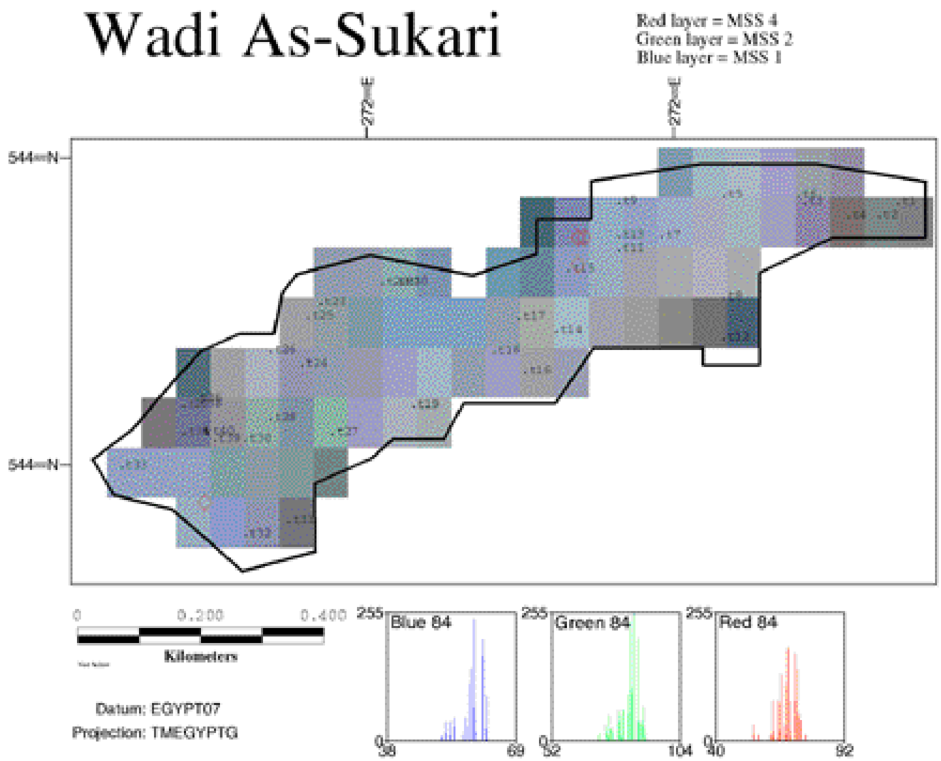
1996 79 m


Wadi As-Sukari
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
0 0.200 0.400
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG
Blue 73
Green 73
Red 73

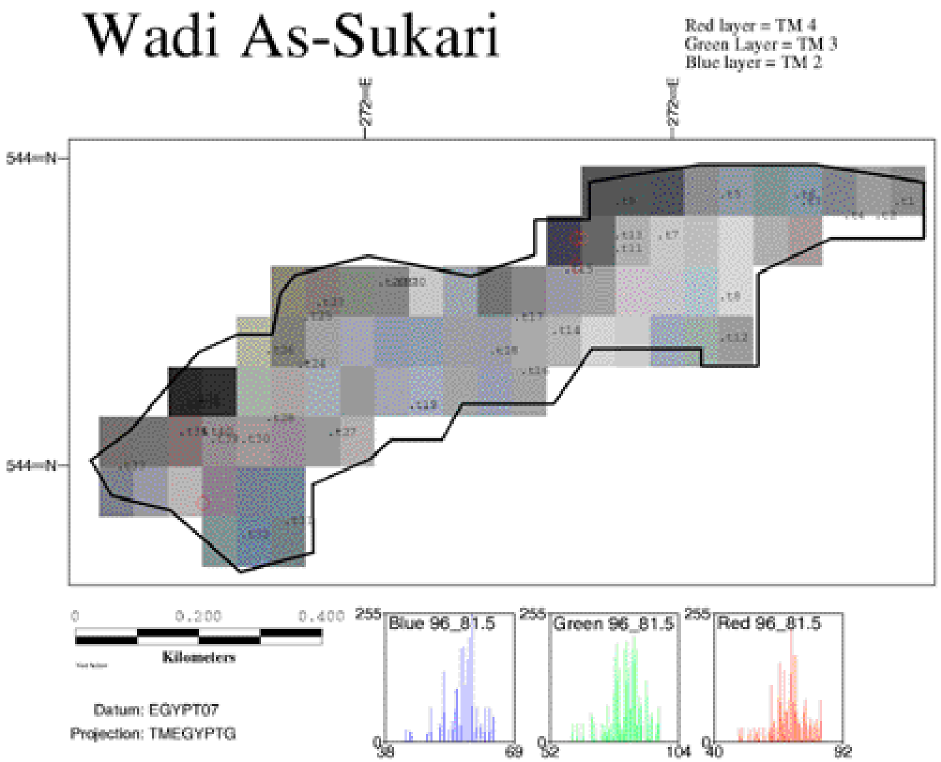
1973


Wadi As-Sukari
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
0 0.200 0.400
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG
Blue 79
Green 79
Red 79

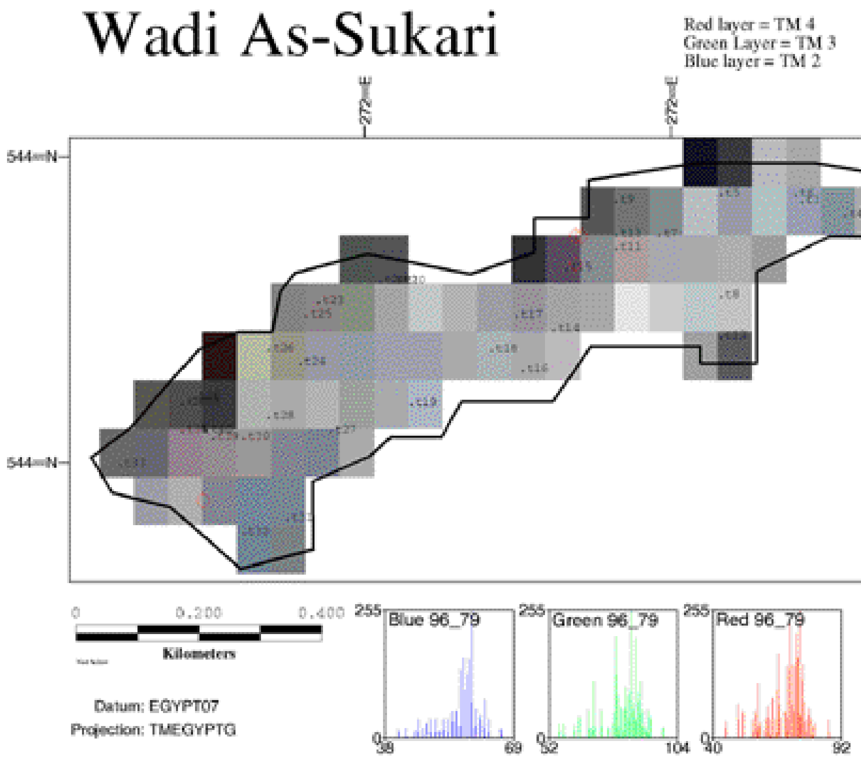
1979



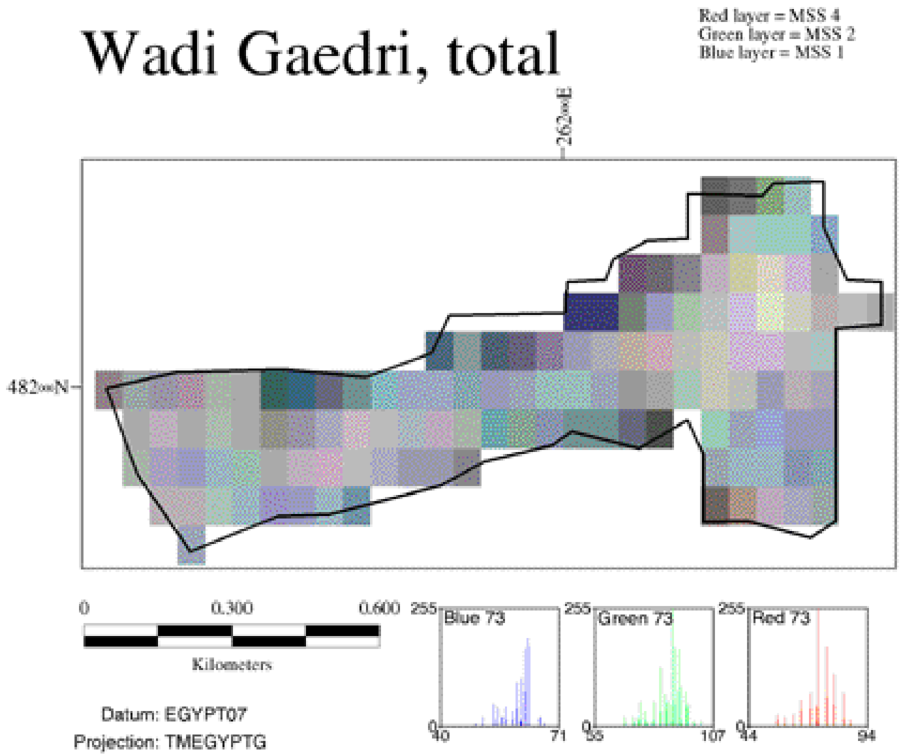
1984



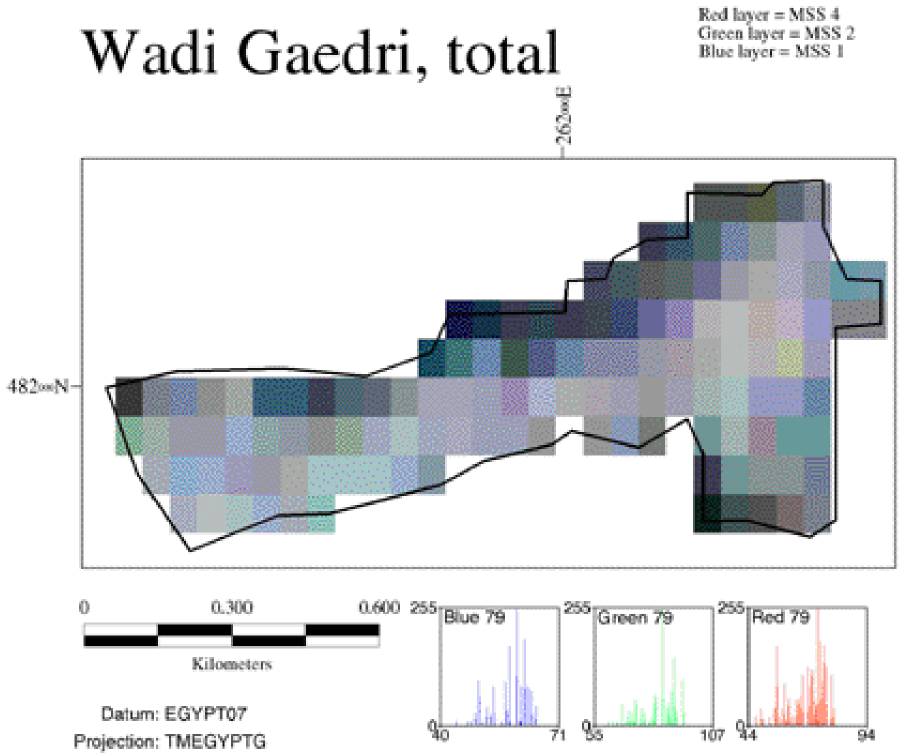
1996 81.5 m



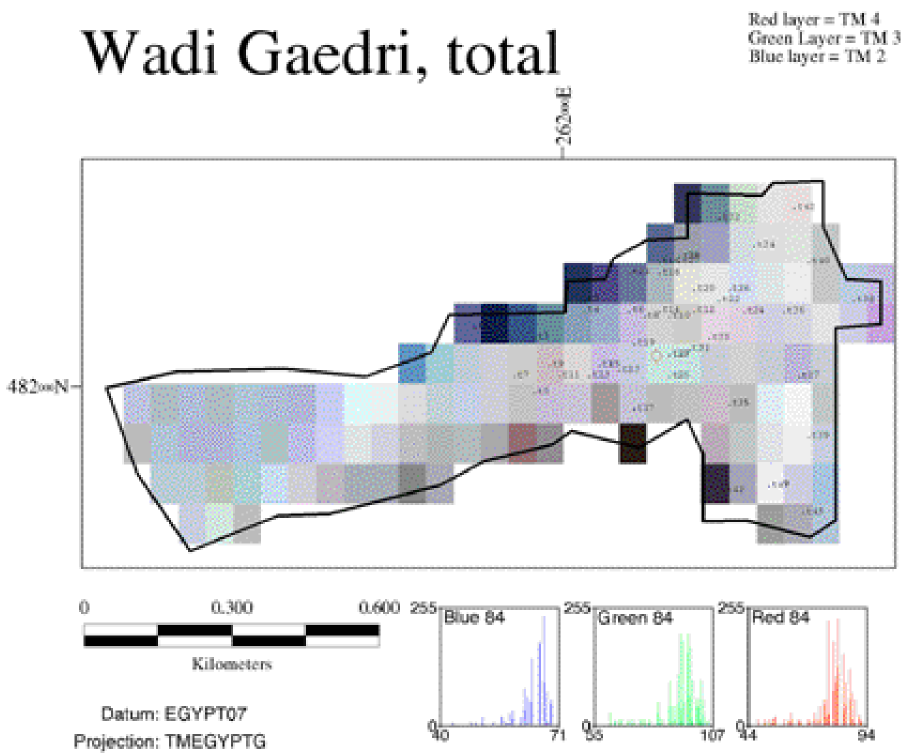
1996 79 m



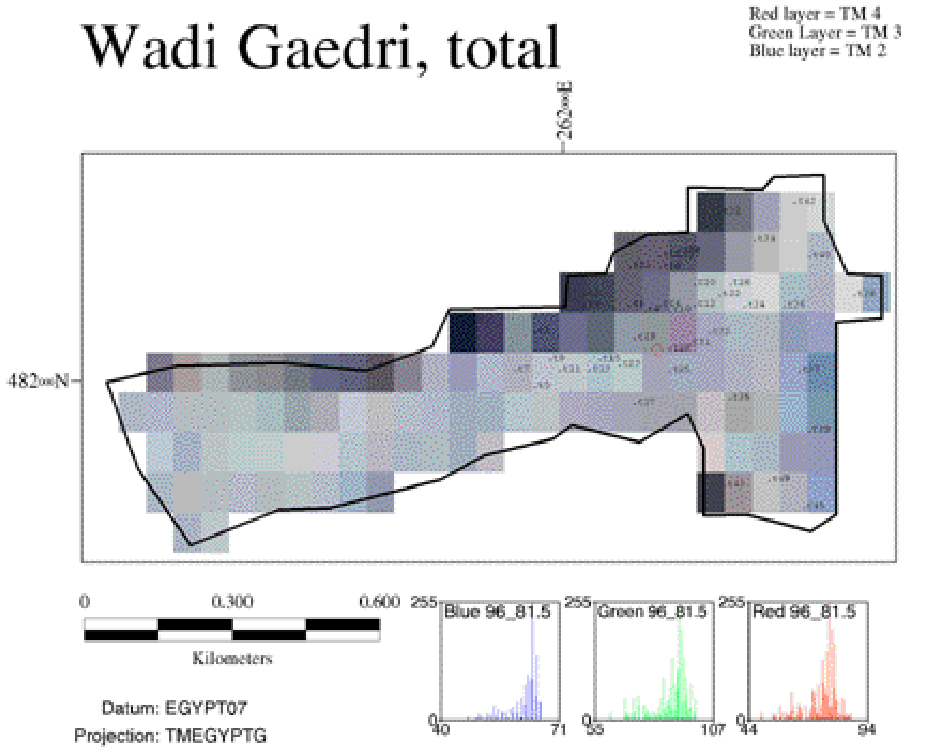
1973


Wadi Gaedri, total
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
262000E
482000N
0
0.300
0.600
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG
Blue 79
Green 79
Red 79
255
0
40
71
55
107
44
94

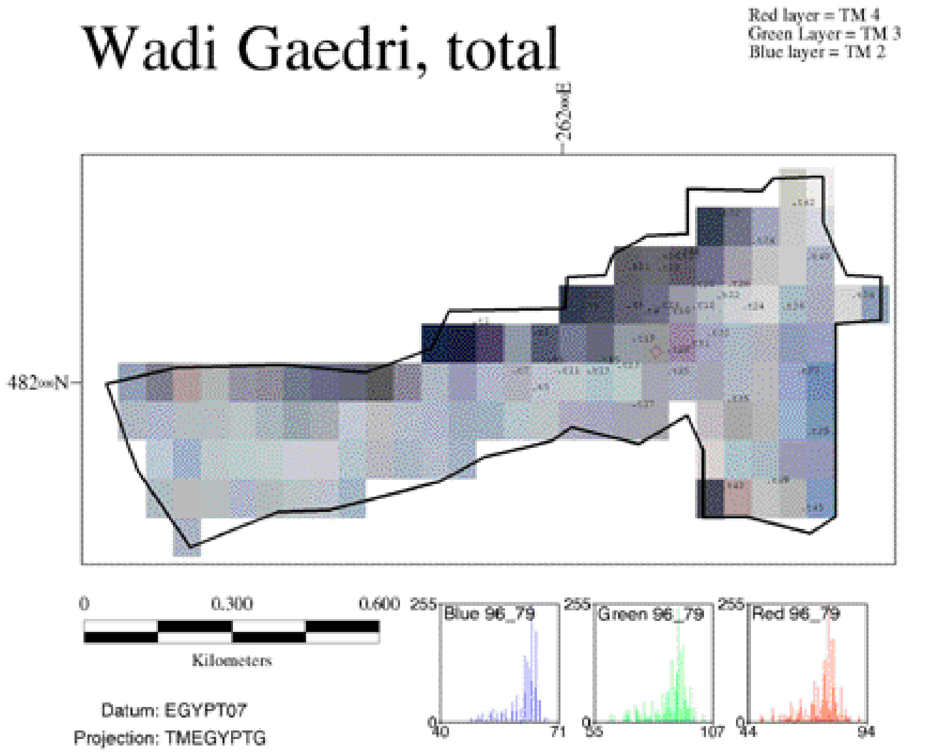
1979


Wadi Gaedri, total
Red layer = TM 4
Green Layer = TM 3
Blue layer = TM 2
262000E
482000N
0
0.300
0.600
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG
Blue 84
Green 84
Red 84
255
0
40
71
55
107
44
94

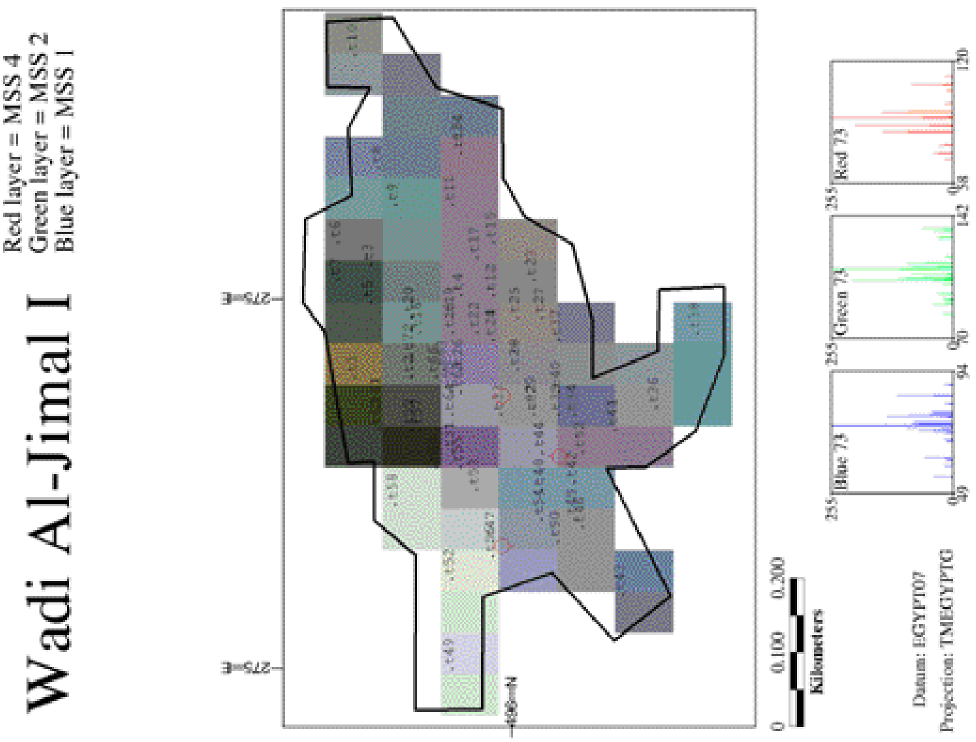
1984



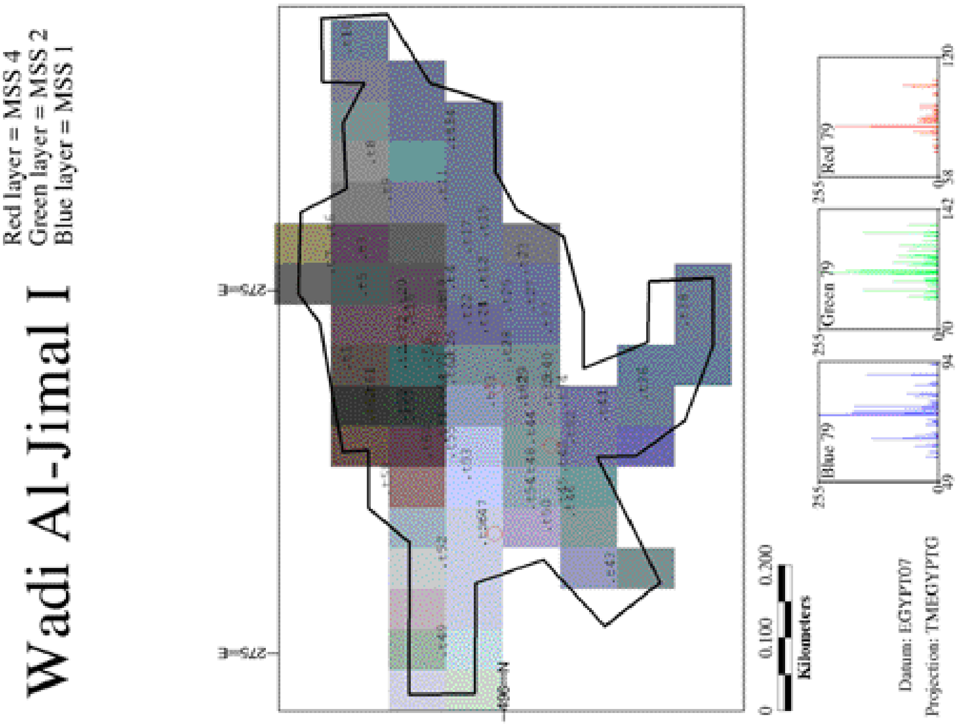
1996 81 m



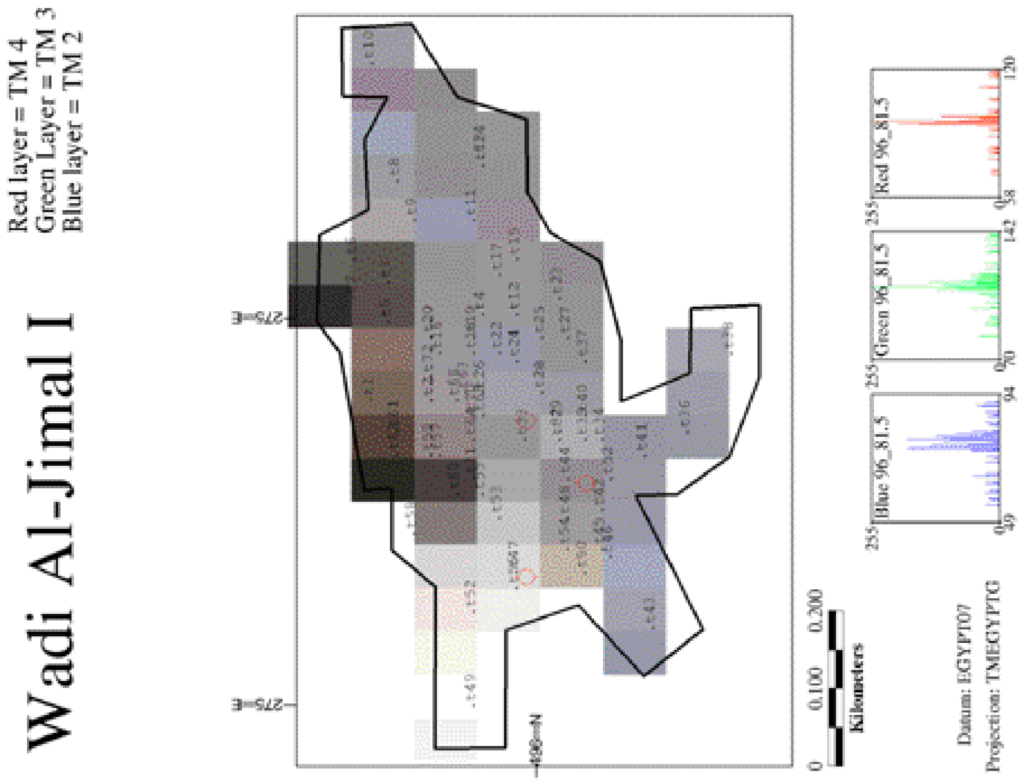
1996 79 m


Wadi Al-Jimal I
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG
Blue 73
Green 73
Red 73

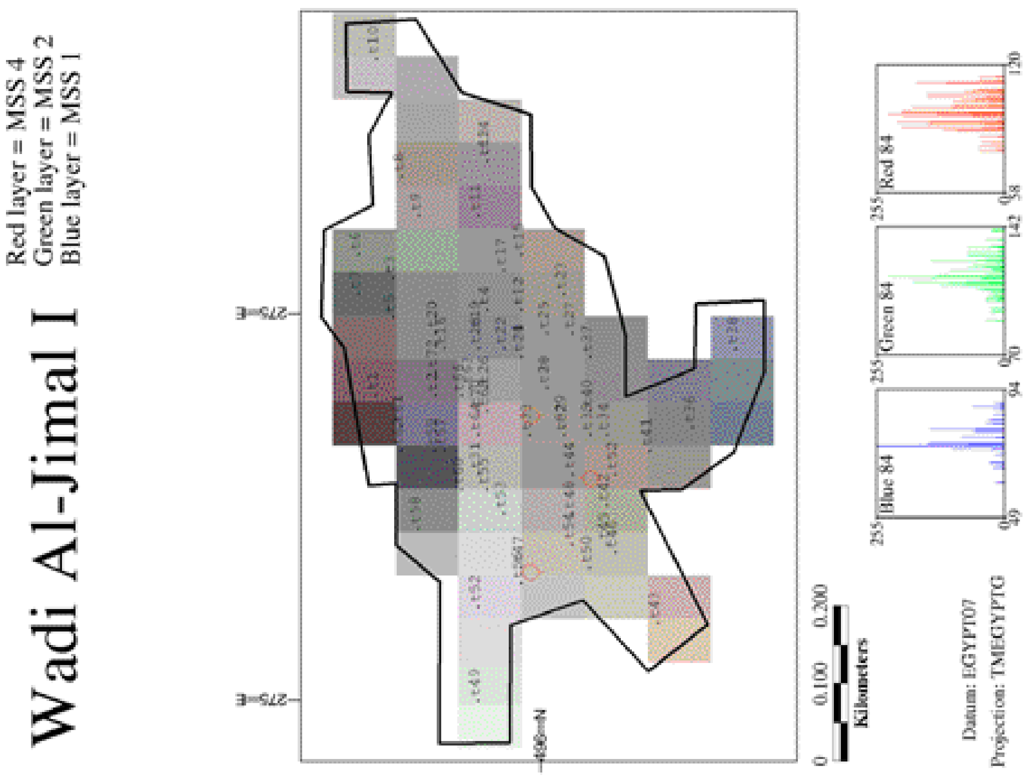
1973


Wadi Al-Jimal I
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG
Blue 79
Green 79
Red 79

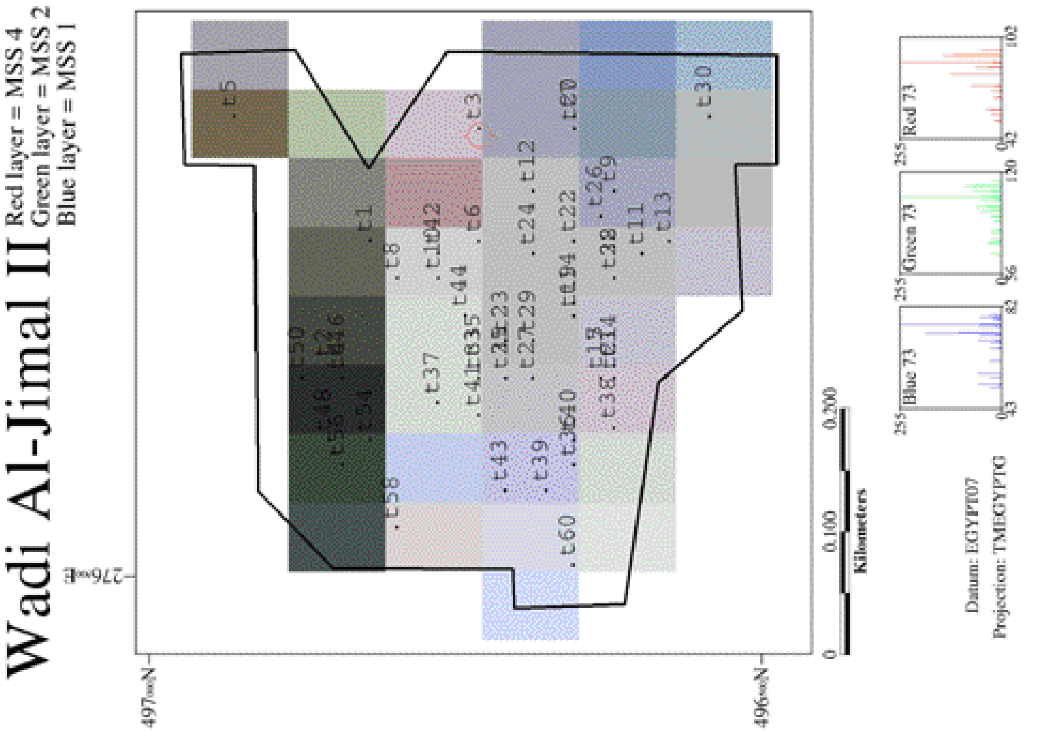
1979



1996 81.5 m

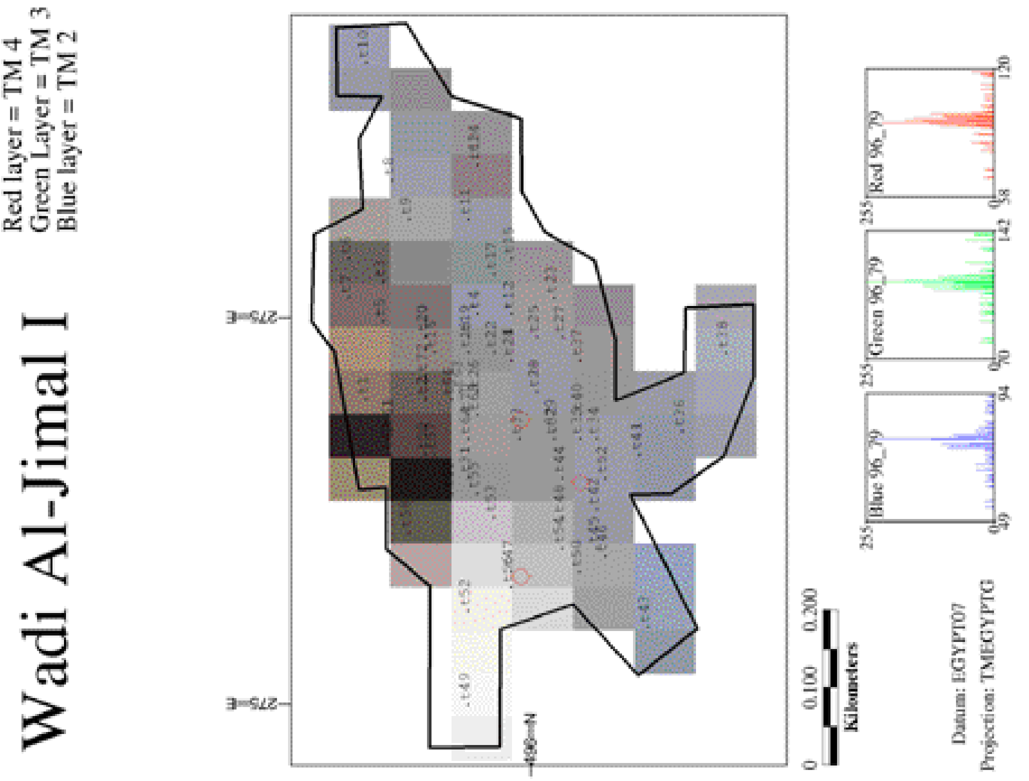


1984

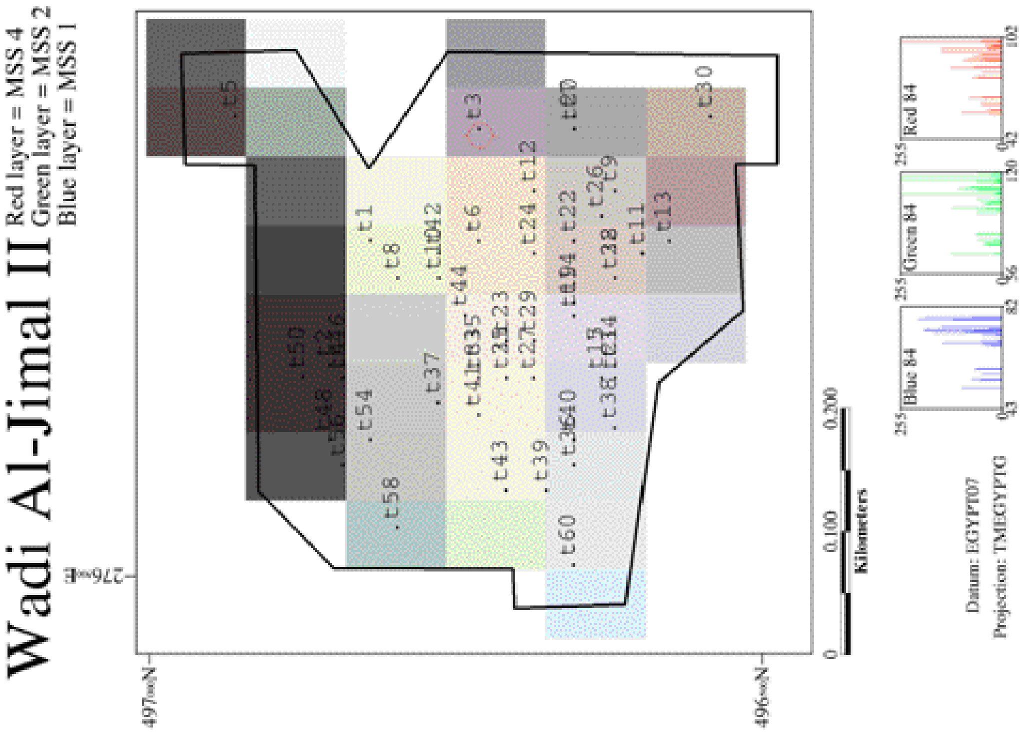


1973

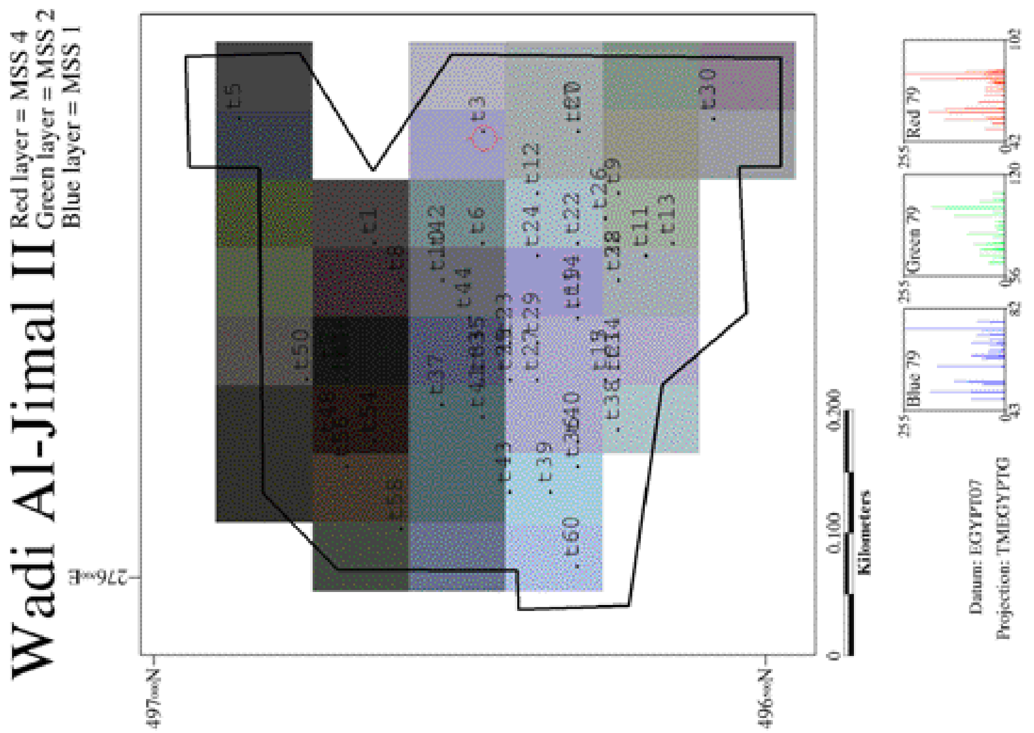
1973



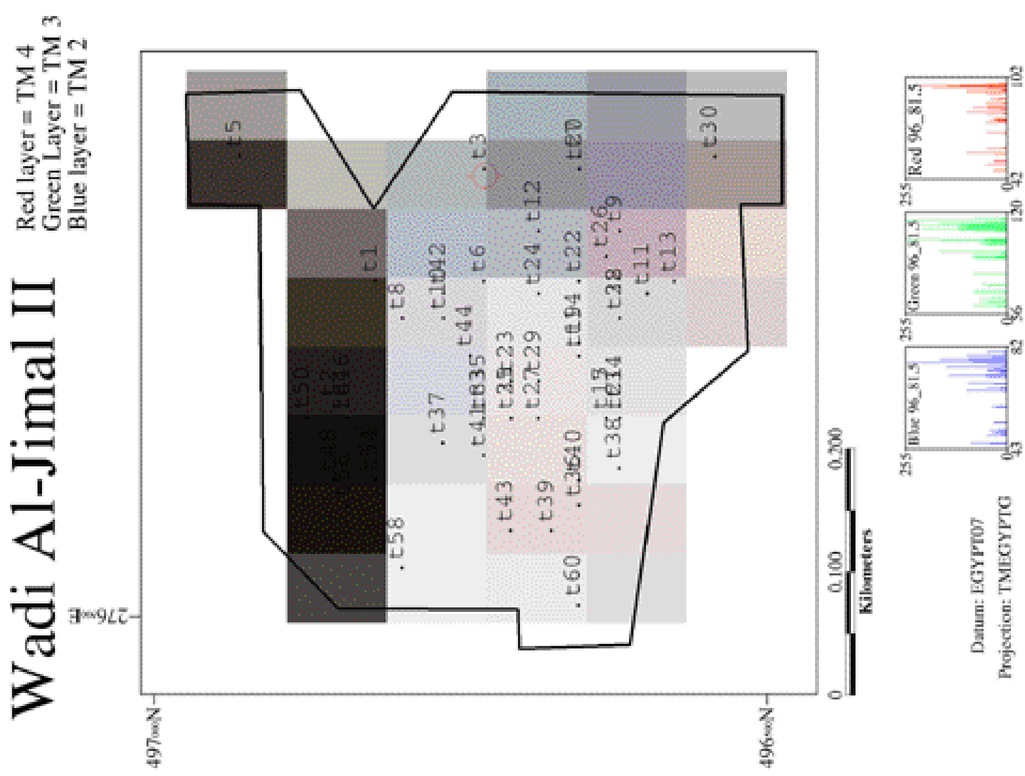
1996 79 m


Wadi Al-Jimal II
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG

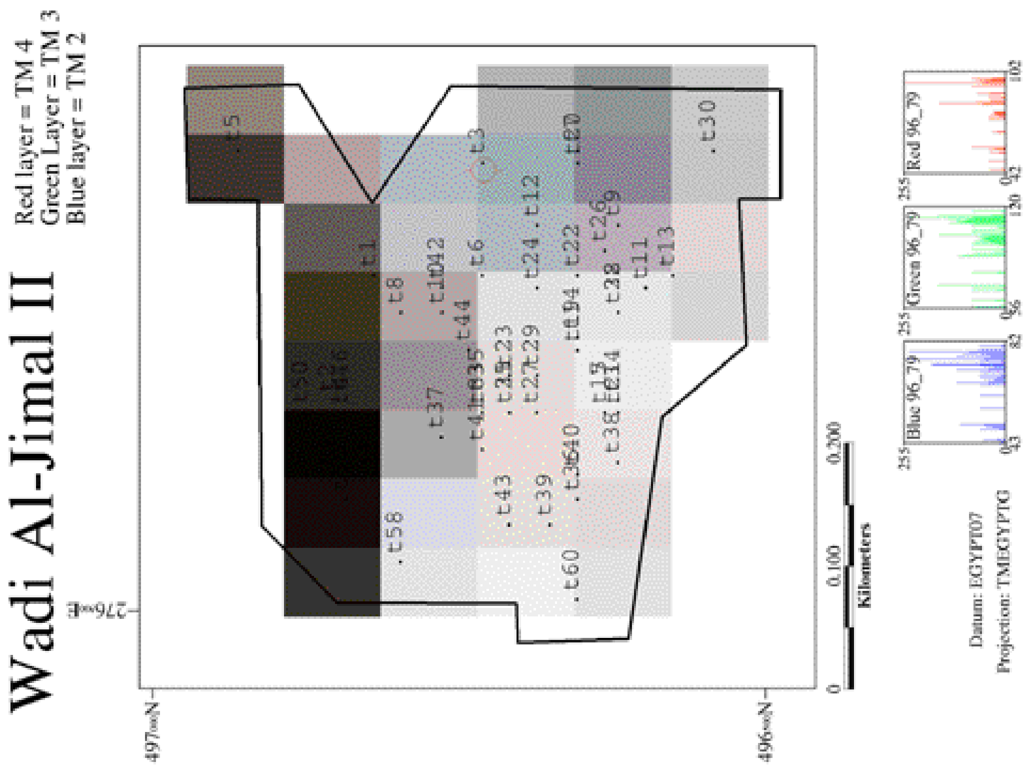
1984


Wadi Al-Jimal II
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG

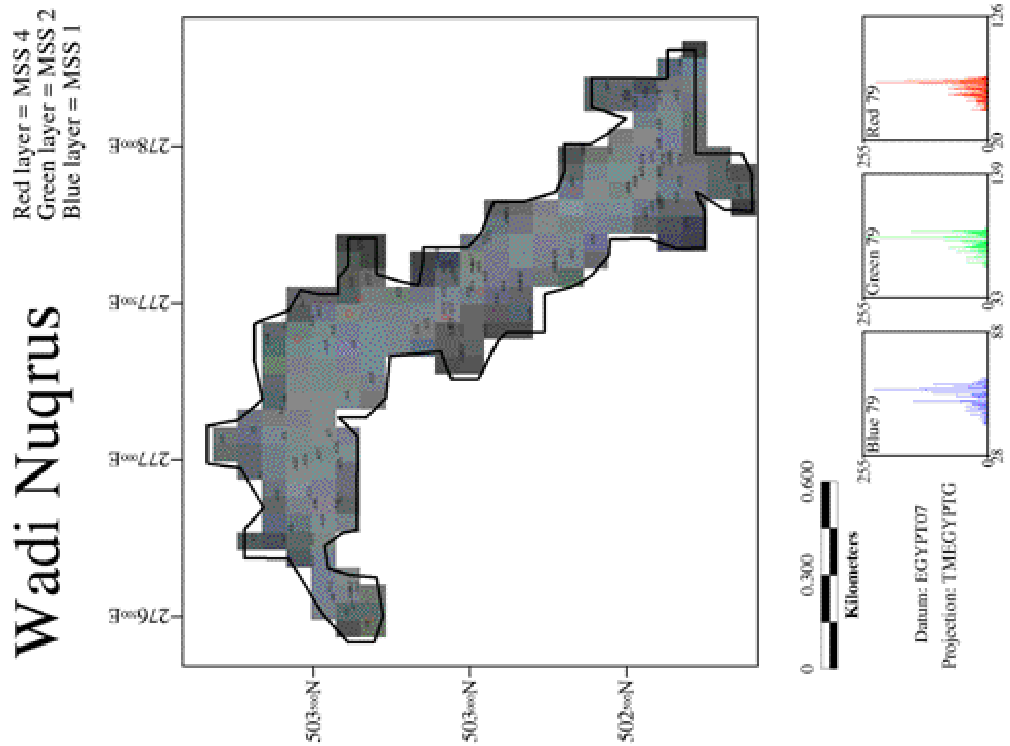
1979



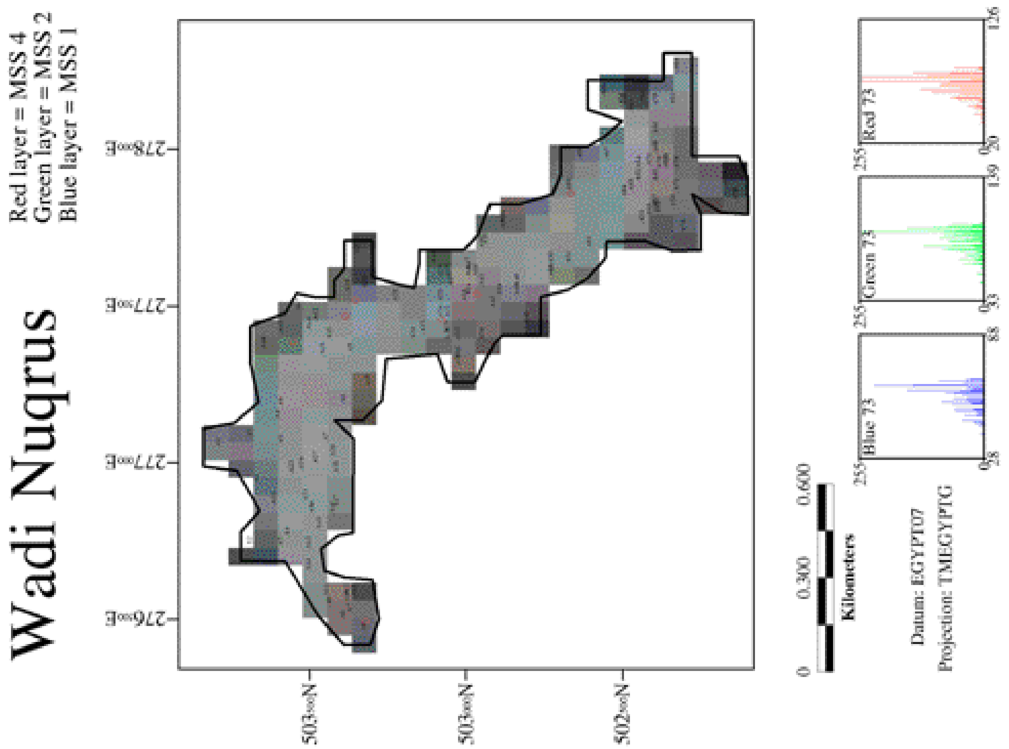
1996 81.5 m



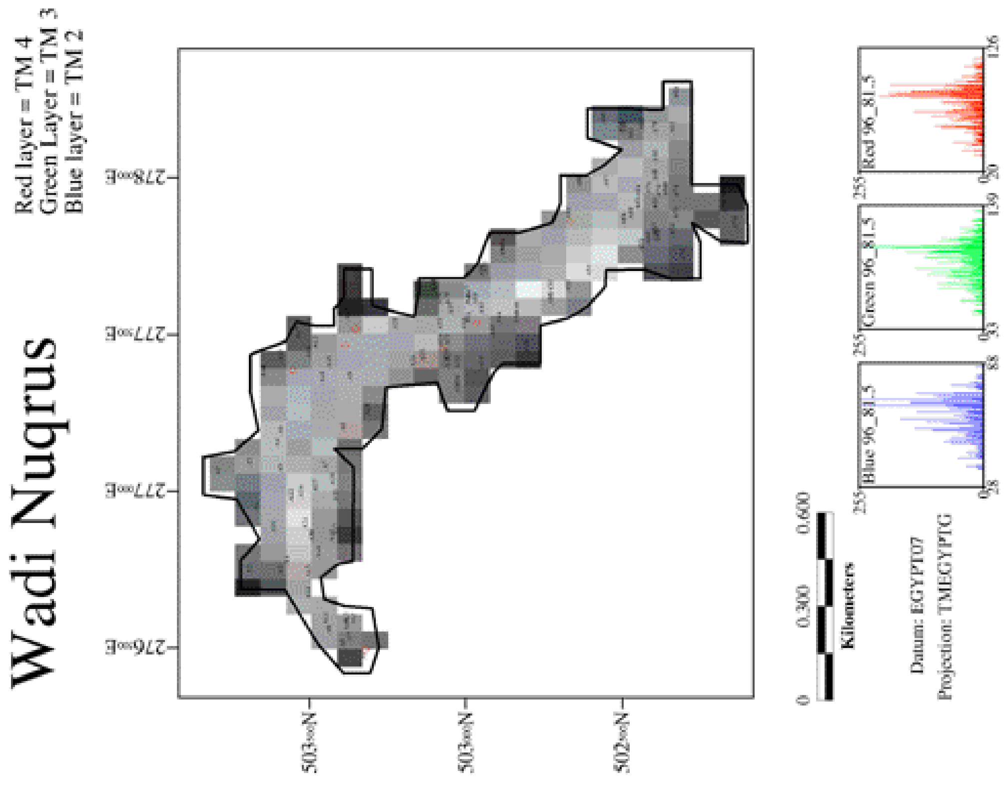
1996 79 m


Wadi Nuqrus
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
276000E
277000E
277000E
278000E
503000N
503000N
502000N
0
0.300
0.600
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG
Blue 79
Green 79
Red 79

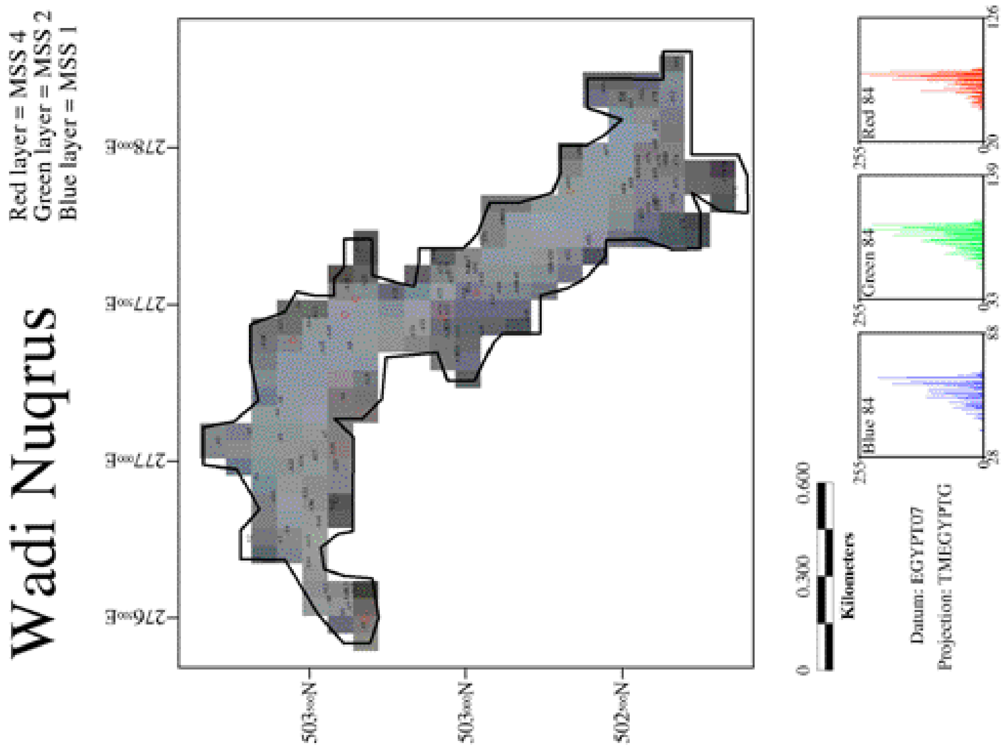
1979


Wadi Nuqrus
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
276000E
277000E
277000E
278000E
503000N
503000N
502000N
0
0.300
0.600
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG
Blue 73
Green 73
Red 73

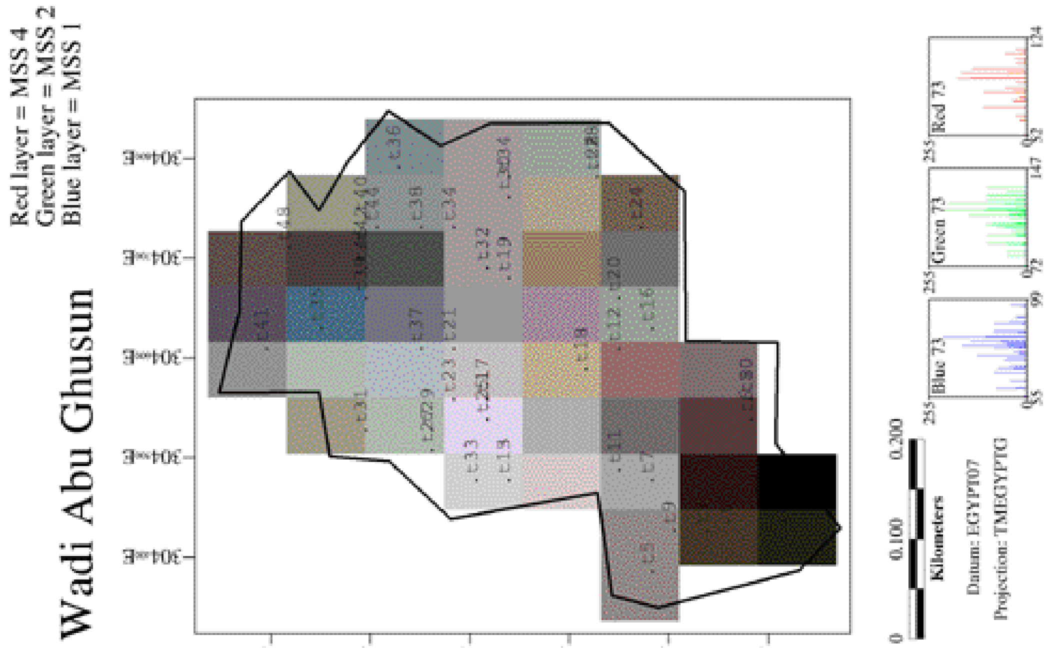
1973



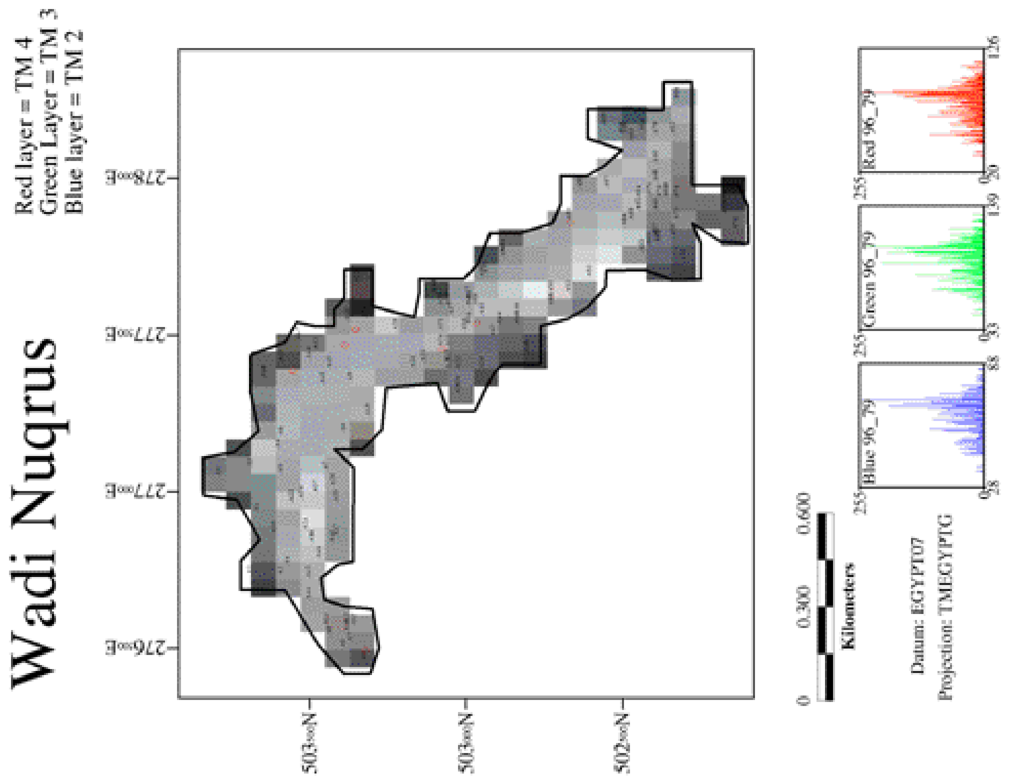
1996 81.5 m



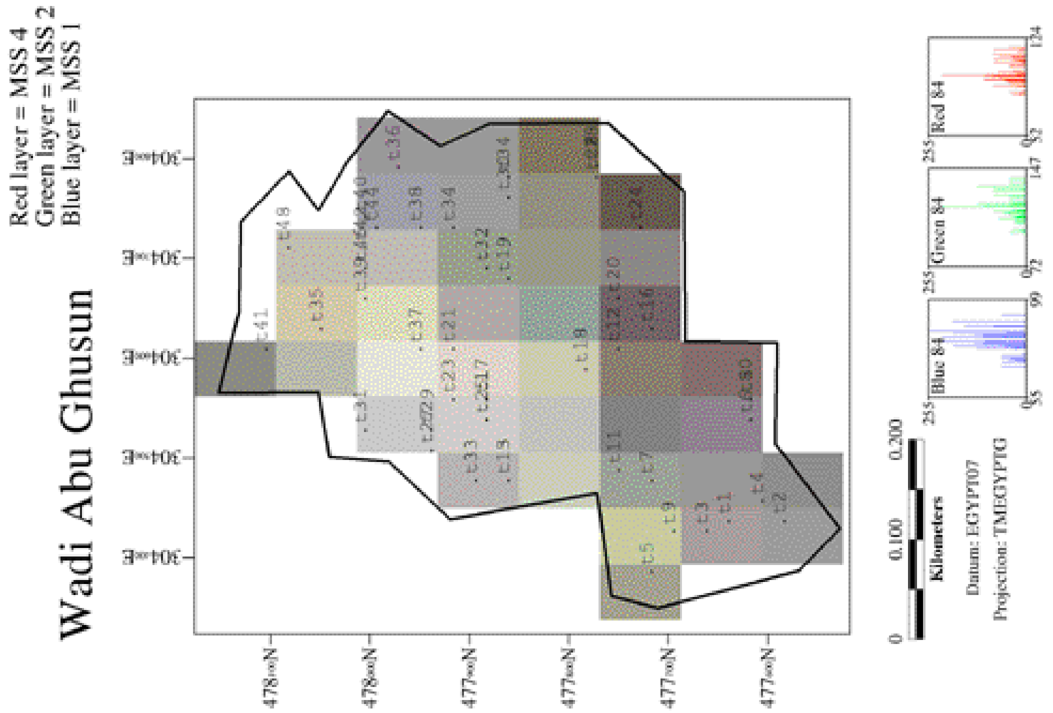
1984



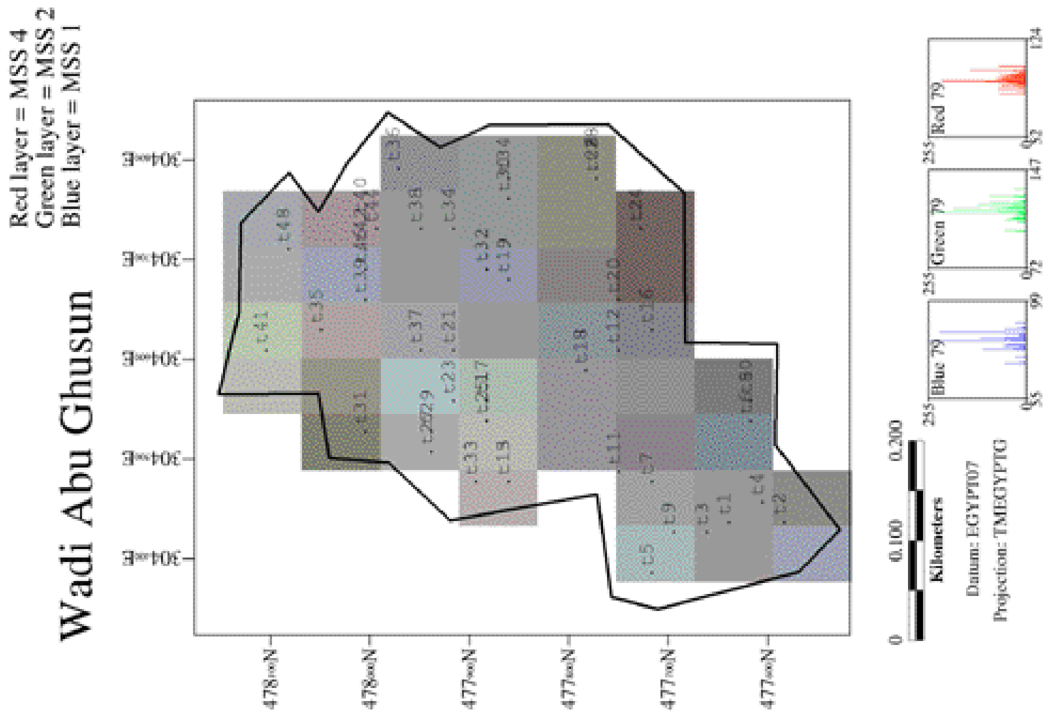
1973



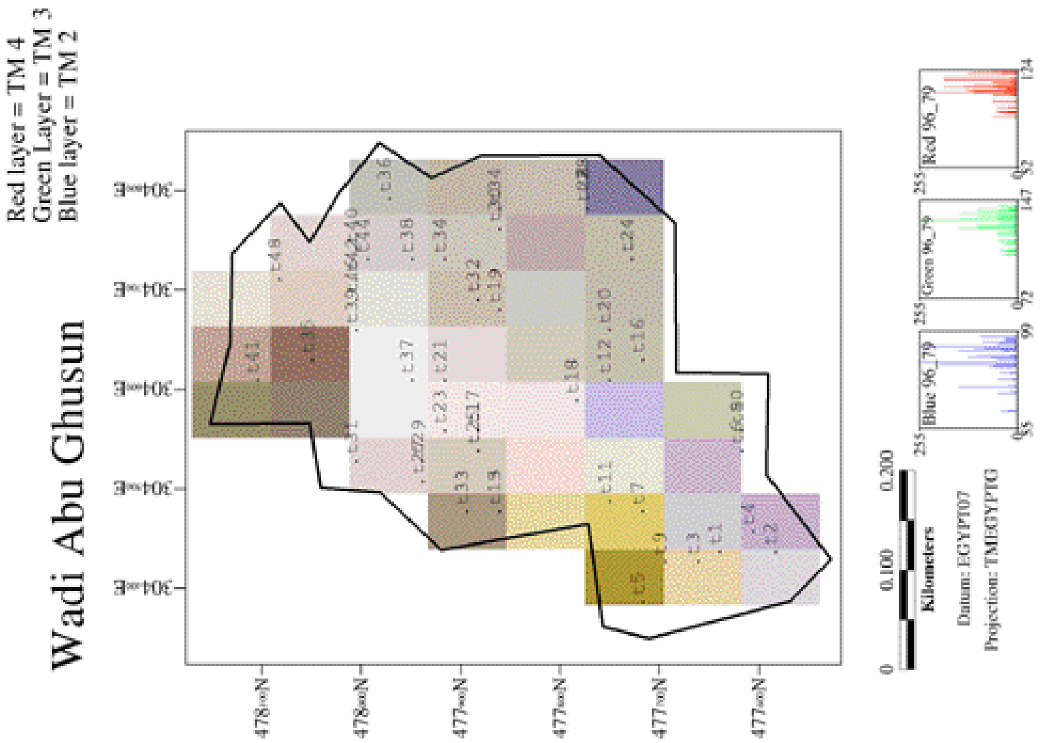
1996 79 m


Wadi Abu Ghusun
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
0
0.100
0.200
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG
Blue 84
Green 84
Red 84

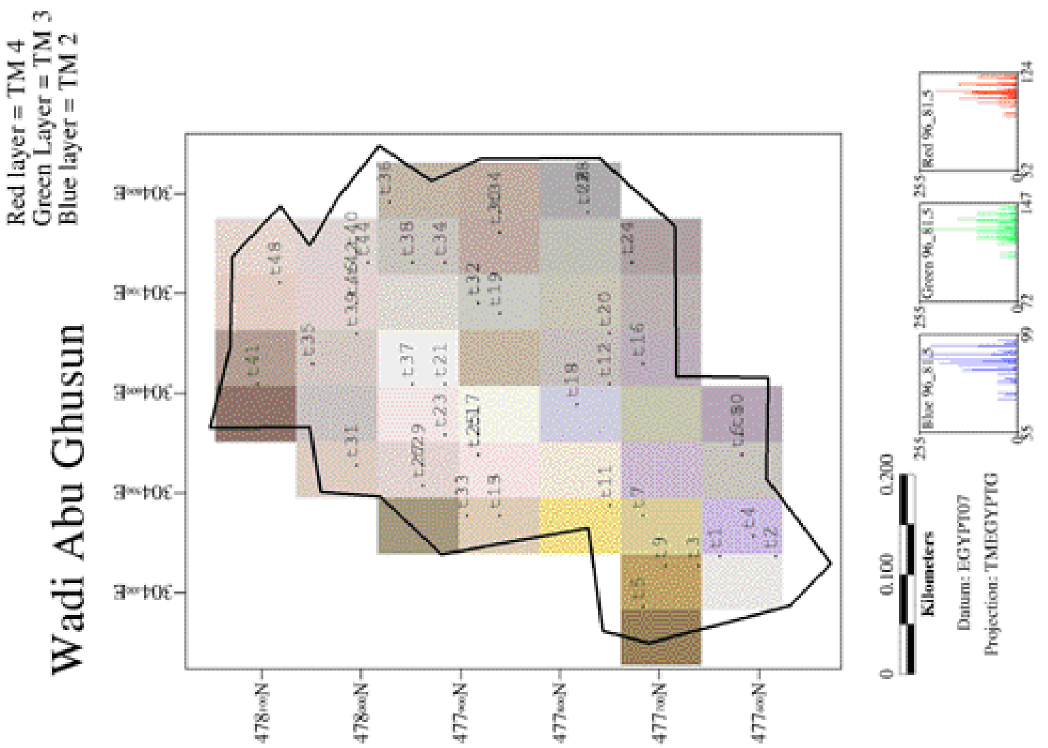
1984


Wadi Abu Ghusun
Red layer = MSS 4
Green layer = MSS 2
Blue layer = MSS 1
0
0.100
0.200
Kilometers
Datum: EGYPT07
Projection: TMEGYPTG
Blue 79
Green 79
Red 79

1979



1996 79 m



1996 81.5 m