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Studying vegetation of the Socotra Island by geoinformation methods

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Brno 2005

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Acknowledgement

I wish to acknowledge all the people of Socotra for their kind help and support during our stay on the island. I gratefully acknowledge the scientific advices of my colleagues from the Faculty of Forestry in Brno. I also greatly appreciate the kind logistical backing of the Environmental Protection Authority of Yemen.

Last but not least, full credit is given to Mohammad “Al Keybání” for his guidance through the mysterious island “Abode of Bliss”.

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LIST OF ACRONYMS

a.s.l. – above sea level
AVHRR - Advanced Very High Resolution Radiometer
AVZ – Altitudinal Vegetation Zone
BT – Biotope Type
DEM - Digital Elevation Model
ENSO - El Nino/Southern Oscillation
EPA - Environment Protection Authority
ERDAS - Earth Resource Data Analysis System
ETM - Enhanced Thematic Mapper
EVI - Enhanced Vegetation Index
FAO - Food and Agriculture Organization
GBT – Group of Biotope Types
GCP – Ground Control Point
GEF - Global Environment Facility,
GIS – Geographical Information System
GPS – Global Positioning System
KB – Knowledge Base
LC - Land Cover
LCC - Land Cover Classification
LCCS - Land Cover Classification System

MAB – Man and Biosphere Programme
MLC – Maximum Likelihood Classification
MODIS – Moderate Resolution Imaging Spectroradiometer
MUAF – Mendel University of Agriculture and Forestry
NDVI – Normalised Difference Vegetation Index
NIR - Near-Infrared
NOAA - National Oceanic and Atmospheric Administration
PC – Principal Component
PCA - Principal Component Analysis
RS - Remote Sensing
SCDP - Socotra Conservation and Development Program
SRTM – Shuttle Radar Topography Mission
TM - Thematic Mapper
TSA – Time Series Analyses
UNDP - United Nations Development Programme
UNEP - United Nations Environment Programme
UNESCO - United Nations Educational, Scientific and Cultural Organization
VI – Vegetation Index
WGS – World Geographic System
WWF - World Wide Fund for Nature

1. INTRODUCTION

This study has been completed in the framework of a bilateral Czech-Yemeni project: "Creating an ecological network and agroforestry, educational and cultural doorway for sustainable development of the Socotra Island (Republic of Yemen - RoY)", which has been realised within the Czech Developmental Assistance Programme rendered to RoY. Objective of the project was to verify existing state of the island biotopes, delimitate ecologically important landscape segments and compose a proposal of the ecological network aimed to: (1) conserve endemic plants and animals; (2) prepare basis for sustainable agroforestry management respecting conservational aims and acceptable by the local community.

In order to contribute to the fulfilment of these objectives, various data and techniques of Remote Sensing (RS) were employed. Existing state of the island biotope types and groups of biotope types was recognised by means of the new land-cover map that was created using Knowledge Base classification of the Landsat ETM image. These data can complement quite insufficient raw vegetation maps that are recently merely available - resulting land-cover map will hopefully help to fill the knowledge gap about the unique worthwile natural area, where until now no satisfactory map of vegetation cover exists.

Using the multi-temporal data of the MODIS satellite also a pilot outline map of Altitudinal Vegetation Zones was constructed. This map is important for well-defined agroforestry management and in connection with the land-cover map also for a proposal of the ecological network.

Besides, big effort was dedicated to the phenological observations. Sustainable agro-forestry management can not be implemented without understanding of seasonal dynamics of vegetation cover and its causalities. It is still very little known even about the climate and its seasonal variation in different parts of the island and comprehensive information about the vegetation phenology is completely lacking. The study of phytophenology is important for the insight it gives into the temporal organization, evolution and functioning of ecosystems. Consequently, knowledge of the phenology of plant communities is relevant to estimating biological productivity, understanding land-atmosphere interactions and vegetation dynamics as well as for the management of vegetation resources (LIETH et WHITTAKER 1975, UNESCO 1979).

It simply was not possible to study phytophenology on Socotra by conventional methods due to their high requirements on labour and time. However, the data and techniques of remote sensing can very effectively overcome this restriction. This approach has become quite common especially in global or large-scale phenological studies using data of low-resolution satellites NOAA-AVHRR (e.g. JUSTICE et al. 1985; MALO et NICHOLSON 1990, PELKEY et al. 2000). One of the outstanding merits of remote sensing procedures in the investigation of phenology relates to the spatially comprehensive overview of vegetation that is provided (JUSTICE et al. 1985). Since the phenology is generally accepted as including not only the timing of recurring biological events but also their causes, especially with regard to meteorological phenomena (LIETH 1974), the synoptic overview provided by RS data is very important, as it enables better understanding of those causalities.

Advancement of new satellites of moderate resolution with globally produced data sets enable to increase precision in global or large-scale studies as well as to apply these methods in regional and local scale with far more detailed interpretation possibilities. The MODIS imagery of 250m resolution could be very strong tool in resembling studies. The last chapters of this study present an attempt to use these data for fine-scale phytophenological study.

2. STUDY AREA

2.1. Location and topography

Socotra is the largest and most easterly island of this Indian Ocean archipelago, lying approximately 240 km east of the Horn of Africa (Cape Guardafui in Somalia) and 380 km south of the Arabian Coast (Ras Fartak in Yemen). The other main islands in the group are Abd al Kuri, and Semhah and Darsa called the Brothers. Abd al Kuri is the closest to the African mainland, only 90 km away. The Islands are separated from one another by relatively shallow seas but from the mainland of Africa by a narrow but deep trench of several hundred fathoms (MILLER et MORRIS 2004) and from the Arabian Peninsula even about 5000m (WRANIK et al. 1999). Socotra, the largest island, is about 130 by 35 km and covers an approximate area of 3625 km² (WRANIK 1996).

The area of interest can be more precisely located as an area between latitudes 12°15' and 12°45' N and longitudes 53°15' and 54°35 E. It is regarded as the biggest of Yemen's 124 islands.

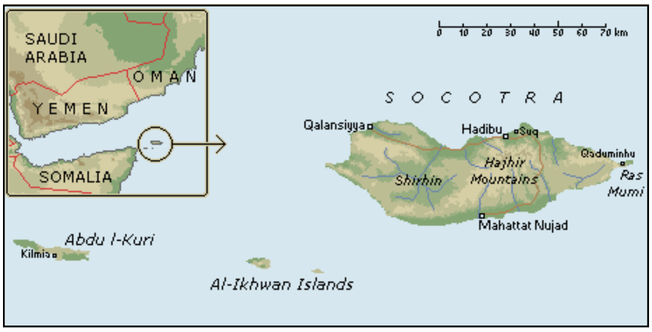


Fig. 1: Location of the Socotra Island.

Socotra is often considered to be part of the Middle East and not Africa because it is administered by Yemen, but geographically and biogeographically it is a continuation of the Horn of Africa. The island can be divided into three physiographic zones: the coastal plains, the limestone plateaus and the igneous Haggeher mountains (MILLER et MORRIS 2004); see also the appendices No. 3 and 6.

The coastal plains (formed by Quaternary sediments) vary in width and length but are usually about 5km wide and about 8km at their widest. The largest unbroken stretch is the Noged in the south, which is about 70km long and averages 5km in width. Along other parts of the Coast, shorter stretches of plain are broken by rocky headlands and by the escarpment cliffs of the limestone plateau. The wadis are mostly choked by boulders and debris so no permanent streams cross the plains although they do flow to the sea when in flood. Many of the north-flowing wadis terminate in small fresh or brackish lakes separated from the sea by spits and bars. In the west there is a large, dry and poorly vegetated drainage basin (the Zahr) (MILLER et MORRIS 2000).

The limestone plateaus extend across a large part of the Island, averaging 300—700m in elevation and reaching over 800m at its highest point in the west (Ma'alah) and up to 1000m in the central part (Dixam). The plateau drops in steep, often almost vertical escarpments either to the coastal plain or directly to the sea. Wadis flow from the central mountains, particularly in the south, cutting deep into the plateau. The summit is rolling or, in some areas, broken by well-vegetated cliffs and gullies. The surface exhibits typical karst features, with in some areas (e.g. Rewgid) large areas of bare pavement, gullies, swallow holes, sinks and cliffs. Few streams are visible on the surface and caves are common (MILLER et MORRIS 2004).

The Haggeher mountains are a high mainly igneous massif (generally above 750m) and dominate the eastern and central part of Socotra island, being perhaps the most spectacular feature of the islands. They rise in a series of dramatic pinnacles radiating from the base of which are deep, moist gullies, steep boulder-strewn slopes and, on gentler gradients, cleared grassland (MILLER et MORRIS 2000). There are several peaks over 1300m and Jebel Skand at 1540m (MR. MOHAMED AMAR 2004 – personal communication) is the highest point of the island. The Haggeher massif forms the most important watershed on the island and numerous watercourses run both north and south from it. Particularly on the northern slopes these streams are permanent in their upper reaches, whereas in the plains they are mostly sporadic, carrying water only during the rains and just after (WRANIK 1996). The rocks of the Haggeher are predominantly red but often appear white from the lichens that cover them.

2.2. Geological history and Biogeography

From a natural history viewpoint Socotra remains one of the most fascinating places in the world, which was in 2003 nominated for Biospherical reserve (sole in the Republic of Yemen) under the Man and Biosphere Programme – MAB (www2.unesco.org/mab). The unique character of the island is related to its geological history.

KOSSMAT (1907) characterised Socotra as one of the "most isolated pieces of land" in the history of the Earth. The high degree of endemism, as a result of this long isolation, makes the archipelago a "living laboratory" of remarkable biogeographic and evolutionary interest and an important place in terms of global wildlife conservation (WRANIK 1996). Although the geological history of Socotra is in many details still imperfectly known, it is possible to suggest that some of the endemic species are relics and descendants of an ancient flora and fauna surviving in the Socotra Haggeher massif, which is considered by geologists not to have submerged since the Mesozoic (UVAROV et POPOV 1957).

2.3. Vegetation

Species diversity projected through altitudinal vegetation zones is markedly influenced by orographical, geological and pedological variability of the habitats. The prehistoric origin of local plants and their degree of endemism reaching some 35% (MILLER et COPE 1997) rank the island among the most environmentally important spots on the Earth.

In general, the islands of the Socotra Archipelago are sparsely vegetated and dominated by xeromorphic life forms (MILLER et MORRIS 2004). There are several distinctive vegetation formations on Socotra, particularly with respect to their physiognomy and structure. Perhaps the most famous, because of its often bizarre appearance, is the shrubland dominated by tree succulents such as *Dendrosicyos socotrana, Adenium obesum* subsp. *sokotranum* and *Euphorbia arbuscula*. This occurs mainly on the foothills of the mountains and the limestone escarpments and is the vegetation type for which Socotra is most renowned (MILLER et MORRIS 2000). Another unique vegetation formation is the evergreen woodland dominated by the dragon's blood tree (*Dracaena cinnabari*) commented upon by WHITE (1983) as the most 'singular community on Socotra'. The finest examples of this are found on the higher slopes of the limestone plateaus, particularly in the centre and east of the island. The coastal plains are vegetated by open shrubland dominated by *Croton socotranus* or in some areas more or less devoid of vegetation (MILLER et MORRIS 2000).

More precise description of the vegetation is given by the first detailed land-cover map of Socotra Island (KRÁL 2005) distinguishing 22 terrestrial land-cover (mostly vegetation) classes (see also appendix No. 2):

(1) Sea
(2) Mangroves
(3) Coastal salted desert
(4) Wetlands
(5) Wadi
(6) Sand dunes

(7) Sparse dwarf shrubland
(8) Low Croton-Jatropha shrubland
(9) High shrubland with suculents
(10) Frankincense woodland
(11) Frankincense forest
(12) Dracaena woodland
(13) Dracaena forest
(14) Submontane grassland and dwarf shrubland
(15) Submontane shrubland
(16) Montane grassland
(17) Montane mosaic
(18) Montane forest
(19) Sedimentary rocks
(20) Basement rocks
(21) Date palm plantations
(22) Urban
(23) Savanna woodland

The information on the extend, characteristic topography conditions, species composition and the distribution of the land-cover (vegetation) classes on Socotra referable to the Landsat imagery classification, GIS multilayer analyses and the field survey are described in further details in a chapter 4.2.

2.4. Climate

A more detailed description of the climate of Socotra follows, as it closely bears on the analysis of phenology, which will be presented in the chapter 4.7.

The island generally falls into an arid tropical zone, but with a climate tempered considerably by monsoons, it is less torrid than that of the adjacent mainland.

Few and discontinuous climatic data are available for Socotra. Several authors tried to make some general comments about the climate of the Socotra archipelago, nevertheless, their conclusions especially about a distribution of rainfalls – a critical environmental variable of the region - were often rather discordant. One fact is certain according to all of them: The climate of the ecoregion is strongly influenced by both the southwest (summer) and northeast (winter) monsoons. However, precise timing of the monsoons as well as their impact on the distribution of rainfalls are judged differently.

DAVIS et al. (1994) write about the summer southwest monsoons (April-October), which bring extremely strong, hot and dry winds from Africa. Accordingly, there is little precipitation and extreme desiccation during these months. The winter monsoon begins in November and lasts until March. Similarly refer EVANS (2001); WRANIK (2000) and Hunting Technical Services Ltd. (1993). According to them, Socotra gets its main rains during the winter monsoon, while the summer monsoon winds are rather dry and stormy. A little advance in description of the climate was made by MILLER and MORRIS (2004). They still describe the summer (June-September) monsoon as hot and dry with extreme desiccating effect on the development of the vegetation. However, they suppose that at higher elevations, and particularly in areas facing the southwest, the season brings drizzle and cloud. The opposite winter monsoon is described to blow from November until January.

Concerning the distribution of rainfalls, for example POPOV (1957) alleges the highest precipitations in November and December, while GWYNNE (1968) mentions maximum rainfalls in August and September. MIES and BEYHL (1996) place a main rainy season between August and October and a secondary rainy season in April and May, however, they incorrectly associate the secondary rainy season with the winter monsoon. MILLER and MORRIS (2004) say that most rain falls between November and January.

KOPP (1999) concluded all the inconsistent findings in a statement that an irregularity is probably the sole rule in precipitation regime of the island. He also mentioned an extreme temporal and spatial variability of the climate, which can be described only by number of climatic stations and long continuous measurement period.

One can agree with above stated extreme temporal and spatial variability of the climate, nevertheless, according to the latest more than 4 years measurements on Firmihin locality and according to the analyses of a time serie of satellite based NDVI images, a serious causality of the seasonal climate and rainfalls has been discovered and described (see below).

The weather-station including automatic dataloger Mini Cube EMSet_99 has been installed on Firmihin locality in November 2000 in approximate altitude 440 m above sea level (see appendix No. 1). The locality represents the medium elevated sites of the limestone plateaus of the southern half of the island, which are exposed to the summer monsoons. The rainfall pattern recorded here, therefore, should be considered as typical for analogical sites. Climate variations of other sites are estimated using data of episodic historical measurements, e.g. rainfall figures recorded by the RAF Station at Ras Karma (Mouri Airport) in years 1943-1945 (POPOV 1957), and employing spatial and temporal analogy based on time series analysis of MODIS NDVI data.

The Firmihin station automatically recorded (in 30min. intervals) variables as follows: Global radiation [W/m^2]; Air temperature [°C]; Wind direction [deg]; Wind speed [m/s]; Air humidity [%]; Rainfall [mm/averaging interval]; Soil water potential [bar] in depth 5cm and 20cm. Unfortunately, several failures occurred during more than 4 year period. The recording failures were caused either by battery flat or damages due to storm and flooding. Therefore, it is likely, that some major rainfalls events have not been recorded! Following overall commentary on the course of climate on Socotra Island (the first overall and the most comprehensive commentary ever) was completed by Czech geographer Martin Culek (CULEK in PAVLIŠ et HABROVÁ 2005) and completed by the author:

After more than four years of measurements of climatic variables on Socotra, it is possible to outline the first generalization. Unfortunately, measured series are discontinuous and, thus, statistical evaluations are not possible. Nevertheless, based on existing periods of measurements, it succeeded to construct the course of weather on Socotra in an ‘ideal year’. The connection of measured sections was carried out by the deviser, manufacturer and seller of the measuring technology Mr J. Kucera, EMS Ltd. The connection of sections of the measurement from particular years is possible because it is evident that weather is characterized by a very similar course throughout every year. Results are given in Figs. 2, 3 and 4, annual statistics of daily mean values are displayed in the table 1. Following characteristic are related to the Firmihin locality where the station was placed. In other parts of the island, weather shows a more or less modified course.

A typical summer monsoon season begins about 8 May. A very stable SW wind begins to blow from the Indian Ocean (course 230°). The average daily wind velocity increased abruptly from 1.5 to 3 m/s and deviations in wind velocity increased by about 30%. The average daily intensity of solar radiation decreases nearly by half in consequence of predominantly overcast sky. The average daily temperature decreased abruptly as against a previous period (the warmest season) by 2.5°C to about 25.5°C, daily temperature amplitudes decreased suddenly to less than half from about 10°C to 0.7-6°C. The average daily relative humidity increased from 70% (the Firmihin station) to 85%. Sometimes the increase is even more marked because at the beginning of monsoon, relatively important precipitation falls on the windward slope of the island. Recorded daily maximum in May is about 10 mm. Due to the station damage, higher values were not probably recorded. For example in 2004, precipitation at the beginning of May caused floods in dry riverbeds (wadis) in the southern part of the island, e.g. wadi Esgego (MOHAMED AL-KEYBANI 2004 – personal communication). In the northern part of the island (at present occurring in rain shadow) it does not rain with the highest probability at this time (similarly as for the rest of the summer monsoon). According to the Mouri station it did not rain even in 1943 and 1944. In May 1945 only 4.3 mm of the rain fell (POPOV 1957). Also according to the analysis of phenology, marked drying up of vegetation occurs in the northern part of the island. The fact proves the local absence of precipitation.

The course of weather lasts virtually without noticeable changes about one month. Only an average temperature decreased to 23.5°C. Precipitation fell most frequently in the first decade of June. However, it did not reach intensity from the beginning of May. The average wind velocity increased suddenly to 6 m/s, deviations were the same. Small changes in the wind course were, however, more significant. The course of wind changed from about 230° to nearly 240°. Thus, the SW air circulation comes to the island by a more western path, i.e. through semi-deserts of Somalia. It results in the smaller decrease of relative humidity of air from average 85 to 75%. Of course, it is a novelty for the period of a culminating summer monsoon. At the beginning of July, the deviation of the course of wind towards west is highest, wind reaches the highest velocity in the year (on average 8.5 m/s) being very gusty, the highest deviations in wind velocity occur and especially differences between particular days are very marked. Intensity of solar radiation increased and temperatures do not decrease any more.

During July until the second decade of August, wind slightly turns to the south and its average velocity slightly decreases, however, deviations remain. Solar radiation is of the same course as in the previous stage but temperatures slightly decrease again up to the average daily temperature about 21.7°C. Relative humidity of air does not decrease any more. No precipitation was recorded from the middle of July.

In the second half of August and in September, the situation is stable. Wind course is about 230° being relatively steady, average velocity markedly decreases to 1.5 m/s and deviations are small. Solar radiation reaches annual minima – the sky is evidently nearly continually overcast. Temperatures begin to increase slightly mean daily temperatures being about 23°C at the end of the period. The temperature is, however, subject to considerable deviations between particular days although daily amplitudes approach annual minima thanks to cloudy weather. The mean daily relative humidity returns nearly suddenly to 85%, maximum values get sporadically near 100%. At the end of the period and at the end of the summer monsoon at all, mean daily relative humidity increases over 90% and in the period of about 14 days, long stages occur with relative humidity amounting to 100%. It is a period when fog lies obviously in Firmihin and rainfalls again recorded daily totals being about 13 to 81 mm (26 September 2002). The recorded maximal daily total in this period - 207 mm (27 September 2002) is by the same mail the annual daily maximum.

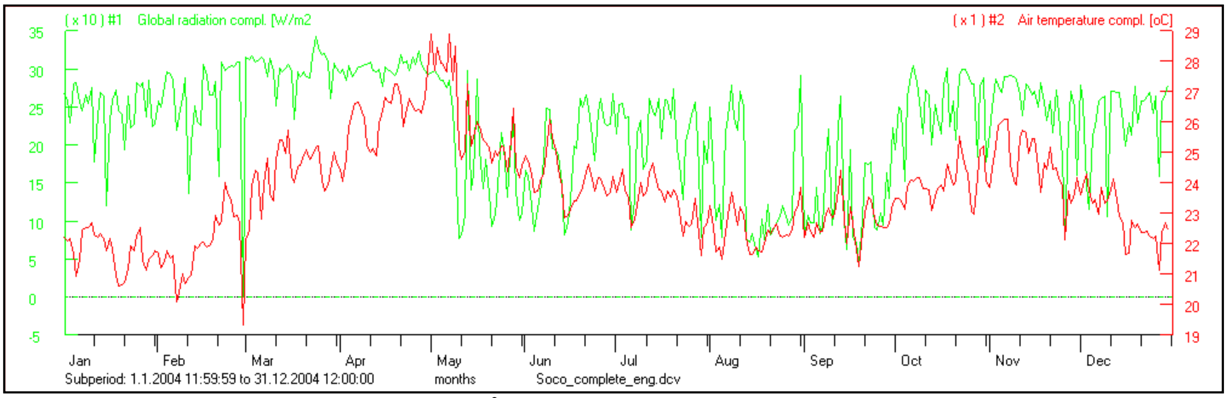


Fig. 2: Daily mean Global radiations [W/m^2] and Air temperatures [°C] in the 'ideal year' at Firmihin.

Autumnal transitional period. Last days in September (sometimes at the turn of September and October), a very abrupt turn in the development of all variables occurs (see diagrams). Above all, a steady SW wind ends and although the SW component of the wind always predominates winds of virtually all courses begin to occur. The predominating wind slowly turns to the east till the second decade of November and lastly to the north-east. In the course of the time when also an eastern wind blows for a short time, cyclones from the Indian Ocean can get to Socotra being accompanied by rainstorms with convection cloudy weather on their back. In October, wind velocities (both average and gusts) achieve annual minima. Sky is cleared up, global radiation of sky is increased more than two-fold, sun shines for the predominant part of day although clouds always occur. Temperatures begin to increase gradually, mean daily temperatures from about 23 to 26°C in the first decade of November. Daily temperature amplitudes increased abruptly from about 2°C to about 7°C exceeding 12°C in mid-November. The relative humidity of air decreased at first a little to mean daily values over 80%, however, after drying up the soil after rains occurring at the end of September, the values begin to decrease sharply and in the first decade of November, the mean daily relative humidity decreases below 50%. Together with a very fluctuating daily temperature also relative humidity varies during the day. Minimum values reaching about 25% were recorded while daily maximum values exceeded 70% and rarely even 85%. In the northern part of the island, according to historical data from the Mouri station and phenological analyses, it is possible to expect the first precipitation in this period.

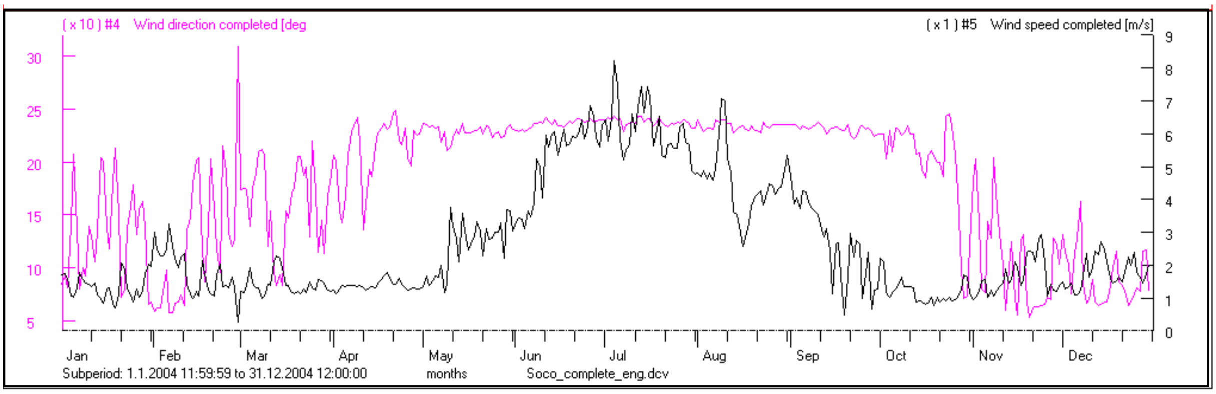


Fig. 3: Daily mean Wind direction [deg] and Wind speed [W/m^2] in the 'ideal year' at Firmihin.

The beginning of a winter monsoon is not so marked as the beginning of the summer monsoon. Abrupt changes in weather characteristics also do not occur. The end of the first decade of November can be considered to be the beginning of winter monsoon. Wind is virtually stabilized in the NE course (45°-55°), however, eastern winds also occur while northern winds are missing. The mean daily wind velocity begins to increase (from annual minima in the transitional period) from 1 to about 3 m/s unsteadiness of wind velocity being very low at least in Firmihin. Solar radiation intensity slightly decreases but based on the data measured it is possible to conclude that it is particularly due to the position of Sun approaching the tropic of Capricorn. Large fluctuations in the intensity of solar radiation are not evident at the beginning of monsoon; cloud formation is thus small (Firmihin, leeward slopes). On the northern - exposed side the cloud cover is probably generally much higher (see also Fig. 106 – bottom part and appendix No. 11).

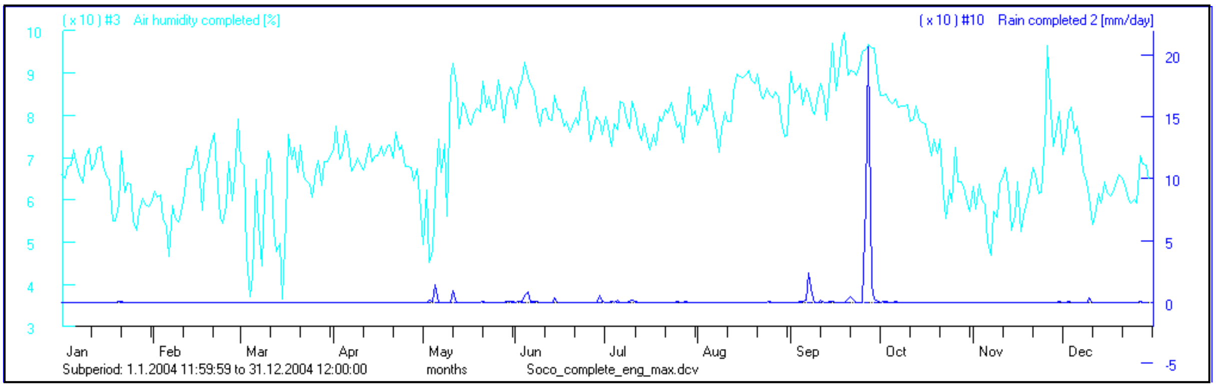


Fig. 4: Daily mean Air humidity [%] and daily totals of Rain [mm/day] in the 'ideal year' at Firmihin.

Mean daily temperatures form the secondary annual maximum temperatures reached at the beginning of November (about 26.2°C) begin to decrease systematically. It is important that daily amplitudes virtually abruptly decreased from about 9-11°C to 5-7°C. However, they do not decrease any more reaching only in cloudy days about 3°C. The mean daily relative humidity is low at first (at the beginning of November 50-60%) from the beginning of monsoon slowly and irregularly increasing exceeding 70% in mid-January. Of course, it is dependent on wind direction. In case of more eastern direction, the relative humidity of air can increase abruptly and in case of northern wind, it can steeply decrease. Since at the beginning of the winter monsoon eastern components predominate, relative humidity sometimes sharply increases and even at localities occurring in rain shadow such as Firmihin, precipitation can occur. Situation in the northern side of the Haggeher Mts is quite different the side being on windward face at that time. Northern walls of the mountains create a barrier for air circulation and thus precipitation is relatively more frequent and very heavy in mountains even under conditions of more northern winds. Generally, it is possible to expect that in the northern side of the island, November is the precipitation-richest month of the year (the 2nd richest is probably December).

Variable	Min	Max	Mean	Records	Suma	Stand. dev.
Global radiation completed [W/m2]	0	343.2	226.6	365	82698.1	72.9
Air temperature completed [°C]	19.3	28.9	23.7	365	8658.2	1.6
Air humidity completed [%]	36.6	99.5	72.6	365	26498.1	11.7
Wind direction completed [deg]	53.4	309.3	182.8	365	66707.5	62.9
Wind speed completed [m/s]	0.3	8.2	2.6	365	965.7	1.8
Rain completed [mm/day] *	0	207.5	1.1	365	418.3	11.8

Tab.1: Annual statistics of 'daily mean values' of selected climatic variables calculated from completed values of the 'ideal year' (2000-2004) at Firmihin locality. * The statistics of the variable 'Rain completed' refer to 'daily totals'.

During the winter monsoon, wind turns increasingly to the north, from 45°-55° in November to 35°-45° in January. However, poorly northern winds begin to occur. Thus, dry continental air comes from Asia being only little affected by a short passage over the Arabian Sea. The wind velocity remains low at Firmihin, however, in the northern coast of the island, it is probably high. Solar radiation decreasing till the third decade of December begins lastly to grow and deep falls signalizing major formation of clouds cease. The mean daily temperature ever decreases, however, from the 3rd decade of December more slowly amplitudes being roughly the same. The relative humidity of air increasing until mid-January begins to decrease. At the end of the 2nd decade of January, last precipitation of the winter monsoon was recorded at Firmihin being rather low (about 5 mm).

The end of the winter monsoon lasts till the end of the first decade of February. Wind begins to turn slightly towards east and its velocity even increases in some years. It is relatively a sunny season with the increasing intensity of solar radiation. In spite of this, the mean daily temperature reaches annual minima (20°C) and daily minimum temperatures occur (sometimes at the beginning of January) reaching even 16°C at Firmihin.

The mean daily relative humidity of air is low ranging about 50%. In drier regions along the northern coast, this character of weather begins already in mid-December (according to a local English speaking inhabitant). In a measurement carried out at the Mouri station in the northern coast of the island in 1943-1945, monthly precipitation in January and February ranged between 0.1-4.8 mm. These values are very low with respect to the windward location of the station and the winter monsoon. This difference is particularly marked as compared with November and December when precipitation in 1943 and 1944 ranged between 60.2 and 89.6 mm per month. Thus, in 1943 and 1944, precipitation amounted to 165 and 123 mm, respectively for both first months of the winter monsoon.

Records from 1945 mention for November only 4.4 mm; in December, the measurements were not carried out. In 2004 in the northern foot of the Haggeher Mts, following values were measured at the Mathre station: 21 January - 15 mm, 5 February - 20 mm and 6 February - 23 mm. However, impacts of surrounding mountains can be involved. In the Haggeher Mts, as against the northern coast (as well as the southern part of the island), the period of precipitation lasts obviously until the end of the winter monsoon, at least till the end of January.

At the beginning of the 2nd decade of February, the period of spring reconstruction and transition begins. The most striking change occurs in the direction of wind. While in the first half of February, winds blowing in the course of 25°-65° predominate and southern and western winds virtually do not occur, in mid-February a sudden turn occurs when SW winds are most frequent (185°-215°) NW winds being also abundant. These courses are naturally the manifestation of a daily and night breeze at the Firmihin station; the occurrence of marked breezes signalizes quite clearly sharp weakening of the monsoon circulation of air. North-eastern courses of winds occur again but they are less frequent and turn towards east, most frequently in the ENE course (65°-75°). The mean daily air velocity also markedly decreased reaching only 1.5 m/s but differences in velocities begin to increase slightly. Solar radiation moderately increases obviously due to the motion of Sun towards equator. It is important that differences in intensities are very rare and, thus, cloud formation is virtually missing. A mean daily temperature steeply increases, viz. from 20°C in the first decade of February to 25.5°C in the second decade of March. A substantial increase in the daily amplitude of temperatures from 5°-7°C to 9°-11°C is also striking. The mean daily relative humidity of air as compared with the end of the winter monsoon steeply increased from 50 to 70% not increasing any more, however, it fluctuates markedly obviously according to predominating winds and quite cloudless warm periods. Daily amplitudes of relative humidity markedly increased, as compared with the previous period twofold. They are highest at the end of the transitional period at the beginning of May when the relative humidity of air ranges between 10-30% and 70–90% during a day. In the second half of the transitional period (from mid-March to the beginning of May), south-western winds begin to predominate. At the Firmihin station, this direction of wind of the macroclimatic circulation is of course added to the direction of breeze which blows incidentally from the same direction at this station. Thus, effects of marked breezes and beginning monsoon circulation from the south-west can be hardly separated. However, in studying the movement of clouds above Firmihin and above the Haggeher Mts. during April 2004, other than S or SW winds were not noticed. In this second half of the transitional period, solar radiation intensity generally decreases obviously due to increasing cumulus clouds during afternoon hours. Thus, mean daily temperatures grow more slowly, namely until the beginning of May when in 2004, a mean daily temperature at Firmihin reached 29°C.

The end of the long spring transitional period is unequivocally the warmest season on Socotra. During the second half of the transitional period, maximum values of the relative humidity of air increase exceeding even 95% which indicates the potential occurrence of night dew. It was also noticed during April being however rather weak. In the course of April, precipitation can already occur, either weak originating from extraordinarily developed cumulus clouds of breeze (at the Firmihin station, a total of 5 mm was once measured) or very intensive as the result of sporadically occurring cyclones coming from the Indian Ocean. These cyclones can arrive just only during the transitional periods when predominating winds turn and east winds blow for a short time there. In 1944 at the Mouri station (airport), precipitation amounting to 31.4 mm was recorded in April, however, in 1943 and 1945, no rain occurred in April. At the beginning of May, regular intense south-west circulation sets and a sharp turn occurs in all characteristics and so a summer monsoon begins.

3. MATERIAL AND METHODS

3.1. Data used

A Landsat 7 ETM image (Path/Row 159/051) acquired on 29 April 2001 was used as a main source of RS data for the present study. Spatial resolution of Landsat ETM visible and infra red bands is 30m, a thermal band has 60m resolution.

A Digital Elevation Model (DEM) at 90m spatial resolution coming from Shuttle Radar Topography Mission (SRTM) was employed for extraction of terrain characteristics (altitude, slope) of particular land-cover classes and vegetation zones, for creation of spatial profiles across Socotra and for testing of dependency between the altitude and NDVI (Normalized Difference Vegetation Index). The SRTM DEM data are recently disposable worldwide free of charge (e.g. ftp://e0mss21u.ecs.nasa.gov/srtm/).

A time serie of NDVI images (from March 2003 to April 2004) from the MODIS satellite was used as main information about the seasonal dynamics of the vegetation and was employed in a classification process as a source of ancillary data for rule-based post-classification sorting. The MODIS (Moderate Resolution Imaging Spectroradiometer) vegetation index products are designed to provide consistent, precise and continuous measures of spatial and temporal variations in photosynthetic activity (HUETE et JUSTICE 1999). In this study the product No. MOD13Q1.4 was used. It is a data set of 16-days NDVI composites at 250m resolution, which has been freely available in internet data-pools since the end of 2002 (e.g. http://edcdaac.usgs.gov/modis/dataproducts.asp#mod13). The goal of compositing methodologies is to select the best observation, on a per pixel basis, from all the retained daily data, to represent each pixel over the compositing period. For example, if at least in one day of a cloudy period there is a cloud free record of a particular site, final 16-days composite will use this cloud free data as the best data available from entire 16-days compositing period. The product specification and complex compositing algorithms evaluating numerous aspects of daily data quality are described in MODIS documentation (HUETE et JUSTICE 1999; HUETE et al. 2002; or numerous websites, e.g. http://tbrs.arizona. edu/project/MODIS/index. php).

The MODIS NDVI is robust spectral transformation of two (visible and near infrared) bands designed to enhance the 'vegetation signal' and allow for reliable spatial and temporal inter-comparisons of photosynthetic activity (HUETE et al. 2002). The NDVI most directly represents the absorption of photosinthetically active radiation (PAR) and hence is physiologically a measure of the photosynthetic capacity of various plant canopies and bulk stomatal or canopy resistance to water vapour transfer (SELLERS 1985). Thus, NDVI correlates with both, the status and abundance of the green vegetation cover (EASTMAN 1999). This index gives a wide variety of applications. The most useful (among others) is the measure of seasonal and inter-annual vegetation variation in phenology observations and change detection studies (JUSTICE et al. 1985; DREGNE, et TUCKER 1988; MALO et NICHOLSON 1990; DEBLONDE et CIHLAR 1993; PELKEY et al. 2000).

Thematic vector layers provided by the local SCDP/EPA office (e.g., geology map, vegetation types (MILLER et MORRIS 2000; 2004) location of fishing villages, etc.) were incorporated in the rule-based post-classification sorting (Knowledge Base classification).

A set of 17 Ground Control Points (GCPs) acquired by GPS during the ground truth was used for geometric corrections. More than 250 reference points located by GPS were gathered during the field investigation in August 2002. According to these points two sets of reference fields (the set of training fields and the set of evaluation fields) were digitised.

Number of phytocoenological releves localized by GPS (cca 130) were made by Doc. Buček, Dr. Jelínek and Ing. Habrová (BUČEK in PAVLIŠ 2002; PAVLIŠ et HABROVÁ 2005) during the field survey between 1999 and 2004. The releves were used mainly as a training data for mapping of altitudinal vegetation zones and partly for land-cover mapping.

A set of 90 GPS localized panoramatic digital photographs acquired by researchers from RBGE in 1998 and 2000 (MILLER et MORRIS 2000; 2004) were used for similar purposes especially in areas with lack of other terrain data.

3.2. Geometric corrections

As a first step, all the Landsat ETM image was georeferenced using 17 GCPs. It was not possible to gather more GCPs since on the surface of the island, there are no sharp features as crossroads or bridges (no presence of any pronounced infrastructure both on the island and on the Landsat image) and, therefore, only natural distinct land-shapes as small distinct capes and inlets could be used. Accordingly, almost all GCPs are located on the seacoast around the island while inland points are (unfortunately) missing. Linear polynomial transformation based on 13 control points was used (4 less reliable points were omitted from the calculation) with overall RMS = 0.000186°, which is less than one pixel (30m).

3.3. First level (spectral based) Land-Cover classification

During the exhaustive terrain survey which was performed in the first stage of the Czech Developmental Assistance Project (1999 – 2001) a lists of Groups of Biotopes Types (GBT) and Biotopes Types (BT) encountered on Socotra Island were defined (BUČEK in PAVLIŠ 2002). This system was improved and completed by Habrová during the second stage of the project in 2002-2004 (HABROVÁ 2004; PAVLIŠ et HABROVÁ 2005). This nomenclature was particularly taken into account in the current land-cover classification. Of course, the definition of LC classes had to be adapted so as to be separable from the RS point of view. Therefore, some classes are distinguished on the level of biotope types and others recognise only groups of related biotopes. Nomenclature of the first-level land-cover classification distinguishes 22 classes, after exclusion of 'Clouds' and their shadows and the 'Sea' 19 terrestrial land-cover classes remain (see Tab. 2).

From numerous reference points (about 250 field notes) coming from the ground truth verification made in August 2002, the set of training fields and the set of evaluation fields were digitised. The terrain notes typically included GPS coordinates; altitude; type of biotope; total vegetation cover; names and cover of dominant trees and shrubs; presence of undergrowth or the cover of the soil surface (sand, limestone, grass, etc.); mostly the altitudinal vegetation zone and also documentation photos.

The sets of training and evaluation fields were individual although not completely independent since for most of the reference points a couple of fields was digitised – one training field for the creation of 'spectral signatures' and one evaluation field for consecutive accuracy assessment. Due to the spectral heterogeneity of most of the land-cover classes, caused for example by the influence of a sunlit or shaded aspect of slopes in mountain areas (known as topographic effect), influence of different parent rocks, surface cover, actual moisture of the surface, etc. multiple spectral signatures for particular classes had to be created. The spectral signatures were processed using the Signature Editor of the ERDAS Imagine software, which enables to create individual signature for each training field. The conformity of particular signatures was evaluated and similar signatures were grouped together. In this manner 37 relatively distinct working classes (spectral signatures) were created. These classes were reclassified in final 22 (19) LC classes after the classification process (see table 2 and 3). As a classification method the supervised Maximum Likelihood Classification (MLC) without prior probabilities was used.

A simple accuracy assessment was carried out comparing the land-cover map and reference evaluation fields. A confusion matrix was created and basic accuracy measures as overall accuracy, producer's and user's accuracy (CONGALTON 1991) were computed.

3.4. Knowledge Base classification (second level)

The first level of the land-cover classification is more directly linked with actual spectral characteristics (physical nature) of the surface, while the ecological background of the classes is rather vague. In order to approach the meaning of classes towards the biotope types distinguished by HABROVÁ (2004; PAVLIŠ et HABROVÁ 2005) the ancillary layers and the expert knowledge had to be incorporated in classification process.

Moreover, in the Maximum Likelihood classification also some misclassifications between spectrally similar classes evolved. It was, e.g. the question of Built-up land which was often mistaken as Dwarf shrubland. It is understandable since dwellings are there built from local natural materials as stones or dry wood, which are in fact physically (and so spectrally) identical with surroundings. Another common confusion appeared between classes 'Grassland on limestone plateau' and 'Montane grassland', etc.

With a view to eliminate or at least restrict above mentioned drawbacks and confusions a rule-based post-classification sorting was applied. For the main it is the question of simple version of a Knowledge Base classification, which is understood as an approach correcting wrong classifications of usual classifiers in a two-stage process: first an usual classification is performed, then the second classification integrating expert knowledge and out-image information is performed in order to improve the previous one. The Knowledge Base classification was also the means used for the cloud cover elimination, so that the land cover under the clouds and in their shadow was classified as well.

The ancillary layers employed in the KB classification are as follows:

- A punctual layer of NDVI (spatial resolution 30m) computed from the Landsat ETM red and near infrared bands (NDVI = [NIR – RED] / [NIR + RED]),
- an outline map of altitudinal vegetation zones (see chapter 4.5. and append. No. 8),
- a vector layer of fishing villages provided by local EPA/SCDP office in Haddibo,
- a vectorized geology map (ANON. 1990) provided by local EPA/SCDP office in Haddibo (see appendix No. 6),
- a layer of slopes (resolution 90m) derived from the SRTM DEM (see app. No. 4),
- a layer of manually digitized major wadis,
- set of additional reference points with geographical coordinates measured by GPS including about 130 phytocenological releves (PAVLIŠ 2002; PAVLIŠ et HABROVÁ 2005) and 90 panoramic views from the years 1998 and 2000 provided by RBGE (MILLER et MORRIS 2000; MILLER et MORRIS 2004; see appendix No. 1),
- a layer of manually digitized polygons carrying information about approximate occurrence of certain land-covers based on field knowledge.

Using the ancillary layers and their combinations, it was possible to divide several existing LC classes and even distinguish some new classes, by means of conditional ("IF, THEN, ELSE") and logical ("AND", "OR") statements. Also the distribution of existing classes was refined using the ancillary data. The rules could be established using the field knowledge and ancillary reference data gathered either by our colleagues during the years from 1999 to 2004 or by the author during the last field trip in October 2004:

The punctual layer of NDVI computed from Landsat ETM bands was employed for improved distinction between woodlands and forests. From existing training and evaluation fields the characteristic NDVI values of forests were calculated. It was found, that NDVI value of known forested areas is usually higher than 0,661. Consequently, this value was used as a threshold separating the two land-covers. The forests (mapped by maximum likelihood classification) having lower NDVI value were in the KB classification considered as woodlands and vice versa.

The map of altitudinal vegetation zones was used in order to split several broad classes in number of narrower classes with clearer ecological sense. It is again the question of forests and woodlands, which were undistinguishable in subclasses by purely spectral classification of one-date Landsat ETM image. Nevertheless, from the ecological viewpoint there is a big difference between local deciduous frankincense forests and evergreen montane forests. Since the montane environment is on Socotra represented by the 4^{th} and the 5^{th} altitudinal vegetation zone, the forests within these two zones were in the KB classification labeled as 'Montane forests', while the forests in lower zones were labeled as 'Frankincense forests'. Similarly, the woodlands of lower altitudinal vegetation zones were mapped as 'Frankincense woodlands', while those within the 4^{th} and the 5^{th} zone as 'Montane mosaic' (the label 'Montane woodland' was found as inadequate, since shrubby biotopes are also found there). This subdivision of forests and woodlands does not concern the Dracaena woodlands and forests, which typically occur on limestone plateaus and have distinct spectral signatures. The altitudinal vegetation zones were analogically used for the clear distinction of 'Montane grassland' and 'Submontane grassland and dwarf shrubland' on limestone plateau, which were in simple maximum likelihood classification often confused.

The vector layer of fishing villages was employed as the out-image information for the improvement of built-up land mapping. A simple assumption that major settlements are in the vicinity of either registered fishing villages or major date palm plantations was used. The occurrence of date palm plantations was taken from the previous supervised classification since this class was classified by the maximum likelihood classifier very well. The vicinity was defined in both cases by 500m buffers.

Analogically the confusion between wadi beds and other purely vegetated classes was eliminated using the 30m buffer around the manually digitized major wadis. The final class 'Wadi' in the KB classification was defined by the overlay (intersection) of the result of spectral classification and the 30m buffer.

The new classes 'Basement rocks' and 'Sedimentary rocks' were distinguished combining the layer of slopes derived from the 90m resolution DEM and the vectorized geology map. Only slopes over 50° occurring either on basement or sedimentary parent rock were classified in these two classes.

Other two completely new classes 'Coastal salted desert' and 'Savanna woodland' occurring solely in south-west part of the island were distinguished combining photo-interpretation of the Landsat image and exhaustive field (extra) survey of the area. Both unique classes were undistinguishable by simple maximum likelihood classification.

Similarly, the old class 'Bare soil' was in the KB classification newly divided in the class 'Sand dunes' and 'Sparse dwarf shrubland' by combination of spectral properties and the field knowledge of the area.

Also the occurrence of final classes 'Submontane grassland and dwarf shrubland', 'Submontane shrubland' and 'Dracaena woodland' was refined by means of additional reference points.

Finally the effect of clouds and its shadows was eliminated using well classified pixels neighbouring with the cloudy area; the set of additional reference points and the vector layer carrying information about approximate occurrence of certain land-covers based on field knowledge. By the help of these three data sources and a simple GIS modeling the likely land-cover class was assigned to the each pixel of the cloudy area.

All knowledge base classification was performed using the 'Knowledge Engineer' and the 'Knowledge Classifier' modules of the ERDAS Imagine software.

Overall information about a relation between the first-level land-cover classes and the final land-cover classes gives the table 2. As evident from the table, some classes of the final KB classification have single counterpart in the spectral based classification, some classes arised by splitting or merging of first-level classes and some final classes were even newly distinguished.

<table>
<tr><th>MLC No.</th><th>Maximum likelihood (MLC) land-cover class (1st level)</th><th>Knowledge Base (KB) land-cover class (2nd level)</th><th>KB No.</th></tr>
<tr><td>0</td><td>Clouds</td><td>No counterpart (classified in appropriate classes)</td><td>-</td></tr>
<tr><td>1</td><td>Shadow of clouds</td><td>No counterpart (classified in appropriate classes)</td><td>-</td></tr>
<tr><td>21</td><td>Sea</td><td>Sea</td><td>1</td></tr>
<tr><td>20</td><td>Mangroves</td><td>Mangroves</td><td>2</td></tr>
<tr><td>-</td><td>No counterpart</td><td>Coastal salted desert</td><td>3</td></tr>
<tr><td>19</td><td>Wetlands</td><td>Wetlands</td><td>4</td></tr>
<tr><td>17</td><td>Wadi</td><td>Wadi</td><td>5</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">Bare soil</td><td>Sand dunes</td><td>6</td></tr>
<tr><td rowspan="2">Sparse dwarf shrubland</td><td rowspan="2">7</td></tr>
<tr><td>3</td><td>Dwarf shrubland (on coastal plains)</td></tr>
<tr><td>4</td><td>Low shrubland (on coastal plains)</td><td>Low Croton-Jatropha shrubland</td><td>8</td></tr>
<tr><td>5</td><td>High shrubland</td><td>High shrubland with succulents</td><td>9</td></tr>
<tr><td rowspan="2">6</td><td rowspan="2">Woodland</td><td>Frankincense woodland</td><td>10</td></tr>
<tr><td>Montane mozaic</td><td>17</td></tr>
<tr><td rowspan="2">10</td><td rowspan="2">Forest</td><td>Frankincense forest</td><td>11</td></tr>
<tr><td>Montane forest</td><td>18</td></tr>
<tr><td>8</td><td>Dracaena woodland</td><td rowspan="2">Dracaena woodland</td><td rowspan="2">12</td></tr>
<tr><td rowspan="2">7</td><td rowspan="2">Potential dracaena woodland</td></tr>
<tr><td>Submontane shrubland</td><td>15</td></tr>
<tr><td>9</td><td>Dracaena forest</td><td>Dracaena forest</td><td>13</td></tr>
<tr><td rowspan="2">11</td><td rowspan="2">Transition between Low coastal shrubland and Grassland on limestone Plateau</td><td>Low Croton-Jatropha shrubland</td><td>8</td></tr>
<tr><td rowspan="2">Submontane grassland and dwarf shrubland</td><td rowspan="2">14</td></tr>
<tr><td>12</td><td>Grassland on limestone plateau</td></tr>
<tr><td>13</td><td>Grassland with shrubs on lim. plateau</td><td rowspan="2">Submontane shrubland</td><td rowspan="2">15</td></tr>
<tr><td>14</td><td>Dense shrubland on limestone plateau</td></tr>
<tr><td>15</td><td>Montane grassland</td><td>Montane grassland</td><td>16</td></tr>
<tr><td>-</td><td>No counterpart</td><td>Sedimentary rocks</td><td>19</td></tr>
<tr><td>-</td><td>No counterpart</td><td>Basement rocks</td><td>20</td></tr>
<tr><td>16</td><td>Date palm plantations</td><td>Date palm plantations</td><td>21</td></tr>
<tr><td>18</td><td>Urban</td><td>Urban</td><td>22</td></tr>
<tr><td>-</td><td>No counterpart</td><td>Savanna woodland</td><td>23</td></tr>
</table>

Tab. 2: Relation between classes of the first level (spectral) classification and the final Knowledge Base classification.

For the purpose of the map output, the result of the KB classification was generalized by modal majority filtering using the 5x5 pixel moving window. Besides the generalization, the filtering has secondary major effect that is a slight improvement of map accuracy caused by incorporation of contextual information. As the Landsat Thematic Mapper system deliver medium resolution products in which the pixel size is usually smaller than general extent of mapped landscape objects, the image exhibit a high degree of spatial autocorrelation (STUCKENS et al. 2000). In other words, the knowledge that a pixel belongs to a certain class increases the probability that its neighbouring pixels belong to the same class. As mentioned above, this assumption is correct only when the pixel size is smaller than the mapped landscape feature. For that reason, the narrow discrete and line-shaped classes as 'Wadis", 'Date palm plantations', 'Wetlands' and 'Mangroves' were excluded from the generalization process.

Particular land-cover classes were described using the data resulting from several GIS overlays. The description includes spatial distribution and total area of the class, its topography characteristics, proportion of characteristic bedrocks, usual altitudinal vegetation zone of occurrence, etc. Typical species composition of the tree layer and the shrub layer of particular class was described using results of field survey of BUČEK (in PAVLIŠ 2002) and HABROVÁ (2004; PAVLIŠ et HABROVÁ 2005). Several notes about the herb layer are based on published account of POPOV (1957). For the occurrence description, an orographical division of the island according to CULEK (in PAVLIŠ et HABROVÁ 2005) was used (see appendix No. 5).

Resulting classes were additionally labeled according to FAO Land Cover Classification System (DI GREGORIO et JANSEN 1998; DI GREGORIO 2004). This recent unifying international nomenclature standard enables to compare the land-cover and vegetation features of Socotra with other world biodiversity hot spots and/or with adjacent mainlands.

Independent accuracy assessment of the final map was not performed, since the evaluation fields and all additional reference points were used for building of the knowledge base.

In the end, simple comparisons with current and historical vegetation maps were carried out.

3.5. Phenological observations using MODIS NDVI time series

First of all, the MODIS 16-days NDVI composites were downloaded from the Internet data-pool. The data are provided in a specific .HDF format in operational spatial units (called tiles or granules) 1200 km x 1200 km using the integerized sinusoidal equal area grid. The tiles from the appropriate period were imported in the IDRISI software format 'rst'. Since the global coordinates were lost during the import operation, the coordinates of tile corners had to be re-set up manually. Then, the subsets of Socotra from the tiles were created. In order to be able to superimpose MODIS NDVI data to other data layers, the coordinate system had to be changed from the Sinusoidal to WGS 84. Since IDRISI does not have defined the Sinusoidal coordinate system, the data were exported to ArcInfo, where the operation was performed. Finally the 'ready to use' data were re-imported in IDRISI software, where the phenological analyses were carried out.

Previous to the proper analyses the quality of used MODIS NDVI images was evaluated using appropriate 'quality flags', which are included in the MOD13Q1.4 data set. It was necessary especially to detect and locate clouds and aerosol in particular NDVI images and compute the percentage of the cloud cover within those images. Essentially, the 'quality flag' is an additional layer supporting information about the quality and reliability of the NDVI value of each pixel. The quality flag decimal number is supporting information relative to 10 different parameters including compositing method, presence of shadow, snow/ice, land/water, mixed clouds, atmosphere corrections, aerosol quantity, general usefulness and quality, etc. However, it is central to the concept of per pixel MODIS quality data that these numbers not be seen as decimal, rather in their basic binary format (bits of 0s and 1s). The MODIS VI algorithm, when dealing with quality data, operates in that fashion: Due to the binary (yes/no) nature of the actual quality component, for example clouds could either be present or not, it was decided that a binary numbering system be adopted to hold this information. Due to the simple nature of this quality information, it was further decided that one integer number (16 bit long) could actually hold several quality information (type of yes/no or small discrete numbers), and subsequently MODIS quality value, being unsigned integer 16 bits long, hold several smaller quality fields or components (HUETE et al. 2002). Whence it follows that in order to be able to read the information coded in decimal numbers, they had to be converted to binary format. Resulting 16 bit long binary numbers were split in appropriate parts referring about particular quality parameters. The quality flag methodology is described in some detail for example in MODIS User Guide (HUETE et JUSTICE 1999).

In view of the fact that the clouds and aerosols cause heavy noise and significantly decrease the NDVI values, the set of cloud free (or very little affected) images was selected using the decoded quality flags. The set of cloud free images was selected throughout the entire annual period representing more or less evenly all year seasons. It is the question of following images: 13.III.2003; 30.IV.2003; 3.VII.2003; 19.VII.2003; 7.X.2003; 23.X.2003; 8.XI.2003; 24.I.2004; 13.IV.2004. The names of images represent the 'mean date' of the 16-days NDVI composite period (e.g. the image called '13.III.2003' represents NDVI composite from 6 March 2003 to 21 March 2003). This cloud-free subset was consequently used in Time Series Analyses (TSA), which was carried out in IDRISI image processing software.

The TSA (based on Principal Component Analyses - PCA) is used for the analysis of long time series of image data. The output from TSA includes both temporal and spatial patterns, which should be interpreted together. The spatial output consists of a set of standardized Principal Component (PC) images, indicating the spatial patterns of major elements of variability over the series. The temporal output consists of a set of loadings graphs. Loadings graphs are produced for each component and, in this context, show the correlation (Y axis) between that component image and each of the original images (X axis – see chapter 4.7., Fig. 92) (EASTMAN 1999). Resulting principal components were tested for dependency on independent environmental variables (e.g. altitude) using the DEM and a REGRESS module of the IDRISI software. Original 90m spatial resolution of the DEM was for this purpose degraded at 250m in order to be comparable with resolution of MODIS NDVI images along image processing.

As a second analysis 10 profiles over space across Socotra were made, using various spatial data sets as DEM (image of altitude), the first and the second principal component resulting from the time series analyses, and selected temporal NDVI images. The profiles over space show values along a transect across an image in graph form (distance is on X axis and values of appropriate pixels of the images are on Y axis).

Finally a profile over time for selected sites was carried out. The profile over time shows summary statistics of pixel values (in this study a Mean statistics was used) at sites defined by a mask (Y axis), summarized and graphed simultaneously over a sequence of images (X axis). In this analysis the whole time serie of NDVI images was used. The profile was made for Socotra as whole and separately for North and South 'halves' of the island, which were delimited by means of the 2nd principal component of TSA. Consequently the profiles were created for major vegetation types. Appropriate sample plots for vegetation types were digitalized by the help of digital Land-cover map and after converted in Idrisi mask image. Several dates of NDVI images were especially on the south half of the island heavily affected by cloud cover. It is in particular the question of images from 4.VIII.2003; 20.VIII.2003 and 21.IX.2003. The NDVI values were in those cases interpolated from adjacent (precedent and following) cloud free or less biased images.

3.6. Outline mapping of Altitudinal Vegetation Zones (AVZ)

Altitudinal Vegetation Zones (vegetation tiers), in general, express the connection of the sequence of differences in vegetation with the sequence of differences in altitudinal and exposure climate (ZLATNÍK 1956). In the years from 1999 to 2003 five Altitudinal Vegetation Zones (AVZ) were distinguished and described in the field by Buček and Habrová (PAVLIŠ 2002; PAVLIŠ et HABROVÁ 2005). Their distribution over Socotra, however, has never been mapped and a total area of altitudinal vegetation zones has never been assessed nor estimated. It was done only combining the field data and the multitemporal remotely sensed data.

More than 320 GPS localized points with known actual altitudinal vegetation zone (phytocoenological releves, field notes, directional or panoramic photos) were used as reference (field) information. The time serie of 16-days NDVI composites from the MODIS satellite (from March 2003 to April 2004) served as information about general abundance of the green vegetation cover and its seasonal variations all over the island. Since the general abundance of the green vegetation on Socotra is strongly dependent on altitude (more precisely on climate variations caused by altitude), the serie of NDVI images might be successfully used for the outline mapping of AVZ by means of image processing.

As in the case of phytophenological Time Series Analysis (TSA), the subset of cloud free images was selected throughout the annual period representing more or less evenly all year seasons. The subset is identical with the subset used for the TSA (see chapter 3.5.). Those nine NDVI images were stacked in one image having nine bands. This image was consequently classified using standard per-pixel supervised classification with 'maximum likelihood' decision rule. The training fields were digitised in vicinity of reference points with known AVZ. Since there are remarkable variations in dynamics of vegetation cover of highlands (caused by monsoon effect), the consequent variations of brightness values within one AVZ had to be represented by multiple 'spectral signatures'. It refers particularly to the 2^{nd} and the 3^{rd} AVZ, where five signatures for the 3^{rd} and even eleven signatures for the 2^{nd} AVZ had to be created. The output resulting from the classification was reclassified in five classes, each representing one AVZ. The final map was smoothed by median modal filter using mowing window 3x3 pixels. This focal filtering operation helped to remove noisy pixels (eliminate 'salt and pepper effect'), while the zonal character of classes was highlighted. Finally total areas of particular AVZ's were calculated.

A simple accuracy assessment was carried out comparing the final map of altitudinal vegetation zones and original reference points. Similarly as for the first-level landcover map the confusion matrix was created and basic accuracy measures were computed.

3.7. GIS multi-layer analyses – extraction of contextual data for ecological synthesis

In order to assess a relation between various data layers several GIS overlays were carried out. Information classes of appropriate layers were cross-tabulated and the proportions of particular classes of the 1^{st} layer within each class of the 2^{nd} layer were calculated.

In this manner the digital map of land-cover was compared with the map of altitudinal vegetation zones, geology map and a map of monsoon impact on seasonal vegetation dynamics. In order to make a linkage between the new land-cover map and currently used simple map of general vegetation types (MILLER et MORRIS 2000; 2004) both layers were cross-tabulated as well. Similarly the relations between altitudinal vegetation zones and other layers (geology, monsoon impact and Miller's vegetation map) were evaluated.

In order to describe the terrain conditions of particular land-cover classes and altitudinal vegetation zones the DEM was employed. From the DEM the layers of altitude and slopes were generated. Combining the digital map of altitudinal vegetation zones and land-cover with the layers of slope and altitude the statistics as a mean slope and mean altitude were calculated for particular land-cover classes and AVZ's. It was realized using the zonal statistics function of the IDRISI software. With a view to describe also a distribution of various altitudes and slopes within particular AVZ's and land-cover units the appropriate layers were overlayed and cross-tabulated. The layer of altitude was previously classified in 15 classes (each class representing 100m range of altitude). The layer of slopes was classified in 6 slope classes defined as follows: 0-3°; 4-10°; 11-20°; 21-30°; 31-50°; over 50°. The slope ranges were defined using the natural breaks of data distribution (slightly modified). Results of the cross-tabulation are presented in sets of synoptic bar charts. Analogical operation was carried-out also for the two general zones of monsoon impact and for entire Socotra.

4. RESULTS AND DISCUSSION

4.1. First level of the land-cover classification

The purely spectral classification, which can be considered as an intermediate stage between raw radiometric data and final land land-cover map, has recognised following 22 classes:

0. Clouds
1. Shadow of clouds
2. BS - Bare Soil (mostly sand and sand dunes)
3. S3 – Dwarf Shrubland on coastal plains (dominance of *Lycium socotranum*)
4. S2 – Low Shrubland on coastal plains (dominant *Croton socotranus* with *Jatropha unicostata*)
5. S1 – High Shrubland (*Jatropha unicostata, Croton spp., Adenium obesum, Euphorbia arbuscula*, etc.)
6. W - Woodland (*Boswellia spp., Commiphora spp., Sterculia africana*, etc.)
7. DW1 – possible occurrence of the Dracaena (*Dracaena cinnabari*) woodland
8. DW2 – Dracaena woodland (*Dracaena cinnabari*)
9. DF – Dracaena forest (*Dracaena cinnabari*)
10. F - Forest (montane forest with dominance of *Euclea balfourii, Euphorbia socotrana* and *Dracaena cinnabari*)
11. S2/G – Transitional class between S2 and G on low undulating hills (often with *Croton socotranus* and *Commiphora socotrana*)
12. G1 - Grassland on limestone plateau
13. G2 - Grassland on limestone plateau with sparse cover of shrubs (*Croton socotranus, Buxanthus pedicellatus*)
14. Sd - Dense shrubland on limestone plateau (higher elevation - *Croton socotranus, Buxanthus pedicellatus* ocassionally *Dracaena cinnabari*)
15. Gm – Mountain Grassland
16. DP – Date Plantations
17. Wadi – wide (distinct) beds of periodical watercourses
18. U – built-up area ('Urban')
19. Wt – Wetland (Lagoons)
20. Mang – Mangroves (*Avicennia marina*)
21. Sea

The 19 terrestrial land-cover classes are from 2 to 20, numbers correspond also to those listed in the table 2, chapter 3.4 and the table3.

In this stage it was possible yet to carry out a simple accuracy assessment of the classification. It was provided via confusion (error) matrix. The confusion matrix gives basic information about the reliability of the classification (see table 3.). As one can see, overall classification accuracy was more than 80%. User's and producer's accuracies of particular classes are listed in the table as well.

Evaluating the correctness of mapping of particular classes by means of the above mentioned accuracy indicators we can find some indispensable misclassifications. The misclassifications evolved particularly between spectrally similar classes. It was, e.g. the question of Built-up land which was often mistaken as Bare soil or Dwarf shrubland. It is understandable since dwellings are there built from local natural materials as stones or dry wood which are in fact physically (and so spectrally) identical with surroundings.

		Refference data																			Classif.	
	Class	2. BS	3. S3	4. S2	5. S1	6. W	7. DW1	8. DW2	9. DF	10. F	11.S2/G	12. G1	13. G2	14. G3	15. Gm	16. DP	17.Wadi	18. U	19. Wt	20. Mang.	**Total**	***User's acc.***
Classification data	2. BS	**3259**	69	42	1	0	0	0	0	0	0	1	0	0	0	0	15	0	0	1	**3388**	***96.2%***
	3. S3	195	**3116**	1489	6	0	0	0	0	0	0	118	0	0	0	13	128	27	4	0	**5096**	***61.1%***
	4. S2	16	891	**10668**	152	2	0	0	0	0	10	121	0	0	3	6	151	4	2	0	**12026**	***88.7%***
	5. S1	1	2	830	**8210**	188	101	4	0	2	9	272	31	2	44	11	107	0	0	0	**9814**	***83.7%***
	6. W	0	0	1	668	**2266**	123	53	0	39	0	69	10	16	280	8	3	0	0	0	**3536**	***64.1%***
	7. DW1	0	0	0	200	45	**383**	32	0	0	0	7	1	1	3	3	0	0	0	0	**675**	***56.7%***
	8. DW2	0	0	0	0	0	0	**92**	15	0	0	2	5	0	0	0	0	0	0	0	**114**	***80.7%***
	9. DF	0	0	0	0	0	0	12	**177**	0	0	0	0	0	0	0	0	0	0	0	**189**	***93.7%***
	10. F	0	0	0	1	149	0	0	0	**1282**	0	0	0	0	0	0	0	0	0	0	**1432**	***89.5%***
	11. S2/G	0	0	15	9	0	0	0	0	0	**581**	232	0	0	0	0	1	0	0	1	**839**	***69.2%***
	12. G1	0	14	44	513	5	3	28	0	0	15	**2095**	180	125	341	4	5	0	0	0	**3372**	***62.1%***
	13. G2	0	0	0	0	0	0	0	0	0	0	0	**235**	0	0	0	0	0	0	0	**235**	***100.0%***
	14. Sd	0	0	0	272	3	4	6	0	0	0	96	35	**395**	124	0	3	0	0	0	**938**	***42.1%***
	15. Gm	0	0	0	0	0	0	0	0	0	0	0	0	0	**993**	0	0	0	0	0	**993**	***100.0%***
	16. DP	0	4	12	15	15	12	2	0	1	0	0	0	0	5	**534**	23	0	10	0	**633**	***84.4%***
	17.Wadi	7	6	27	0	0	0	0	0	0	0	0	0	0	0	10	**3011**	0	0	0	**3061**	***98.4%***
	18. U	25	18	41	4	0	0	0	0	0	0	0	0	0	0	3	5	**460**	0	0	**556**	***82.7%***
	19. Wt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	**1242**	0	**1245**	***99.8%***
	20. Mang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**162**	**162**	***100.0%***
Refer.Total		**3503**	**4120**	**13169**	**10051**	**2673**	**626**	**229**	**192**	**1324**	**615**	**3013**	**497**	**539**	**1793**	**595**	**3452**	**491**	**1258**	**164**	**48304**	
Prod..accur.		***93.0%***	***75.6%***	***81.0%***	***81.7%***	***84.8%***	***61.2%***	***40.2%***	***92.2%***	***96.8%***	***94.5%***	***69.5%***	***47.3%***	***73.3%***	***55.4%***	***89.7%***	***87.2%***	***93.7%***	***98.7%***	***98.8%***	**Overall ac. 81.1%**	

Tab. 3: Confusion matrix for the first level (spectral based) land-cover classification.

Another example gives the confusion between classes S2 (Low shrubland) and S3 (Dwarf shrubland) where especially sparse S2 was in places misclassified as the class S3. Consequently, the area of S3 may be overestimated and S2 underestimated. Similarly, dense 'High shrubland' (S1) was sometimes classified as 'Woodland' (W) and subsequently the area of the class W might be overestimated (see table 3). Since in both cases, it is often the question of continuous transitions between those classes the confusion is to a certain extent natural and inevitable.

Another remarkable confusion occurred between the class Wadi and other sparsely vegetated classes as Bare soil, Dwarf shrubland or Low shrubland. These confusions should be restricted using the Knowledge Base approach.

The last (commented) indispensable occurrence of misclassifications was between classes S2/G and G1. Nevertheless, these two classes belong to the same general group of biotopes types: G. – Pastures (HABROVÁ 2004). Moreover, in the final classification both classes will be largely merged together forming the class 'Submontane grassland and dwarf shrubland'. Thus, the results can be still considered as fair.

4.2. Final land-cover based on Knowledge Base classification

Using the expert system (knowledge base) described in the chapter 3.4. the final landcover map has been created. Since all existing training and evaluation fields as well as all additional reference points were used for the classification, an independent accuracy assessment could not be performed. As reported by many authors (e.g. KONTOES et ROKOS 1996; ALLAN 2001; KRÁL 2003), the accuracy of two-stage knowledge base classification is usually higher than the accuracy of the input classification, if keeping the number of mapped classes. May be even more important is the fact, that possible misclassifications of the KB system are more acceptable for final user than confusions of common, purely spectral classification approach. On the other hand, in this work the knowledge base was employed both for correction of mistakes of common classifier, and for the distinction of new land cover classes. Accordingly, an approximate overall accuracy does not need be necessarily higher than the accuracy of the input (spectral) classification. As a consequence, final accuracy can be estimated to be similar to the first-level classification, which is about 80%.

For final map-output purposes the resulting digital map was filtered by a moving window. With moving windows, contextual information is extracted from the pixels immediate neighbourhood by imposing a search window, computing a contextual parameter within that window, and assigning that value to the original picture. While a 3x3 pixel kernel is probably the most widely applied window size, larger windows are appropriate for small pixel sizes and/or large land cover entities (STUCKENS et al. 2000). In this case, the 5x5 pixel window was employed with exclusion of narrow discrete and line-shaped classes from the filtering. In this manner wider surroundings were considered extracting contextual information, while the detail resolution of marginal narrow classes (e.g. Date palm plantations, Wadis, Mangroves, Wetlands) was not lost.

Postclassification context integration generally involves filtering with a majority filter, whereby each pixel is recorded to the majority class of a neighbourhood defined by the filter (STUCKENS et al. 2000). This approach was applied also in this case. Not only does this operation reduce the “salt-and-pepper” effect typical for per-pixel classifiers, it also results in lager classification units that might adhere more to the human perception of land cover. However, final classification accuracies do not necessarily improve dramatically. THUNNISSEN et al. (1992), for example, report an improvement of only 2% compared to a pure per-pixel classifier.

The main output of this work is thus the first detailed Land-cover map of Socotra Island distinguishing 22 terrestrial land-cover (mostly vegetation) classes (see also appendix No. 2):

(1) Sea
(2) Mangroves
(3) Coastal salted desert
(4) Wetlands
(5) Wadi
(6) Sand dunes
(7) Sparse dwarf shrubland
(8) Low Croton-Jatropha shrubland
(9) High shrubland with suculents
(10) Frankincense woodland
(11) Frankincense forest
(12) Dracaena woodland

(13) Dracaena forest
(14) Submontane grassland and dwarf shrubland
(15) Submontane shrubland
(16) Montane grassland
(17) Montane mosaic
(18) Montane forest
(19) Sedimentary rocks
(20) Basement rocks
(21) Date palm plantations
(22) Urban
(23) Savanna woodland

Their description and especially the species composition is based on field work made within years 1999-2004 by Czech Research team aimed in the Developmental Assistance Project (PAVLIŠ 2002; PAVLIŠ et HABROVÁ 2005) and multilayer GIS analyses. The information on the extend and the distribution of the land-cover (vegetation) classes on Socotra referable to the KB classification may be summarized as follows:

(2) 'Mangroves' (mangrove forests) occur as local narrow betls at three points along the coasts of Socotra. The best examples of mangroves dominated by *Avicennia marina* are found along the coast at Neet and in Bandar Shu'ub, further major occurrence is reportedly at Qow'har (MILLER et MORRIS 2004), although the latter case was not distinguished from the Landsat image. A small single patch of mangroves (cca 20x20m) was recorded also on Qa'arah coast (coordinates measured by GPS are 12° 18, 554' N and 53° 48,168' E). Mangroves are believed to exist to a limited extend in other parts of the island in the past, for example in coastal lagoon near Ghubbach in Had'ale plain on the northern coast (dead residuals of *Avicennia marina* are still evident there), and possibly elsewhere. At present, mangroves grow on estimated area 177ha (see also the table 6).

Fig. 5: Mangrove forest.

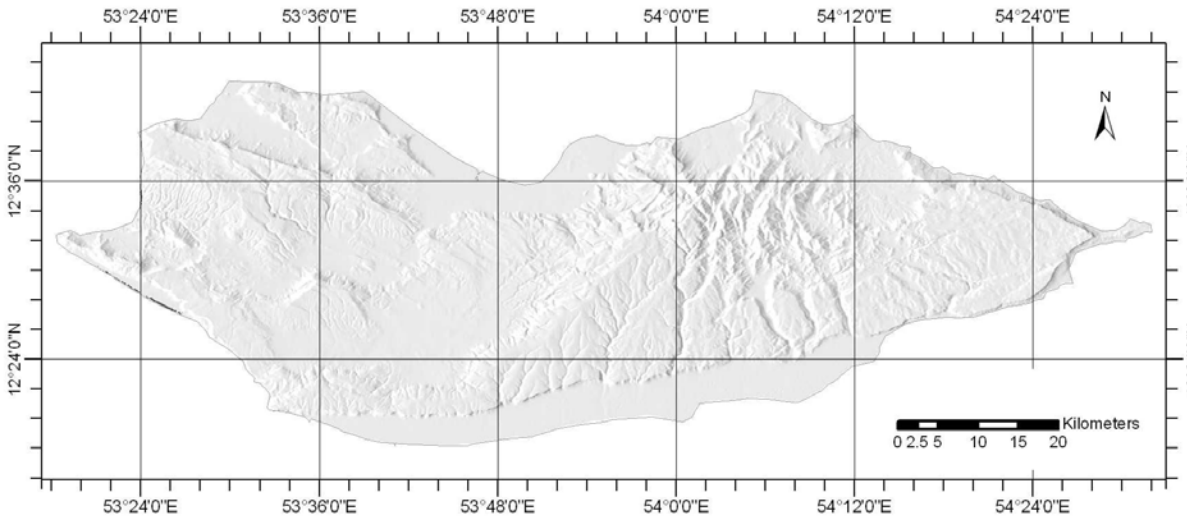


Fig. 6: Spatial distribution of 'Mangroves' on Socotra

Although this mangrove vegetation is not unique to Socotra, it is a vulnerable vegetation type that supports a rich endemic fauna and is also an important breeding ground for various animal species (MILLER et MORRIS 2004).

The figure 7 does not reveal some unexpected findings, nevertheless, it is suitable for presentation of possible inaccuracies caused by uneven spatial resolution of land-cover map (30m) and DEM used (90m). One can observe that mangroves, according to GIS overlay, encroaches also higher slope classes, although it is evident that in reality may occur only in the first slope class.

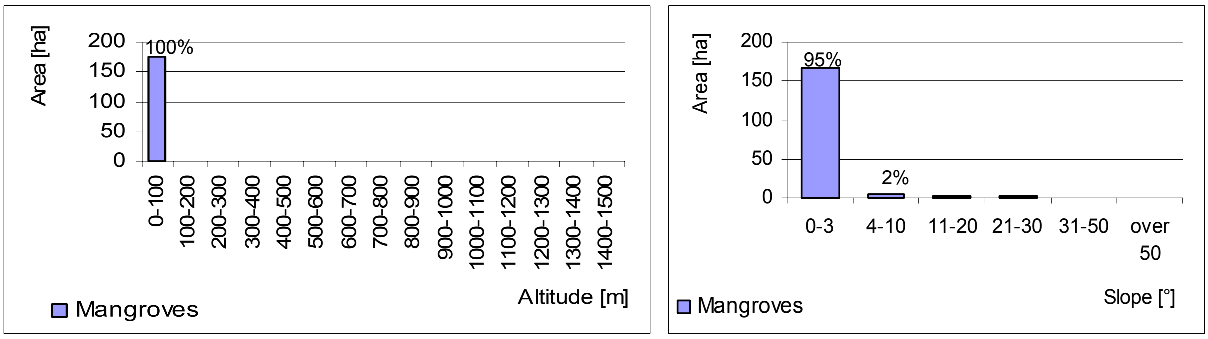


Fig. 7: Distribution of altitudes and slopes within the land-cover class 'Mangroves'

This land-cover class can be directly ascribed to biotope type F.2. – Mangrove forest (*akrhom*) described by HABROVÁ (2004).

In the LCCS world's classification system it could have a label: Semi-Evergreen Medium High Forest On Temporarily Flooded Land; Major Landclass: Level Land, Plain, Slopeclass: Flat to Almost Flat; Water Quality: Saline; Floristic Aspect: Mangroves (*Avicenia marinna*). LCC level: A3A12B2C2D1E1F1-B6E3-L11L5R3Zt20.

(3) 'Coastal salted desert' as a unique land-cover class occurs on larger areas (cca 240 ha) solely at Neet (behind the narrow belt of mangroves). Limited (punctual) examples are found also on the northern coast. The flat area of salt costal marshes, almost without vegetation, is affected by periodical tidal flooding.

Fig. 8: Coastal salted desert.

Figure 8 shows that these areas are locally used for marine salt extraction.

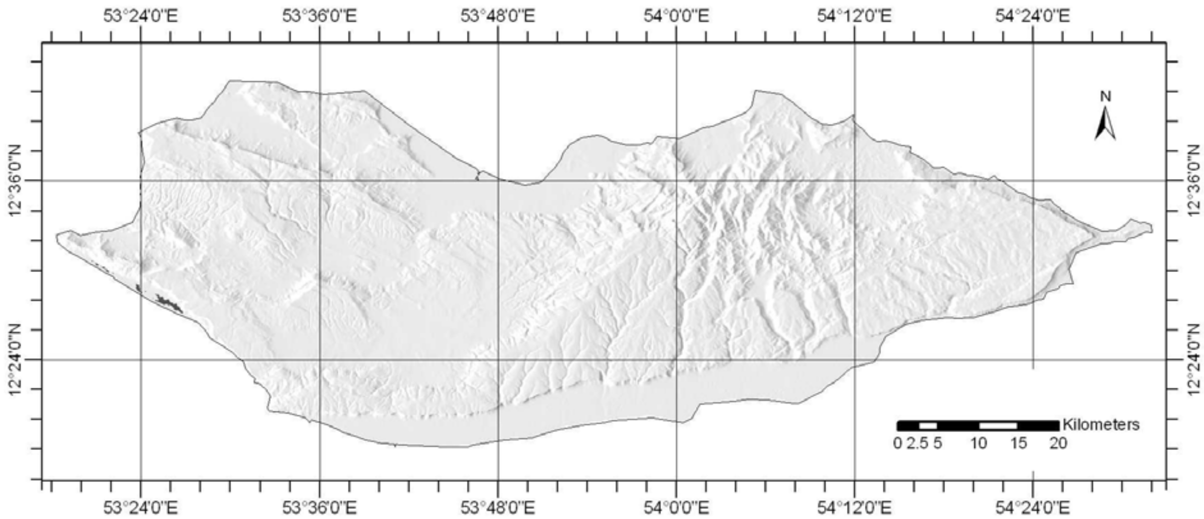
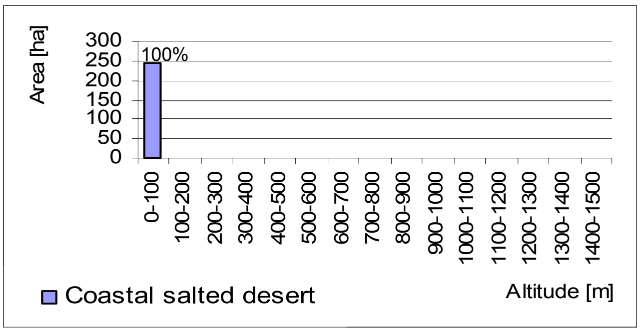


Fig. 9: Spatial distribution of 'Coastal salted desert' on Socotra.

The biotope type DS.2. – Salted desert (*milho*) (HABROVÁ 2004) can be directly ascribed to this land-cover class. In the LCCS it has a label: Tidal Area (Standing); Surface Aspect: Sand); Altitude: < 50 - 300 m; Salinity: Brine. LCC level: A1B3-A5B6-P1V5.



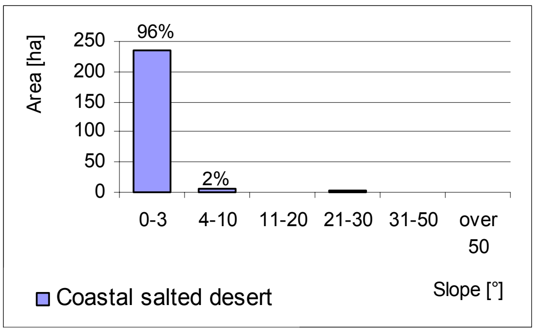


Fig. 10: Distribution of altitudes and slopes within the land-cover class 'Coastal salted desert'.

(4) '<u>Wetlands</u>' occur particularly on the northern coast mainly in estuaries of north running wadis as small fresh or brackish lagoons separated from the sea by spits and bars. The largest lagoon is found near Qalansiyah on northwest part of Socotra. A number of small sized wetlands lie along the north coast in Had'ale plain, Hadiboh plain, Kariid'e (Lhasi) basin etc.,

one small is found also in Bandar Shu'ub (see figure 12). The total area of this land-cover class is about 390ha (main part forms Qalansiyah lagoon). In past they were in some cases vegetated by mangroves (e.g. the lagoon in Had'ale plain).

Fig. 11: Wetlands.

The fact that wetlands occur solely around the seacoast is evident also from the figure 13 and from topography statistics in the table 5. Of course, the area of lagoons itself is completely flat, nevertheless some gentle slopes (4-10°) may occur in the surroundings (e.g. lagoon in the Lhasi basin).

The semi-aquatic community, dominated by *Juncus arabicus*, forms along most estuaries, as well as along some of the stagnant pools and springs in the interior (POPOV 1957).

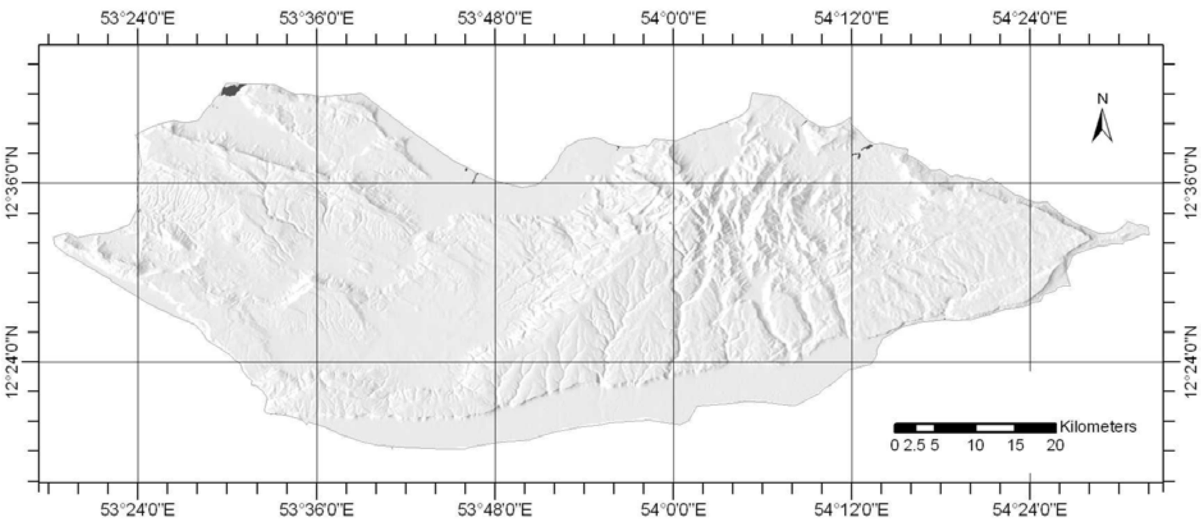


Fig. 12: Spatial distribution of 'Wetlands' on Socotra.

Lower beds of wetlands are naturally formed by quaternary sediments (see figure 75). The biotope type Wt. - Coastal logoons (*choor*) (HABROVÁ 2004) can be safely attributed to this land-cover class. The LCCS label of this land-cover class would be: Tidal Area (Standing); (Surface Aspect: Sand); LCC level: A1B3-A5B6.

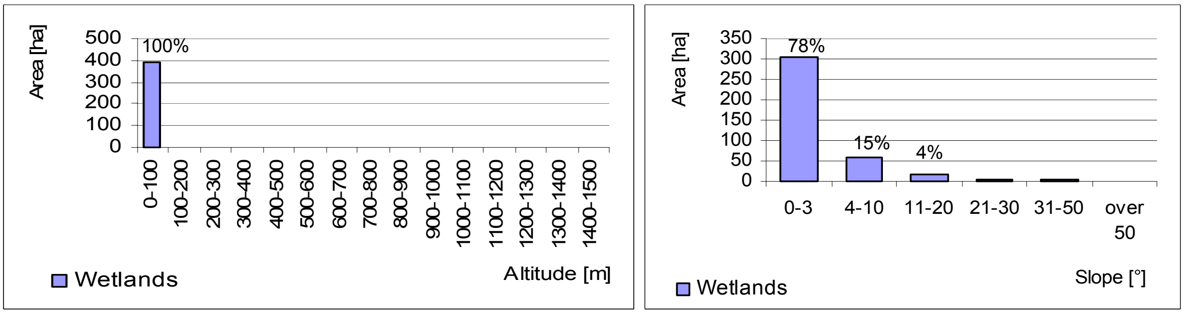


Fig. 13: Distribution of altitudes and slopes within the land-cover class 'Wetlands'.

In the land-cover class (5) '<u>Wadi</u>' only wide distinct riverbeds of sporadic watercourses are depicted. Due to the resolution of input Landsat data only beds more than 30(20)m in width could be distinguished. As shows the picture 15, the wadis are near the coast mostly choked by sediments so no distinct streams cross the plains, although they do flow to the sea when in flood. These streams carry water only during and for a short time after rains; only in river estuaries on the northern coast water retains for a grater part of the year or all the year round (see 'Wetlands'). There are also several permanent streams in the Haggeher mountains. Some of them provide a water supply for urban inhabitants in Hadiboh.

Fig. 14: Wadi.

Figure 15 shows that most of the wadis originate in central Haggeher Mts., although there are several distinct streams also in the western part of the island (e.g. in the Zahr basin,

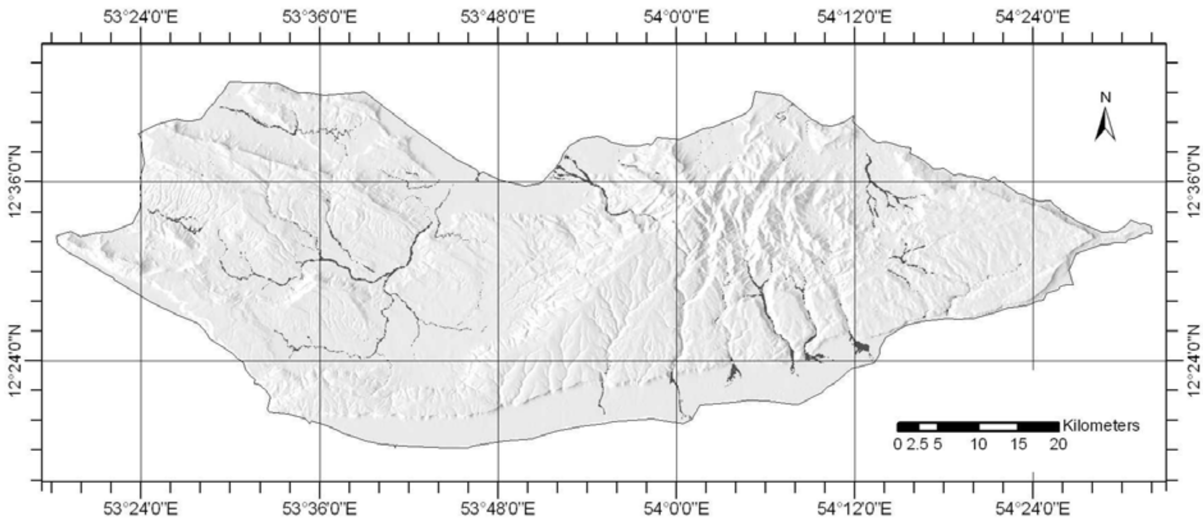


Fig. 15: Spatial distribution of 'Wadis' on Socotra.

Djaahel plain and in Shu'ub. In the east it is for example the wadi in the Lhasi basin flowing north and wadi Matiaph flowing south from the Momi plateau. Moreover, from the figure 15 it looks like a majority of streams originating in the Haggeher montains are running south splitting the limestone plateau. In a matter of fact the streams flowing north are on coastal plains greatly vegetated by Date palms (e.g. Hadiboh plain) and therefore they do not appear in this class. The total area of sporadic riverbeds on Socotra, as mapped using the Landsat ETM image, is about 4 700ha.

As in the previous cases, the topography conditions may be evaluated (Fig. 16) overlaying the wadi beds with the hypsography map (appendix No. 3) and the map of slopes (appendix No. 4). Not surprisingly, most of the wide distinct wadis lie in flat lowlands (altitude until 100m a.s.l. and slope 0-3°), although they occur even at altitude 300m a.s.l. and on slopes exceeding 10°. In higher elevations and on steeper slopes the wadis are probably too narrow to be mapped by means of Landsat ETM data. The mean slope of this LC class is approximately 4° (see table 5).

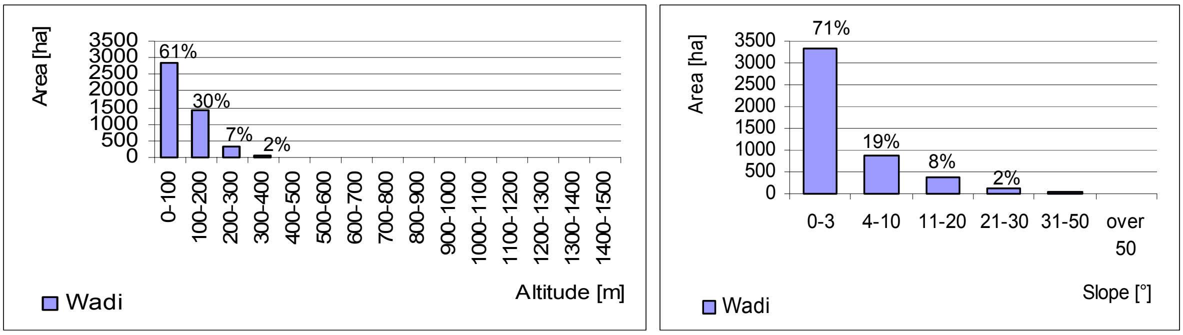


Fig. 16: Distribution of altitudes and slopes within the land-cover class 'Wadis'.

The surface of the streams is formed by diverse boulders, debris and gravel usually without any vegetation cover. Only the stream with the water at or near the surface are lined with groves of *Ficus salicifolia* (POPOV 1957), the drier, sandy stretches of main watercourses, where surface water is absent most of the year, are characterized by *Zizyphus spina-christi*, and such shrubs as *Buxus hildebrandtii*, *Croton socotranus*, *Cissus subaphylla* and *Acridocarpus socotranus* (POPOV 1957; HABROVÁ 2004). More biotope types of HABROVÁ (2004) may be attributed to this land-cover class. For the main it is the question of Wa. – River valleys (*ed'hajo*); formations of *Ficus salicifolia* can be ascribed to the biotope S.1.2. - Ficus shrubland and those of *Zizyphus spina-christi* to W.5. – Riverine woodland.

In the LCCS classification system it is labelled as: Non-Perennial Natural Waterbodies (Flowing); the LCC Level: A1B2-A4.

(6) '<u>Sand dunes</u>' are present over relatively large areas along the coast of Socotra, particularly on Noged plain, however they occur to a limited extend also on the northern coast for example at Ras Howlef and at the north-eastern edge of Momi plateau (see figure 18). Total area of 'Sand dunes' is approximately 6 600ha that is almost 2% of total area of the island.

One can observe in the figure 19 that sand dunes occur (besides the flat coastal lowlands) also on steeper slopes up to approximately 200m a.s.l. (the occurrence above 200m a.s.l. as indicated in Fig. 19 is probably result of an mis-overlap of GIS layers). It is just the question of the north-eastern edge of Momi plateau, where the sand dunes occupy considerable sharp incline (see appendix No. 12, Fig. 1).

Fig. 17: Sand dunes.

On the southern coastal plain of Noged many of the dunes are completely devoid of vegetation, while others often support a thin growth of plants (see Fig. 17). Along the northern coast, at Ras Howlef *Acacia edgeworthii* forms a thin growth, while on the southern coast *Tamarix nilotica* predominates and other species such as *Limonium socotranum*, *Indigofera spinuflora*, etc. occur.

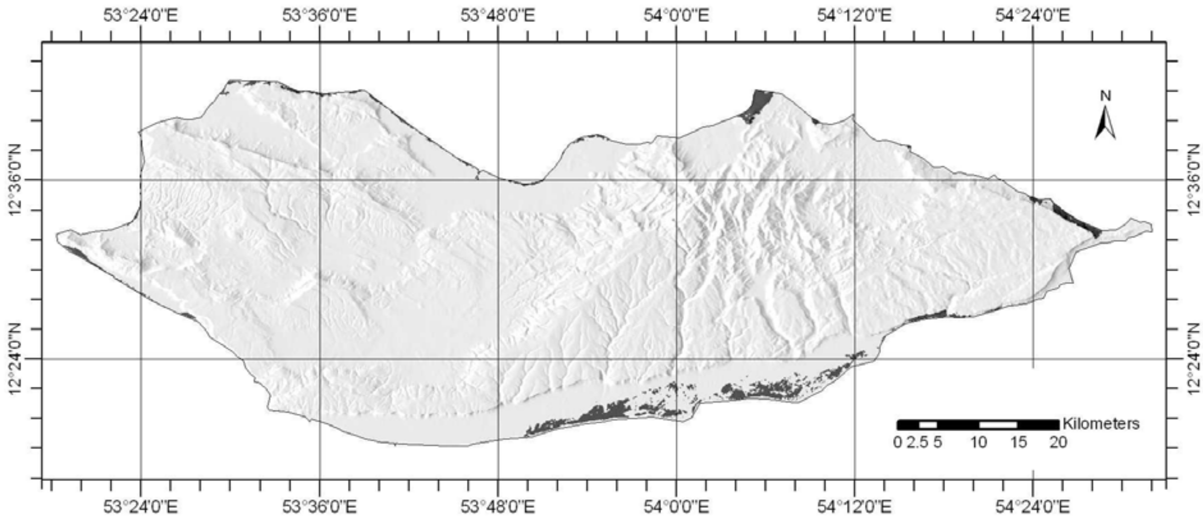


Fig. 18: Spatial distribution of 'Sand dunes' on Socotra.

The biotope type of HABROVÁ (2004): DS.1. – Sand dunes is a direct counterpart of this land-cover class. Edges of dunes on Noged plain vegetated by *Tamarix nilotica* than would fall into the biotope: S.2.6. – Tamarix shrubland (*etahal*).

According LCCS it is classified as LCC Label: Shifting Sands / Dune(s); LCC Level: A6B1.

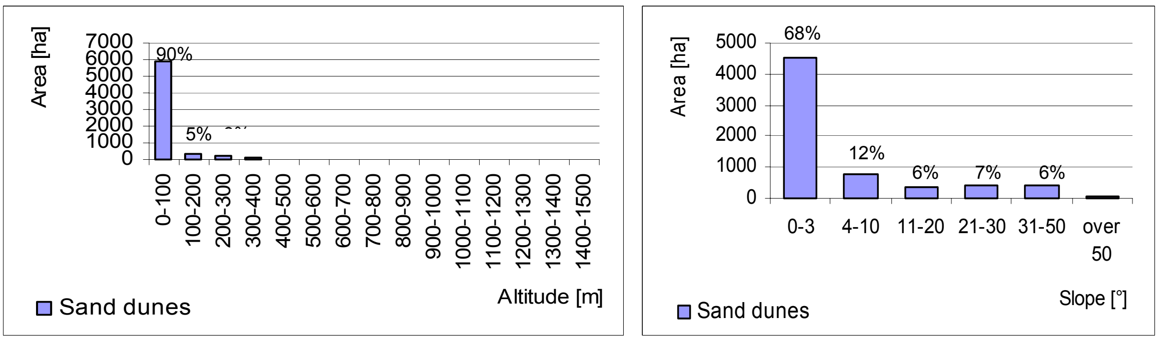


Fig. 19: Distribution of altitudes and slopes within the land-cover class 'Sand dunes'.

(7) '<u>Sparse dwarf shrubland</u>' is the first well represented class occurring essentially on all coastal and inland plains of Socotra (see figure 21). It covers approximately 50 000ha that is about 14% of total area of the island (see table 6). This shrub zone is fairly wide, extending from the coast to the river basins and sometimes up to foothills, where it merges into the Croton or mixed Croton-Jatropha shrubland on the lower adjoining slopes (especially on the northern side of the island), or ends at the foot of the limestone cliffs (e.g. Noged plain). This is apparent also from the figure 22, which shows that about 70% of the area lie in altitude not exeeding 100m a.s.l. and on slopes from 0 to 3°. The rest occupy lower gentle slopes (see fig. 22). The mean altitude of the occurrence is approximately 85m a.s.l., the mean slope 4°. Consequently, this landcover class is typical for the first altitudinal vegetation zone (see figures 82 and 83 in the chapter 4.5.).

Fig. 20: Sparse dwarf shrubland.

The spatial distribution of the class is reflected also in appropriate parent rocks. More than 60% is formed by quaternary sediments, dolomitic limestone is also well represented (cca 22%, see figure 75, chapter 4.3.).

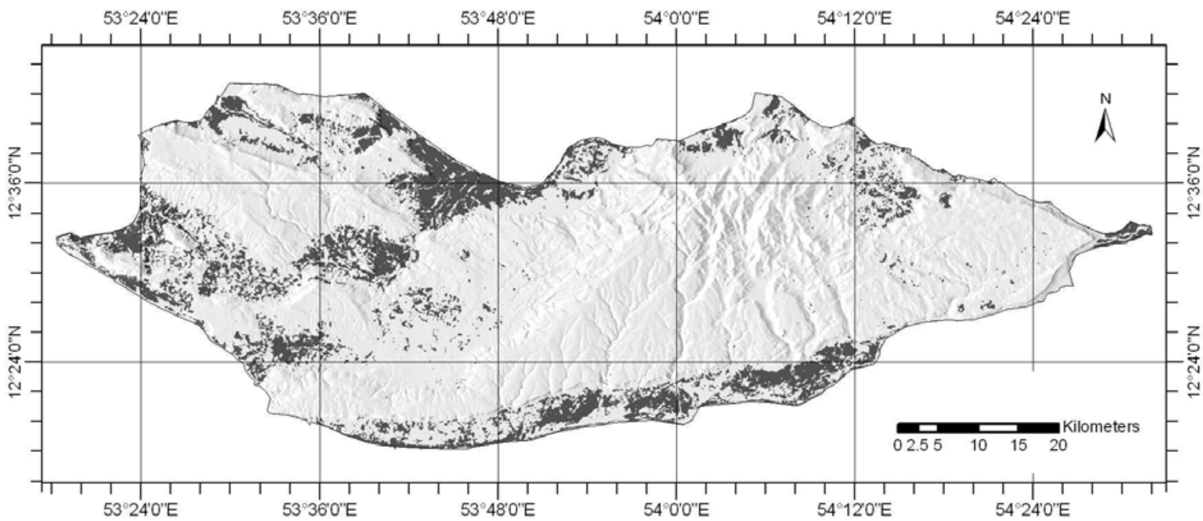


Fig. 21: Spatial distribution of 'Sparse dwarf shrubland' on Socotra.

The landcover class merges all sparse dwarf shrublands of lowlands (their height usually do not exceed [0.5]1m), either natural – shaped by unfavourable climate and soil conditions (e.g. dry tough winds, high salinity, etc.), or man made biotopes, which are influenced by heavy overgrazing and wood collection and often arise by degradation of Croton shrubland. Thus, more biotope types of Habrová may be attributed to this land cover class. For the main it refers to S.3.1. - Dwarf shrubland from lowland and low highland (*shirmihin-digdeďe*) composed of dwarf (overgrazed) forms of *Placopoda virgata*, *Ballochia* spp., *Commiphora socotrana*, *Lycium socotranum*, *Ormocarpum coeruleum*, *Pulicaria stephanocarpa*, *Indigofera* spp., *Senna* spp., *Tephrosia holosericea*, locally also *Cissus subaphylla*, *Croton socotranus*, *Jatropha unicostata*, *Acacia edgeworthii*, etc. (HABROVÁ 2004). Other biotope, which can be ascribed to this landcover class, is S.3.3. – Dwarf coastal shrubland (*karshebhon*) found particularly on the southern seashore at Neet and Noged. This vegetation influenced by 'marine-salt' winds is composed mainly of *Limonium socotranum* or *Limonium paulayanum* and other halophytic undershrubs and woody-based herb species as *Atriplex griffithii, Aristida adscensionis*, *Zygophyllum qatarense, Salsola spinescens, Pulicaria stephanocarpa*, etc. Also the biotope type D.1. – Degraded land (*digded'e*), which occur in a vicinity of major settlements as Hadiboh and Qualansiyah, falls within this class. The dominant species are *Senna holosericea* and *Tephrosia apolinea* (HABROVÁ 2004).

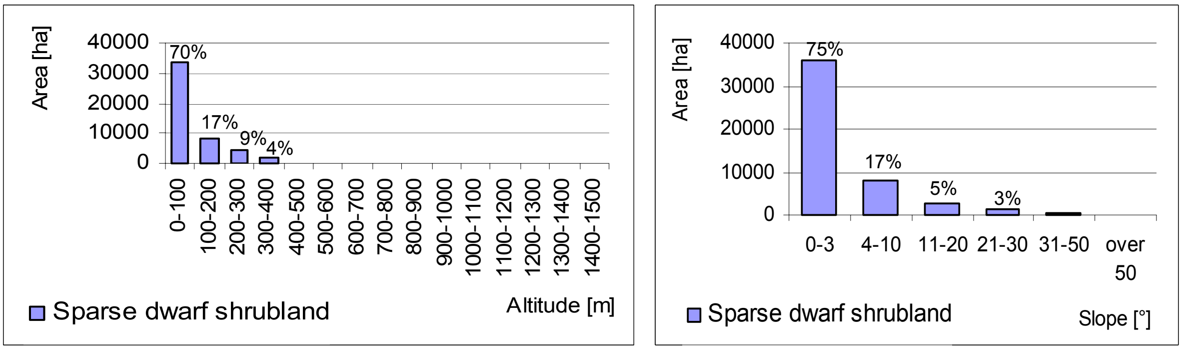


Fig. 22: Distribution of altitudes and slopes within the land-cover class 'Sparse dwarf shrubland'.

According to the LCCS it is classified as: LCC Label: Sparse ((20-10) - 4%) Dwarf Shrubs; Major Landclass: Level Land, Plain, Slopeclass: Flat to Almost Flat; Altitude: < 50 - 300 m; Floristic Aspect: low shrubland (*Croton*); LCC Level: A4A14B3-A15B10-L11L5P1Zt2.

Concerning the impact of monsoons on phenology of the formation, as depicted by NDVI time series, only small differences have been observed between the northern and southern side of the island. The vegetation abundance of this class is probably so low, so that seasonal differences reflected by MODIS sensor are very slight (more in the chapter 4.7.3., Fig. 108).

(8) '<u>Low Croton-Jatropha shrubland</u>' occupy coastal and inland lowlands; it frequently encroaches on neighbouring low rolling hills and often remains dominant there. In places it extends to the steeper foothills of Haggeher Mts. or limestone plateaus, where it merges with the 'High succulent shrubland' (more below). The height of the main shrub layer usually do not exceed 2(3)m.

Fig. 23: Low Croton-Jatropha shrubland.

It is found mainly in central Zahr basin; Qa'arah plateau and northern part of the Noged plain on the southern coast; Djaahel plain in the northwest and at foothills of all northern plains including Had'ale plain, Karma plain, Hadiboh plain and the Lhasi basin (see Fig. 24). It is the most distributed landcover class on Socotra occupying roughly 112 000ha that is about 32% of total area of the island.

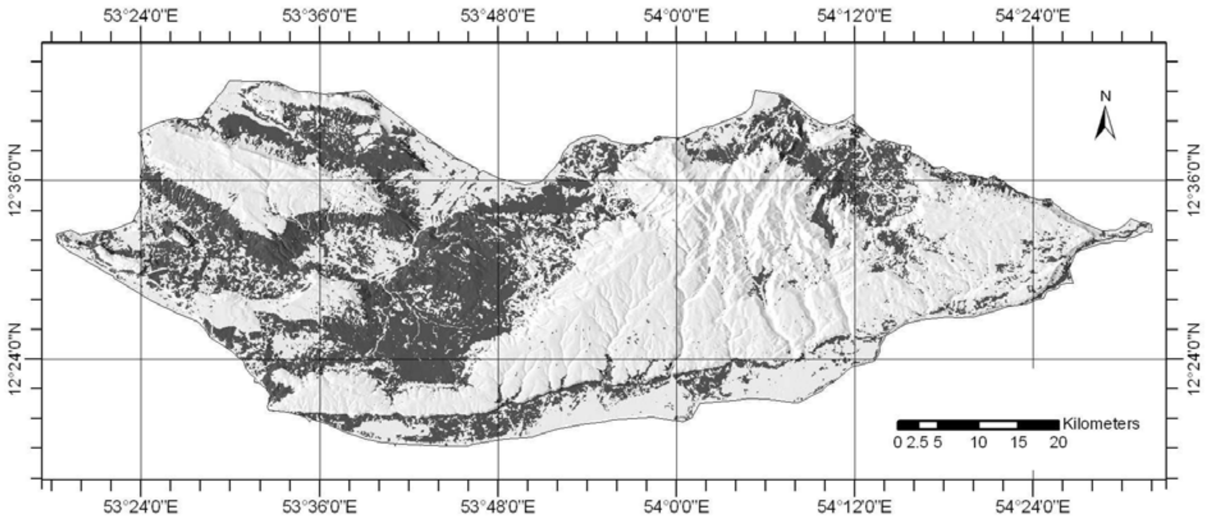


Fig. 24: Spatial distribution of 'Low Croton-Jatropha shrubland' on Socotra.

The figure 25 shows a remarkable shift in typical topography pattern of the class as compared with the 'Sparse dwarf shrubland.' The lowest altitudes and slopes are still well represented, though majority of the class occur in elevations above 100m a.s.l. Similarly the slopes often exceed value of 3°. Consequently, the mean altitude of the class occurrence is cca 184m above sea level and the mean slope is about 7°.

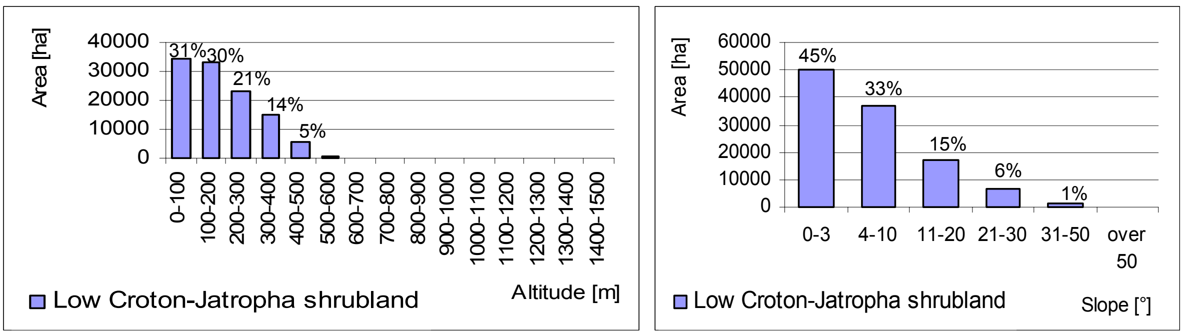


Fig. 25: Distribution of altitudes and slopes within the land-cover class 'Low Croton-Jatropha shrubland'.

Majority of the class already belongs to the 2nd AVZ; the remaining part (about 40%) still lies in the 1st AVZ (see Fig. 83).

Characteristic bedrock (Fig. 75) corresponds to the distribution of the class. About 30% are Quaternary sediments, majority (more than 50%) is formed by dolomitic limestones, 5% are calcareous sediments, 5% Schist and Gneiss and the rest consists of other igneous and metamorphic rocks.

As for the species composition, the class is dominated by *Croton socotranus* further represented by *Jatropha unicostata, Cissus subaphylla*, *Lycium sokotranum Trichocalyx* spp., *Plagopoda virgata, Zygocarpum coeruleum, Ballochia* spp. etc. Occasionally *Adenium obesum* ssp. *sokotranum* and *Euphorbia arbuscula* may occur. Concerning to biotope types of HABROVÁ (2004) it refers particularly to S.2.1. - Croton socotranus shrubland (*meterhel*), S.2.2. - Jatropha shrubland (*seborhi*) and S.2.3. – Mixed deciduous shrubland (*shirmihin* *d'efer*). At Neet and Shu'ub biotope S.2.7. – Low coastal shrubland (*karshebhon*) occur in limited areas. This local biotope is composed of *Limonium socotranum, Limonium paulayanum, Accacia sarcophylla*, etc.

In some localities, particularly at a height of 150-250m the Croton-Jatropha shrubland becomes at least partly replaced by the *Commiphora* community represented by such xerophilous elements as *Commiphora socotrana, Commiphora parviflora*, *Aloe perryi*, etc. (Popov 1957). This Commiphora community, however, was not for a certainty detectable by means of remote sensing and therefore is not mapped as an extra unit. As it develops in more elevated parts, one can assume that parts of the 'Low Croton-Jatropha shrubland' that occur in the 2nd altitudinal vegetation zone can be often attributed to the Commiphora shrubland. This vegetation type can be truly ascribed to the biotope type of Habrová: S.1.4. - Myrh tree shrubland (*laakam*). Besides *Commiphora* spp. it is dominated by *Jatropha unicostata* and *Croton socotranus.*

All this LC class is according to the LCCS classified as follows: LCC Label: Broadleaved Deciduous Medium High Shrubland; LCC Level: A4A11B3C1D1E1-B9.

Impact of monsoons on seasonal dynamics of the class is described in the chapter 4.7.3. (see Fig. 109).

(9) '<u>High shrubland with succulents</u>' is another well-represented vegetation type occupying steep foothills and slopes of central granitic mountains as well as foothills of most of the limestone plateaus. It is easy to regard this community as a transition between the scarcely vegetated lowlands and relatively more abundant vegetation of central Haggeher Mts. or scarcely vegetated but elevated limestone plateaus. The height of the general level of the upper canopy usually range from 2 to 4(5)m, though at some exposed sites (especially on basement rocky slopes) can be considerable lower.

Fig. 26: High shrublands with succulents.

Figure 27 clearly shows a pattern of occurrence. The shrubland forms a belt comprising foothills and lower parts of (steeper) slopes all over the island. Major areas occur in inland valleys south of the Haggeher mountains (e.g. Tzidet, Diasmu, Dishten, Salhoan, Teida, etc.) as well as in deep canyons of south flowing wadis (e.g. Esgego, Darho, Saneiamo, Azrho, Farho, Ohgash). It covers approximately 49 000ha, which is about 14% of the total area of the island.

According to figure 28, it is evident that the succulent shrubland develop on medium and steep slopes in altitudes ranging from 100 to 600(700)m. The mean calculated altitude of the class amounts to 322m and mean inclination to19° (see table 5). The LC class is typical for the 2nd altitudinal vegetation zone, although partly belongs also to the 3rd AVZ (see figure 83).

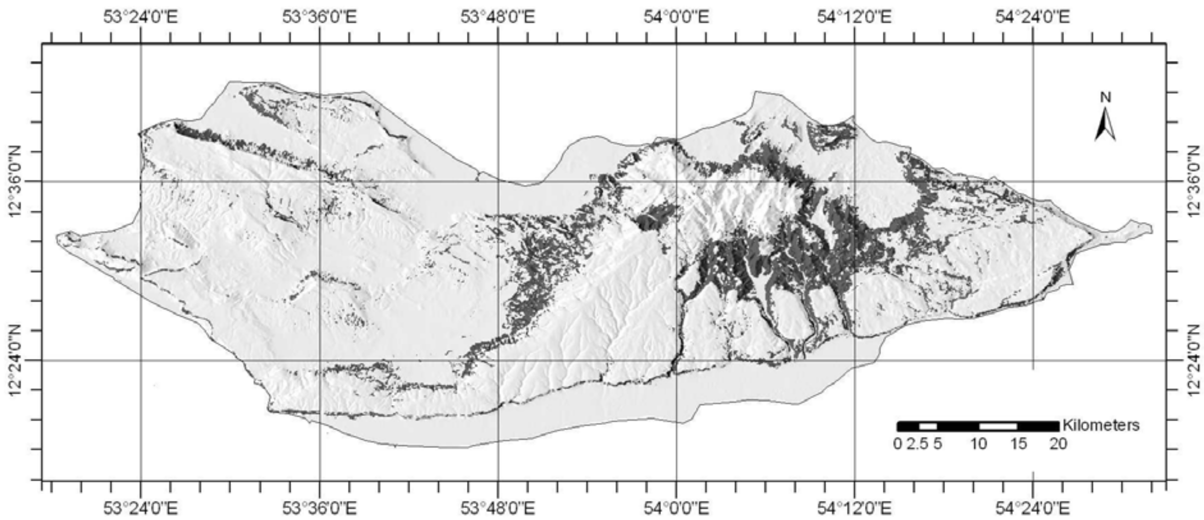


Fig. 27: Spatial distribution of 'High shrublands with succulents' on Socotra.

Parent rocks are rather diverse, Dolomitic limestone, Calcareous sediments as well as most of the igneous and metamorphic rocks are presented (see Fig. 75).

The shrubland is to a large extent composed of *Adenium obesum* ssp. *sokotranum* and *Dendrosicyos socotrana*, other common species are *Jatropha unicostata, Croton socotranus, Euphorbia arbuscula, Cissus subaphylla*, *Trichocalyx* spp., *Lycium sokotranum,* etc. Occasionally, emergent trees typical for frankincense woodlands (e.g. *Boswellia* spp. *Commiphora* spp., *Maerua angolensis, Sterculia africana, Lannea transulata*, etc.) may occur. As for the biotope types of HABROVÁ (2004) it refers particularly to S.1.3. – Succulent shrubland (*esofid*) sometimes also to S.2.2. - Jatropha shrubland (*seborhi*) and S.1.4. - Myrh tree shrubland (*laakam*).

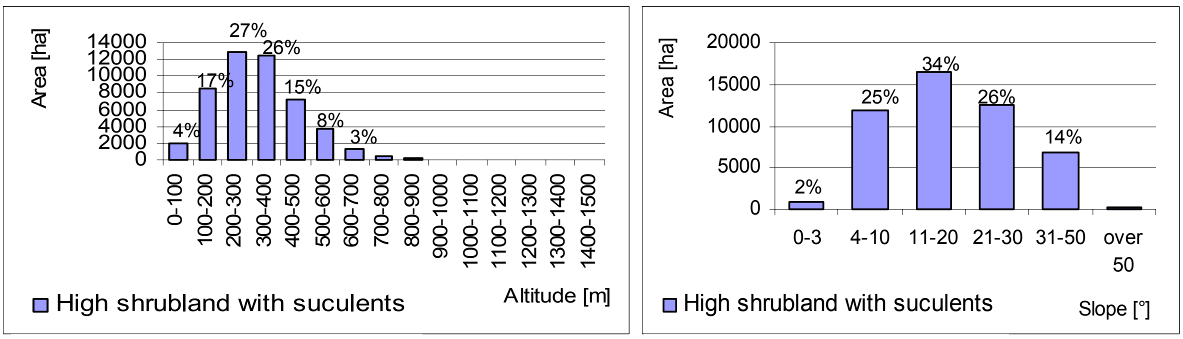


Fig. 28: Distribution of altitudes and slopes within the land-cover class 'High shrublands with succulents'.

According to the LCCS it is classified as: Semi-Deciduous (40 - (20-10)%) High Shrubland With High Shrub Emergents; Major Landclass: Steep Land, High-Gradient Escarpment Zone, Slope class: Steeply Dissected to Mountainous; Soils: Soil Surface, Very Stony (40 - 80 %); Floristic Aspect: *Adenium obesum, Dendrosicyos socotrana, Jatropha unicostata;* LCC Level: A4A11B3XXD1E2F2F6F10G3-A13B8E4G8-L33L9N2N5 Zt9

As evident from the figure 27 and 94, 'High shrubland with succulents' occurs on both the northern side of the island affected by the winter monsoon and the southern side affected by the summer monsoon. Accordingly, remarkable differences in vegetation phenology exist within this vegetation type (more in the chapter 4.7.3., Fig. 110).

Deciduous (10) '<u>Frankincense woodland</u>' develops on steep hill-sides and stony slopes. It is often a continuation of 'High shrubland with succulents' in higher parts of slopes. From the previous class it is distinguished by presence of tree species. The canopy closure of trees that are higher than 4(5)m should range from 5 to 30%. Since it was not possible to estimate canopy closure over vast areas by a field survey and spatial resolution of Landsat ETM was too coarse to discriminate tree canopies, the Normalised Difference Vegetation Index computed from the Landsat red and near infrared bands was used as a proxy indicator. In the concrete it is the question of the threshold NDVI value (0.661) that was considered accordant with 30% canopy closure (see chapter 3.4.). Analogical approach was used for example by JUWA (1998) and SHRESTHA et ZINC (2001).

Fig. 29: Frankincense woodland.

As evident from Fig. 30, Frankincense woodland occurs particularly in central Haggeher Mts. forming a 'belt' in altitudes ranging from 200 to approximately 900m a.s.l., although usually between 300-700m (see Fig. 31). To a large extend it occupies hill sides of Rowgied and Rewged and the entry of wadi Ayhaft. In the west it partly covers steep slopes and cliffs separating Kaidhed'e plateau from Djaahel plain; in the south it partly occupy slopes between the Zahr basin and south-eastern limestone plateaus as well as steep slopes of deep wadis (e.g. Saneiamo, Azrho). In the north-east it refers to hill-sides of Hamadero and Homhil. In total it extends on approximate area of 11 360ha that is about 3% of total area of the island.

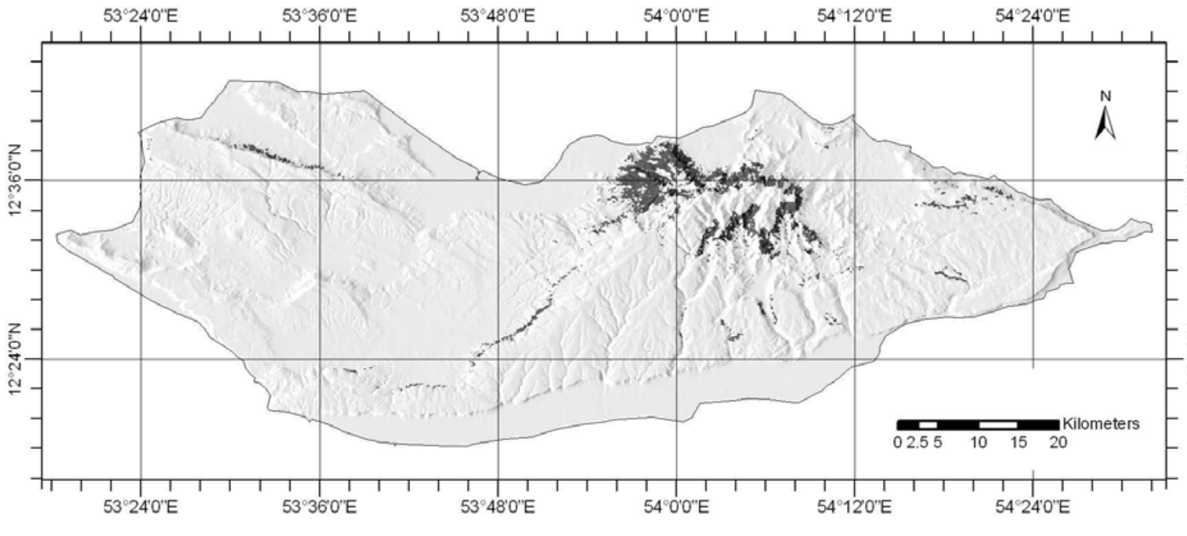


Fig. 30: Spatial distribution of 'Frankincense woodland' on Socotra.

Mean altitude of its occurrence, as calculated by means of DEM, is approximately 500m above sea level; the mean slope is about 22°.

With respect to altitudinal vegetation zones (AVZ), it refers particularly to the 2nd one (about 60%), the rest belongs to the 3rd AVZ.

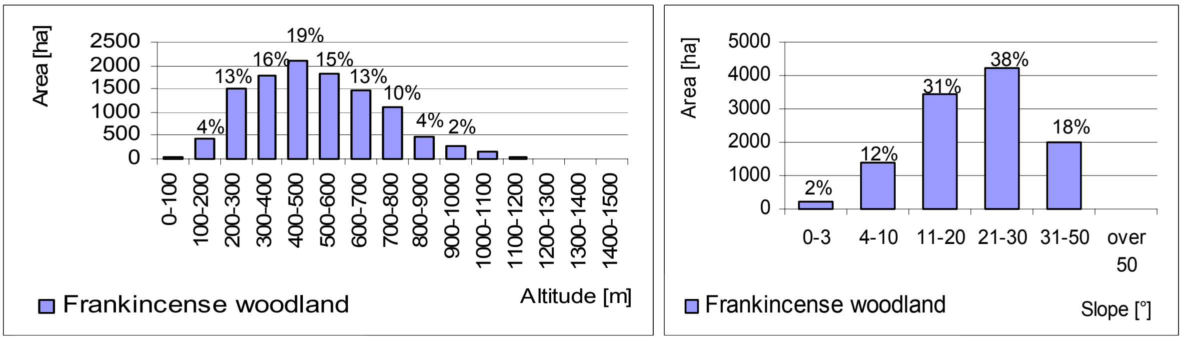


Fig. 31: Distribution of altitudes and slopes within the land-cover class 'Frankincense woodland'.

Fig. 75 demonstrates the proportion of various bedrocks within this land-cover class. Almost 50% is formed by peralkine granite (Riebeckit), Dolomitic limestone (cca 35%) and Calcareous sediments (cca10%) are also well represented.

The species composition is a rich and varied one, dominated by deciduous trees and shrubs such as (trees): *Boswellia elongata, B. ameero, B. socotrana, Commiphora ornifolia, C. parvifolia,* occasionally *Maerua angolensis* var. *socotrana, Commiphora socotrana,* in some places also *Lannea transulta,* on stony slopes *Sterculia africana* var. *socotrana* and *Euphorbia arbuscula,* and in higher parts *Dracaena cinnabari*. The shrub layer is composed of species that are common also in lower sites, such as: *Croton socotranus, Jatropha unicostata, Adenium obesum* ssp. *sokotranum, Trychocalixs* spp., *Anisotes diversifolius,* etc.

As for the biotope types of HABROVÁ (2004), it can be attributed especially to W.2. - Deciduous frankincense woodland (*emhar*) and also to W.6. – Debris woodland (*ebjben*).

In the LCCS it is labelled as: Semi-Deciduous (40 - (20-10)%) Woodland With Open Medium High Shrubs; Major Landclass: Sloping Land, Medium-Gradient Hill, Slopeclass: Hilly; Soils: Soil Surface, Stony (5 - 40 %); Climate: Tropics - Dry semi-arid; Altitude: 200 - 1000m; Floristic Aspect: *Boswellia* spp., *Commiphora* spp.; LCC Level: A3A11B2C1D1E2F2 F6F7G3F1-A13B6E4F9G9-L22L8N2N4O1O11P2Zt10

The class (11) '<u>Frankincense forest</u>' is very similar to previous one. Generally it grows on analogical sites, nevertheless, it preferably occupies sheltered valleys and ravines. It is largely composed of the same species as frankincense woodlands, however, it differs by closer canopy class (over 30%) of the tree layer. It is likely that 'Frankincense woodland' originated from 'Frankincense forest' by degradation (long-term overgrazing disable a natural regeneration of tree species).

Fig. 32: Frankincense forest.

Remnants of deciduous frankincense forests occur particularly in sheltered valleys and ravines of the north faced slopes of the Haggeher Mts. and in the Ayhaft wadi (see Fig. 33), which is (besides the Firmihin and Scant localities) probably the most forested area of the island. Some patches of deciduous frankincense forests occur also in inland valleys south of the Haggeher mountains. The total area of the class is about 1250ha (see table 6).

About 70% of the forest is situated at an altitude ranging from 500 to 800m, nevertheless, it can achieve heights even about 1000m a.s.l. (see Fig. 34). The inclination ranges between 10 and 50°, whereas the slopes class 21-30° is the most common. The mean altitude of its occurrence is approximately 630m a.s.l., the calculated value of mean inclination (25°) ranks the class among the steepest habitats on the island. It typically belongs to the 3rd altitudinal vegetation zone (see Fig. 83), although important part lies also in the 2nd AVZ.

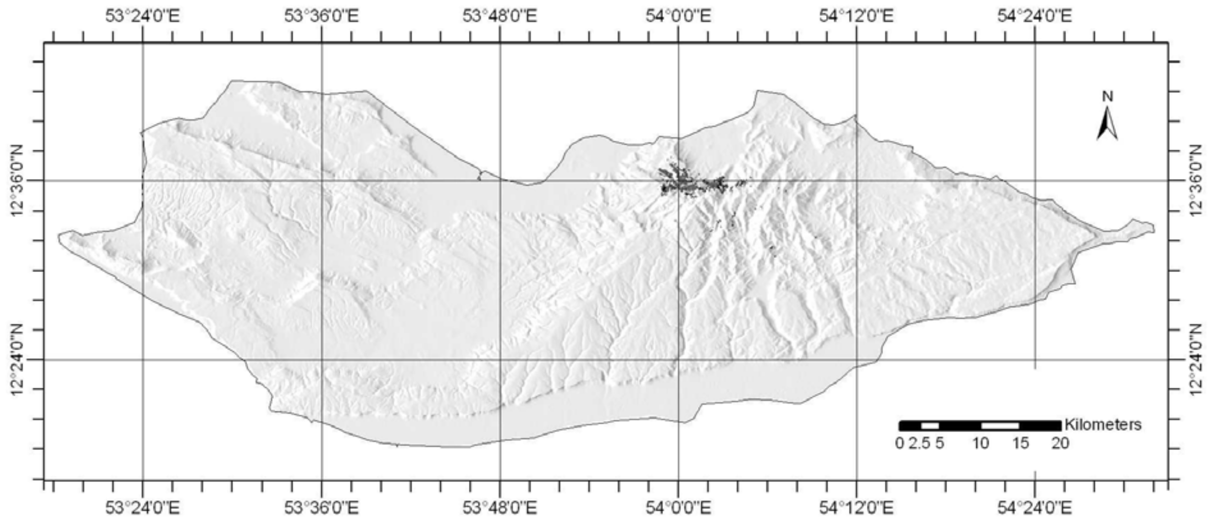


Fig. 33: Spatial distribution of 'Frankincense forest' on Socotra.

Parent rocks are rather uniform. As it is mostly confined to Haggeher Mts., more than 80% of the parent rock consist of Riebeckit. The rest is formed mainly by calcareous sediments (i.e. wadi Ayhaft).

The species composition is very similar to frankincense woodlands. Among trees *Boswellia elongata* preponderates, other common tree species are as follows: *Boswellia* spp., *Commiphora ornifolia, C. parvifolia,* occasionally *Maerua angolensis* var. *socotrana,* sometimes also *Lannea transulta,* on stony slopes often *Sterculia africana* var. *socotrana* and *Euphorbia arbuscula,* and in higher parts *Dracaena cinnabari*. The shrub layer is composed of common species such as: *Jatropha unicostata, Croton socotranus, Accacia pennivenia, Adenium obesum* ssp. *sokotranum, Trychocalyx* spp., *Acridocarpus socotrana*, etc.

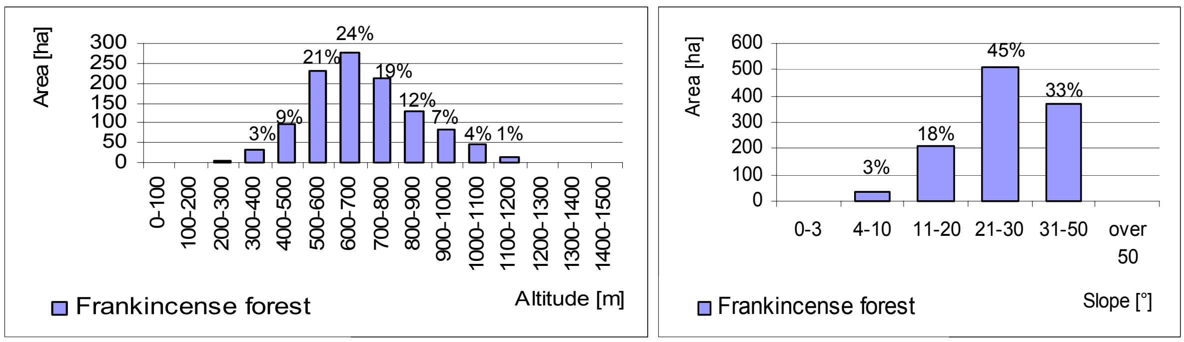


Fig. 34: Distribution of altitudes and slopes within the land-cover class 'Frankincense forest'.

With respect to the biotope types of HABROVÁ (2004), it can be ascribed in particular to F.3. - Deciduous frankincense forest (*emhar*) and also to F.5. – Debris forest (*ebjben*).

As for the LCCS classification system, it is labelled as: Semi-Deciduous Medium High Forest With Open Medium High Shrubs; Major Landclass: Sloping Land, Medium-Gradient Hill, Slopeclass: Hilly; Climate: Tropics - Dry semi-arid; Altit.: 300-1100m; Floristic Aspect: *Boswellia* spp., *Commiphora* sp; LCC Level: A3A10B2XXD1E2F2F6F7G 3F1-B6E4 F9G9L2 2L8O1O11P2Zt10.

(12) ‘Dracaena woodland’ represents a typical vegetation type of Socotra that is characterised by evergreen endemic tree *Dracaena cinnabari.* In order to be mapped as this class, the canopy closure of ‘Dragon’s blood trees’ in the formation should range between 5 and 30%. Nevertheless, in some cases, it is possible that areas with lower canopy closure were included. Consequently, the total area of that class, as calculated from the map (cca 5 800ha, see Tab. 6), may be slightly overestimated.

Fig. 35: Dracaena woodland.

Dracaena woodland, as one of the vegetation types confined to limestone plateaus, occupies limited areas on Dixam and Shibehon, southern part of Firmihin and slopes of the Hamadero and Homhil (see Fig. 36). It is usually restricted to steeper slopes on plateau edges and wadi valleys (e.g. wadi Zorik, Esgego, Darho, Saneiamo, Farho, etc); however, as evident from the figures 35 and 37, it can grow also on flat areas and gentle slopes. It is believed, that many vegetation communities of limestone plateaus (including Dracaena woodland) are better developed in ravines and gorges, where the adjoining cliffs afford some protection against the outstanding winds (POPOV 1957; MILLER et MORRIS 2004). This is, at least in some areas (e.g. Ma’alah), certainly true, and strong winds act as limiting climatic factor there. However, in some localities can an absence of certain vegetation types on flat - well accessible sites point rather to another limiting factor – overgrazing. Some species (including *Dracaena cinnabari*) are on steep slopes and cliffs of plateau edges surely better protected against goats and other livestock. The limitation of graze enables natural regeneration, which is crucial for an existence of tree formations; however, long-term overgrazing affects a species composition of vegetation more or less all over the island. Similar conclusions were made also by MIES et BEYHL (1996): ‘Browsing animals eliminate the palatable species, cause a severe and constant ecological pressure and provide changes for non-palatable and even poisonous species to invade and dominate. Some Socotrans plants, which are favored by browsing animals, are mutilated and deformed as if pruned by a skilled gardener. Other plants, the seedlings of which are grazed upon by animals, can only survive in localities which are inaccessible by their steepness.’ The impact of graze on vegetation was on Socotra studied also by HABROVÁ (2002, 2003).

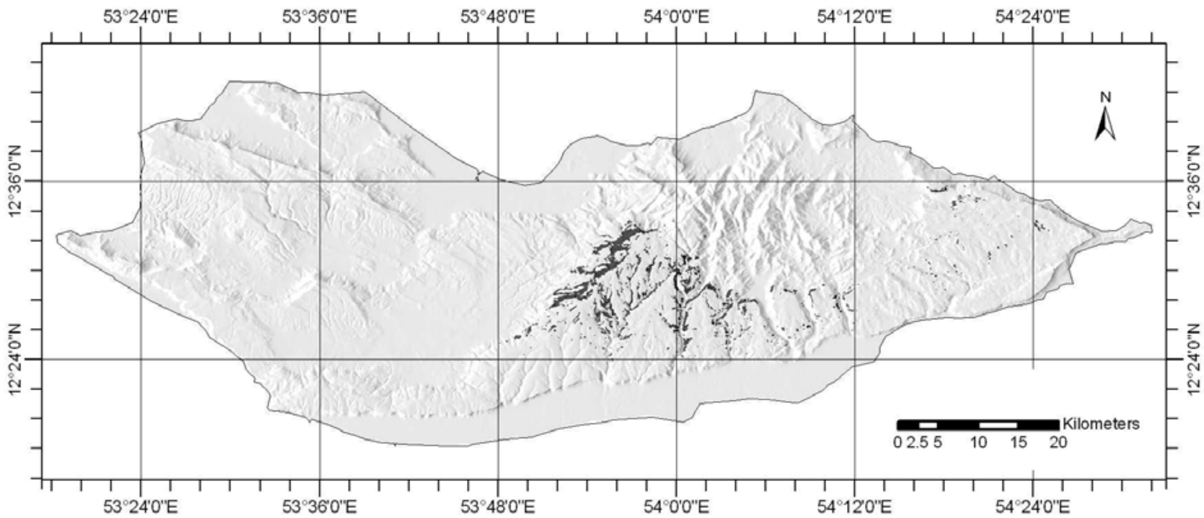


Fig. 36: Spatial distribution of 'Dracaena woodland' on Socotra.

According to Fig. 37, it is evident that the scope of altitudes is relatively wide, ranging from (200)300m to 900(1000)m a.s.l., which approximate the total altitudinal range of limestone plateaus, nevertheless, it falls mostly within the 3rd altitudinal vegetation zone (see Fig. 83). As for the slope incline, most of the class occupies steep slopes and cliffs; however, more than 30% grows at slopes not exceeding 10°. The mean altitude of the occurrence is about 620m a.s.l., the mean slope is approximately 15°.

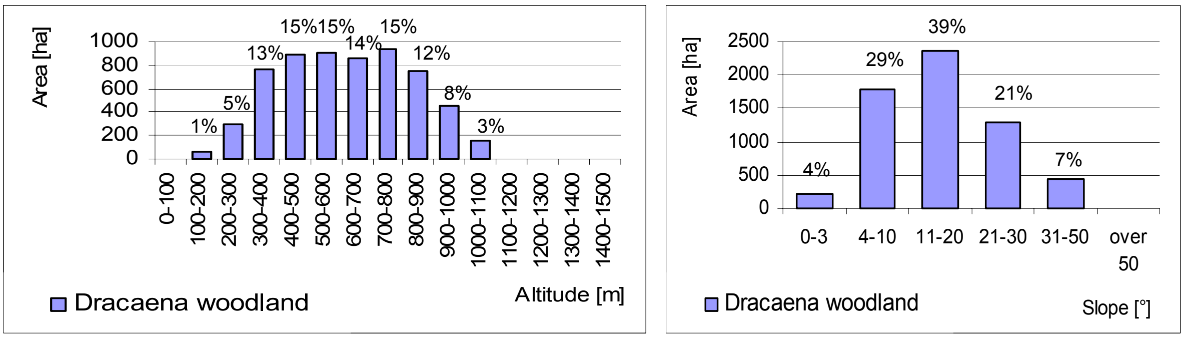


Fig. 37: Distribution of altitudes and slopes within the land-cover class 'Dracaena woodland'.

A fact that the class is typical for limestone plateaux is also corroborated by the occurrence of bedrocks (Fig. 75) nearly of 80% formed by limestone. The rest (cca 20%) consists of calcareous sediments (i.e. edges of limestone plateaus).

The tree layer is formed and dominated by *Dracaena cinnabari;* at some localities individuals of *Boswellia dioscorides, B. ameero, Commiphora planifrons, C. ornifolia*, *Euphorbia socotrana* can occur. The shrub layer is composed of deciduous species, such as *Croton socotranus „B"* (HABROVÁ 2004), *Jatropha unicostata*, *Trichocalyx* spp., *Lycium sokotranum, Cissus hamaderohensis, Buxanthus pedicellatus* (evergreen), *Withania* spp., *Rhus thyrsiflora, Gnidia socotrana, Cryptolepis intricate,* etc. Among herbs *Aloe perryi* is common, as well as geophytes - e.g. *Babiana socotrana*, which grows under the crowns of dragon's blood trees (HABROVÁ 2004).

Of course, the determinant species - *Dracaena cinnabari* - determining a community of Dracaena woodlands and forests, occurs frequently also in granitic Haggeher Mts. However, in these areas it acts only as an admixture among other tree species. Moreover, some morphological differences between individuals from the Haggeher mountains population and those from the limestone plateaus evolved. It refers to a suggestion that two ecotypes of *Dracaena cinnabari* probably exist on Socotra (HABROVÁ et MADĚRA 2004).

In the biotope classification of HABROVÁ (2004) the landcover class 'Dracaena woodland' can be directly ascribed to the biotope type W.1. – Dragon's blood tree woodland (*ariob*); areas with the lowest cover of *Dracaena cinnabari* would be probably classified also as S.2.4. - Low shrubland with *Croton socotranus* "B" and/or *Buxanthus pedicellatus* (*meterhel-maatan*).

In the LCCS it is labelled as: Semi-Evergreen Fragmented (Cellular) (40 - (20-10)%) Woodland with Open Medium High Shrubs; Major Landclass: Sloping Land, Slope class: Rolling; Lithology: Calcareous rock; Soils: Soil Surface, Very Stony (40 - 80 %); Climate: Tropics - Dry semi-arid; Altitude: 300 - 1000 m; Floristic Aspect: *Dracaena cinnabari* / Semi-Deciduous Fragmented (Cellular) ((70-60) - 40%) Medium To High Shrubland With Shrub Emergents; LCC Level: A3A11B2C2D1E2F2F6F7G3F1-A13B6C5E4F9G9-L2L7M230N2 N5O1O11P2Zt12 / A4A11B3C2D1E2F2F6F10G3-A12B14C5E4

Comparing the distribution of 'Dracaena woodland' with the zones of the monsoon impact (see Fig. 94), we can note that about 80% of the class is under the marked influence of the summer monsoon. One can guess, whether it is a simple coincidence caused by location of limestone plateaus mostly in the southern part of the island, or it has some other, less apparent reasons. The phenological analyses revealed, that summer monsoons bring precipitations (largely formed by horizontal rain) for longer period than the winter monsoons (more in the chapter 4.7). Together with the notion, that dragon blood trees are very well adapted to capture horizontal rainfalls (ADOLT et PAVLIŠ 2004), it can suggest a hypothesis, that areas under marked influence of the summer monsoon (or both monsoons) are for *Dracaena cinnabari* more favourable. This is more or less in accordance also with findings of MILLER and MORRIS (2004), who stated that the pattern of distribution of *Dracaenas* closely matches areas receiving frequent low cloud, mists and drizzle during the monsoon (they spoke probably about the summer monsoon). For example at Ma'alah plateau there are no *Dracaenas* and this plateau is also concerning rainfall benefits largely affected rather by the winter monsoon (and therefore could be for *Dracaenas* less convenient). On the other hand, Hamadero and Homhil localities are also affected rather by the winter monsoon and despite of it bear vital population of *Dracaena cinnabari*.

The class (13) 'Dracaena forest' is analogical to the previous one, distinguished only by higher canopy closure of the determinant tree *Dracaena cinnabari* (over 30%). It is restricted to Firmihin locality (see Fig. 39), since no other stands on Socotra reach sufficient density. This vegetation type is unique to Socotra and as such is extremly important. A total area of the class is approximately 230ha.

Fig. 38: Dracaena forest.

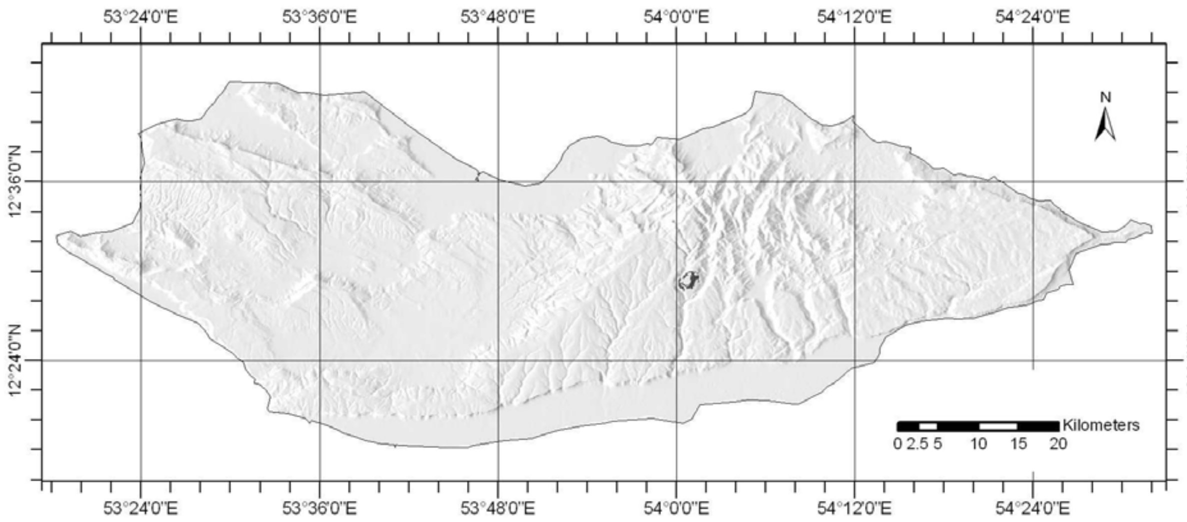


Fig. 39: Spatial distribution of 'Dracaena forest' on Socotra.

As evident from the figure 40, the range of altitudes is markedly narrower (from 500 to cca 750m a.s.l.) and the slopes are milder (approximately 50% of the area do not exceed the incline of 10°), when compared to those of Dracaena woodland. Accordingly, the mean altitude of occurrence is similar to that of Dracaena woodlands (cca 650m a.s.l.), while the mean slope is noticeably lower (cca 12°, see Tab. 5).

The class belongs to the 3rd altitudinal vegetation zone.

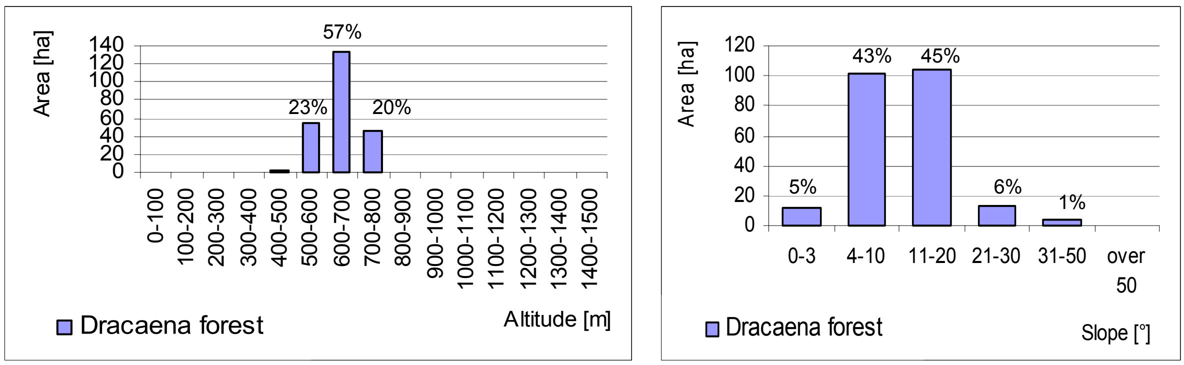


Fig. 40: Distribution of altitudes and slopes within the land-cover class 'Dracaena forest'.

Parent rocks are rather uniform, formed by Dolomitic limestone and Calcareous sediments (see Fig. 75).

Species composition is equivalent to Dracaena woodlands: The tree layer is represented by *Dracaena cinnabari*; the shrub layer is composed of deciduous species, such as *Croton socotranus „B"* (HABROVÁ 2004), *Jatropha unicostata*, *Trichocalyx* spp., *Lycium sokotranum, Cissus hamaderohensis, Buxanthus pedicellatus* (evergreen), *Withania* spp., *Rhus thyrsiflora, Cryptolepis intricata,* etc. In the herb layer *Aloe perryi* occurs frequently (HABROVÁ 2004).

As for the biotope types, the class can be directly attributed to the biotope F.1. – Dragon's blood tree forest (*ariob*).

According LCCS it is classified as - LCC Label: Semi-Evergreen Medium High Forest with Open Medium High Shrubs; Major Landclass: Sloping Land, Slopeclass: Rolling; Lithology: Calcareous rock; Soils: Soil Surface, Very Stony (40 - 80 %); Climate: Tropics - Dry semi-arid; Altitude: 500 - 900 m; Floristic Aspect: *Dracaena cinnabari*. LCC Level:

A3A11B2C2D1E2F2F6F7G3F1-A13B6C5E4F9G9-L2L7M230N2N5O1O11P2Zt12 / A4A1 1B3C2D1E2F2F6F10G3-A12B14C5E4

The class occurs (similarly as in the case of Dracaena woodland) in areas affected by precipitations of the summer monsoon.

(14) 'Submontane grassland and dwarf shrubland' is another well-represented landcover class, comprising the grass and woody based herb communities of the limestone plateaus with scarce individuals of dwarf shrubs (their height usually do not exceed 0.5m). It occupies especially flat summits of lower plateaus, where a karst phenomena is strongly developed affecting macro-, mezzo- as well as a micro-relief. POPOV (1957) described the surface of plateaus summits as follows: 'They are less steep, composed of tumbled-down slabs and chunks of rocks and shelves separated by stony screes. Not only is the whole limestone block honeycombed with fissures, caves and ledges, but the individual rocks are scoured with cracks and hollows, where particles of soil accumulate, affording foothold for vegetation.' In the east and southeast, on lower flat plateaus, broad shallow depressions (karst sinks – 'polje'), where deeper soils have accumulated, are quite common (see Fig. 2 in appendix No. 12). They occur particularly on Momi in the east, though they are found also on Sheezeb, Serhan and Serbe plateaus in the south, as well as on Khaidhed'e (Ma'aleh) plateau in the west, where the great Fedik depression is found. There are extensive areas of flat grasslands at the bottom of the depressions, although, soil and moisture conditions would surely allow growth of shrubs and trees. The grasslands evolved there as a result of human long-term influence (they are used as productive pastures). Water lost in the sinks rise in number of small brooks and rivulets at plateau foothills; undersea freshwater springs have been also reported (WRANIK 1996).

The class covers in total about 68 400ha that is nearly 20% area of the island.

Fig. 41: Submontane grassland and dwarf shrubland.

As shows the figure 42, submontane grassland covers most of the southern plateaus, namely: Momi, Falang, Sheezeb, Serhan, Serbe, Kileem, Dyfshe, Katd'kh, Qatariyah, and Keyrakh; in southwest it refers to Matad'aloh and Ajdhedjo plateaus and in northwest to Khaidhed'e (Ma'aleh) and Shibereh plateau. In the north it occupies summits of Rewged and Bitgobihir.

Altitudes of the occurrence range from 200 to approximately 800m a.s.l., while nearly 80% lie between 300 and 600m a.s.l. (Fig. 43). The slopes (as mentioned above) are rather gentle, flat relief of broad depressions (sinks) is quite common. The mean altitude of its occurrence is cca 480m a.s.l.; the mean inclination is about 8°. Most of the class belongs to the 2^{nd} AVZ, the highest parts fall in the 3^{rd} AVZ.

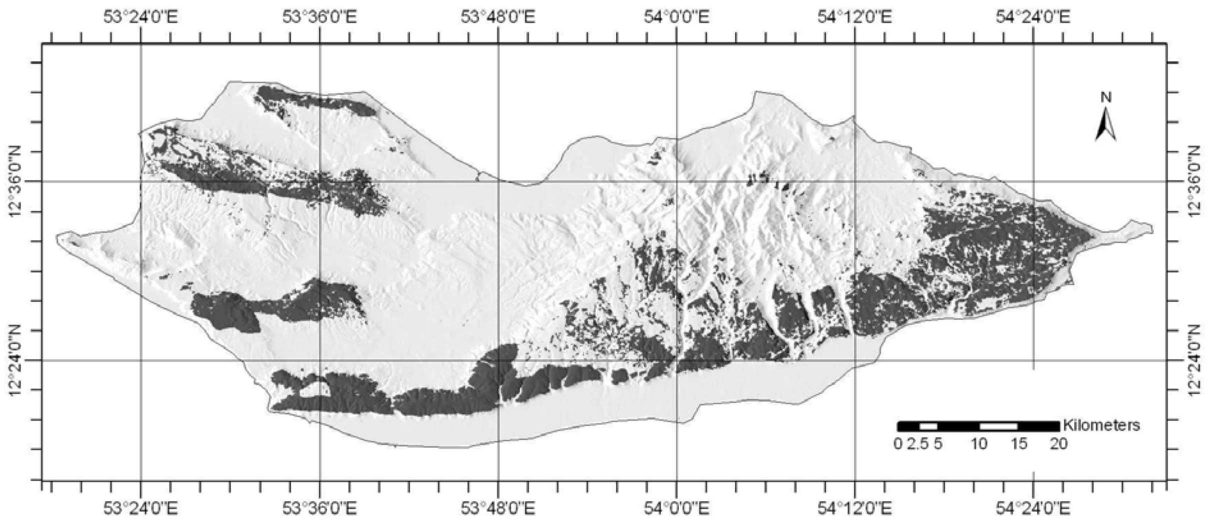


Fig. 42: Spatial distribution of 'Submontane grassland and dwarf shrubland' on Socotra.

A characteristic bedrock (Fig. 75) corresponds to the distribution of the class. Over 90% are Dolomitic limestones, about 6% are Calcareous sediments and the rest consists of igneous and metamorphic rocks (i.e. fragments of lower gentler slopes of the Haggeher Mts. that were not included in the 'Montane grassland').

The perennial vegetation is rather scanty, consisting of individual stunted shrubs of *Lycium sokotranum, Solanum incanum, Croton socotranus, Euphorbia astemperi, Cryptolepis intricata, Withania* spp., *Aloe perryi*, *Kalanchoe farinacea,* etc. (HABROVÁ 2004); occasionaly also *Buxanthus pedicellatus, Jatropha unicostata, Adenium obesum* ssp. *sokotranum,* etc. Vegetation of the herb layer is more abundant, being chiefly composed of grasses such as *Hyparrehenia hirta, Arthraxon lancifolius, Aristida funiculate, Cymbopogon* spp., and *Penisetum setaceum;* some herbs – *Craterostigma pumilum, Asphodelus tenuifolius, Digera alternifolia, Achyranthes aspera* and some others (POPOV 1957).

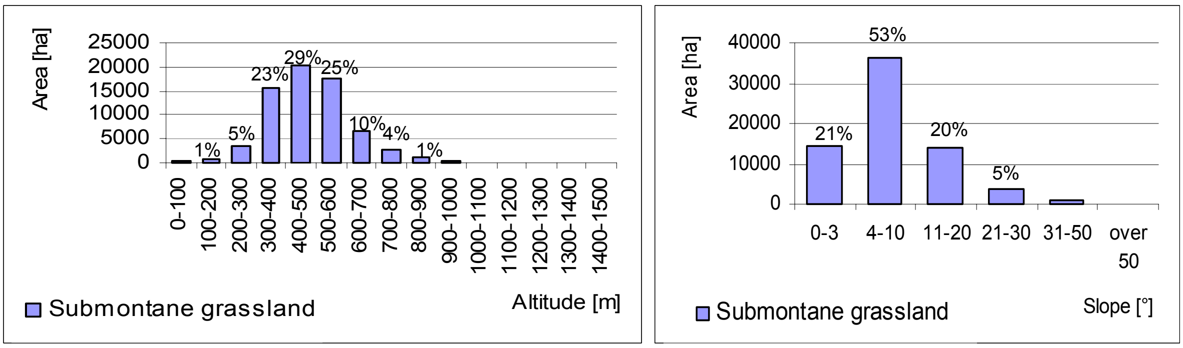


Fig. 43: Distribution of altitudes and slopes within the land-cover class 'Submontane grassland and dwarf shrubland'.

The biotope type G.2. – Pastures on limestone plateau - *kozoho* (HABROVÁ 2004) can be truly ascribed to this landcover class. It can partly refer also to sparse form of S.3.2. – Dwarf shrubland from highland (*shirmihin-kozoho*) and on Ma'aleh also to S.3.4. – Eolic dwarf shrubland (*rah shirmihin*). The latter formation is specific to Ma'aleh area (and some edges of limestone plateau elsewhere), where the outstanding strong and tough winds stunt the woody vegetation, so that common shrubs such as *Croton socotranus* do not exceed height of 0.5m. It is further composed of *Euphorbia spiralis, Gnidia socotrana, Jatropha unicostata, Cryptolepis intricata, Cissus hamaderohensis, Leucas* spp., *Pulicaria stephanocarpa,* etc. (HABROVÁ 2004).

In the LCCS it would be labeled as: Short Grassland with Shrubs; Major Landclass: Level Land, Plateau; Slopeclass: Gently Undulating to Undulating; Lithology: Calcareous rock; Altitude: 300 - 1000 m. The LCC Level is: A6A10B4C1E5F2F6F10G3-B13-L12L6M230P9.

Semi-deciduous (15) ‘Submontane shrubland’ occupies analogical sites as the class ‘Dracaena woodland’ and/or ‘Submontane grassland and dwarf shrubland’. The scope of altitudes of its occurrence is very similar to that of Dracaena woodland (although with significant ‘peak’ between 500 and 700m a.s.l; see Fig. 46). On the other hand, distribution of slopes is parallel to that of Submontane shrubland (compare figures 46 and 43). Hence, the value of the mean altitude (606m) is comparable with the mean altitude of Dracaena woodland (624m), while the mean slope is (8°) is the same as the mean slope of Submontane grassland (see also Tab. 5). It follows that ‘Submontane shrubland’ forms a transitional formation between Dracaena woodlands, which at present occupy only preserved (less exposed) sites, and Submontane grasslands, which are typical rather for lower limestone plateaus.

Fig. 44 : Submontane shrubland.

Some authors therefore suppose that ‘Submontane shrubland’ probably originates from Dracaena woodlands and forests as a stage of degradation caused by long-term graze and absence of natural regeneration (ADOLT 2001; ADOLT et PAVLIŠ 2004; HABROVÁ et MADĚRA 2004). Hence, also the species composition of the shrub layer (height about 2[3]m) is very similar in both formations. Man’s interference with the species composition of Socotra has been refereed also by HABROVÁ (2002, 2003); BEYHL (1995) and MIES et BEYHL (1996). The latter for example stated: ‘On the Momi plateau in the east of Socotra, the former forest has been cleared, except some *Dracaena cinnabari* trees which were left to provide people with an easy access to collect dragon’s blood. Other trees were felled for timber or cut for firewood, or their occurrence was depressed over the centuries by a constant influence of man on flora and vegetation’.

Total area of ‘Submontane shrubland’ is approximately 30 500ha, which is almost 9% area of the island.

As evident from the figure 45 and as stated above, the class is confined to summits of higher limestone plateaus. In central part it refers to Diksam, Shibehon and Khod’olhel, in the west it is the question of less exposed parts of Ma’aleh, in the southwest it concerns to Hihed’e and a summit of Rad’khd’mum. There are also some fragments on Momi in the east and on Rewged and Bitgobihir in the north. More than 60% of the class lies in the 3rd altitudinal vegetation zone, the rest belongs to the 2nd AVZ.

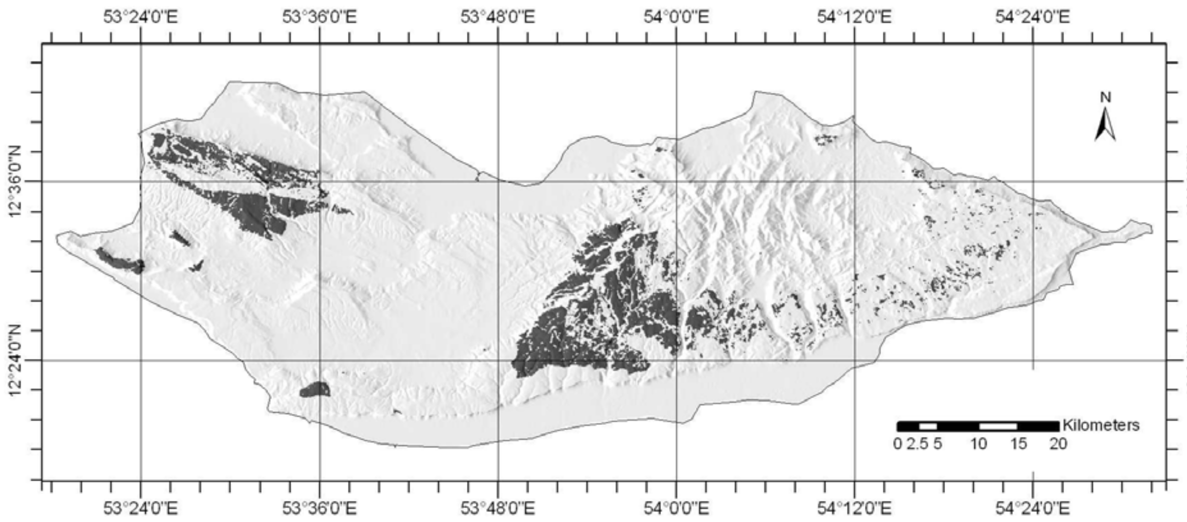


Fig. 45: Spatial distribution of 'Submontane shrubland' on Socotra.

The bedrock is naturally formed by Dolomitic limestone (cca 95%) and Calcareous sediments (cca 5%).

The woody vegetation is dominated by *Buxanthus pedicellatus* and *Croton socotranus „B"* (HABROVÁ 2004); emergent trees of *Dracaena cinnabari* occur. The shrub layer consist of many other species such as *Lycium sokotranum*, *Jatropha unicostata*, *Cryptolepis intricata*, *Ochradenus socotranus*, *Euryops arabicus*, *Trichocalyx* spp., *Kalanchoe farinacea*, *Cissus hamaderohensis*, *Withania* spp., *Gnidia socotrana*, perennial *Aloe perryi* in higher parts also *Punica protopunica*, *Euphorbia socotrana,* etc. (HABROVÁ 2004).

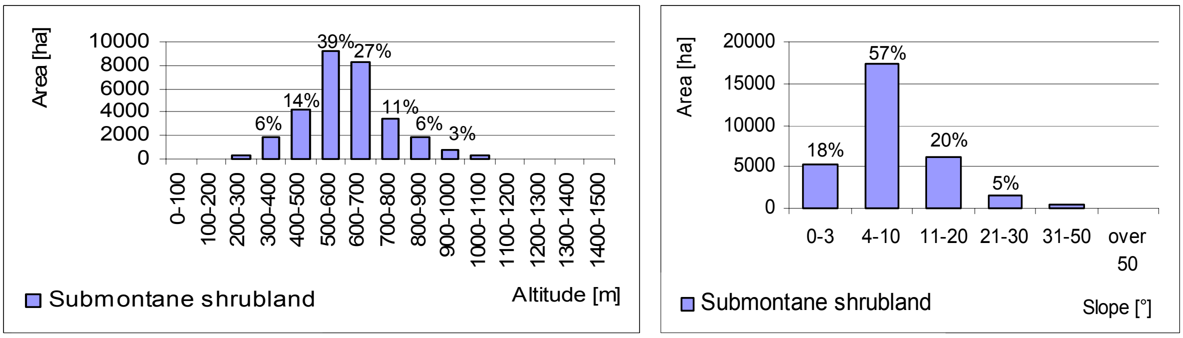


Fig. 46: Distribution of altitudes and slopes within the land-cover class 'Submontane shrubland'.

A biotope type S.2.4. – Low shrubland with Croton socotranus "B" and/or Buxanthus pedicellatus - *meterhel-maatan* (HABROVÁ 2004) can be in a straight line attributed to this landcover class. The shrubland on Ma'alah plateau, which is dominated by *Lycium sokotranum* with an admixture of *Jatropha unicostata* and *Vernonia cockburniana* better corresponds to the biotope S.2.5. – Lycium shrubland (*serhan*). In higher parts of Dixam it can refer also to S.3.2. - Dwarf shrubland from highland (*shirmihin-kozoho*), where some species typical for montaneous vegetation may additionally occur (e.g. *Rhus thyrsiflora* and *Allophylus rubifolius.)*

According LCCS it is classified as - Semi-Deciduous ((70-60) - 40%) Medium High Shrubland With Shrub Emergents; Major Landclass: Steep Land, High-Gradient Hill; Lithology: Calcareous rock; Altitude: 400 - 1000 m. LCC Level is: A4A11B3C1D1E2F2F6 F10G3-A12B9E4-L32M230P9

The vegetation of (16) 'Montane grassland' is confined to gentle slopes of the Haggeher Mts., generally above the height of 800m. It is the first of the three truly montane landcover classes that has been recognised on Socotra. The three montane landcovers were distinguished by the help of ancillary layer of altitudinal vegetation zones (they could be mapped only within the 4th and the 5th AVZ). Similar approach was used by HELMER et al. (2002) mapping forest types and land cover of tropical island Puerto Rico, using environmental factor-based ecological zones: 'This approach limited labelling woody vegetation to one of a pre-determined group of formations within the boundaries imposed by the ancillary data for each image mapping zone'.

A drawback of this approach is that the image mapping zones not only segmented the classification, but also defined the extents of some formations and therefore could only approximate the boundaries between them. The resulting visible and even boundaries between zones, which were approximately mapped by medium resolution MODIS satellite (250m), does not depict patchy ecotones of montane formation too realistically. Integrating spectral data with continuous climate (if available) and elevation data using machine-learning algorithms along with incorporating more extensive field-derived reference observations from transitional areas could yield maps that depict patchy and uneven transitions between montane and submontane formations more realistically.

Fig. 47: Montane grassland.

According to figure 48, it is evident that Montane grassland occurs particularly in the central (Dadhd'je) and eastern (Ditfahed) parts of the Haggeher Mts. In the southeast of Haggeher it refers to Teirebeh. In total it covers approximately 1000ha. They are used, as the best productive pasture grounds, especially for a cattle grazing (unlike the limestone plateaus or costal plains, where the goats and sheeps predominate).

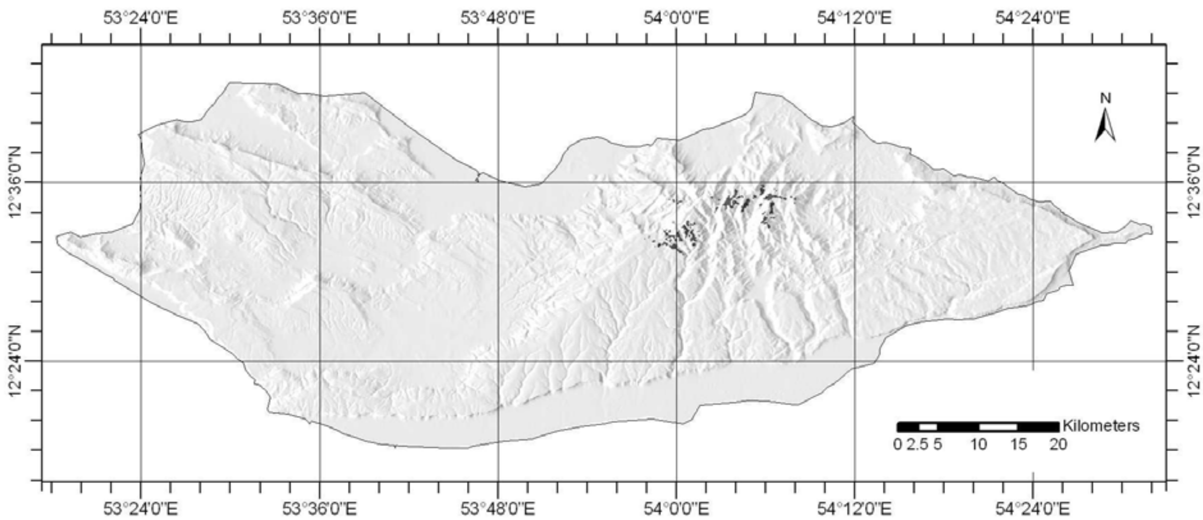


Fig. 48: Spatial distribution of 'Montane grassland' on Socotra.

Altitudes of its occurrence range from 800 to 1200(1300)m while nearly 65% lie between 900 and 1100m a.s.l. (Fig. 49). As for slopes, montane grasslands occupy the easiest grades and 'flat' summits (saddles) of the Haggeher Mts. More than 35% of the area does not exceed 10° and on about 46% of the area the inclination ranges between 11 and 20%. The mean calculated altitude of the class amounts to 1010m and the mean inclination is about 13° (see Tab.). The class is typical for the 4th altitudinal vegetation zone with some overlaps to the 5th AVZ.

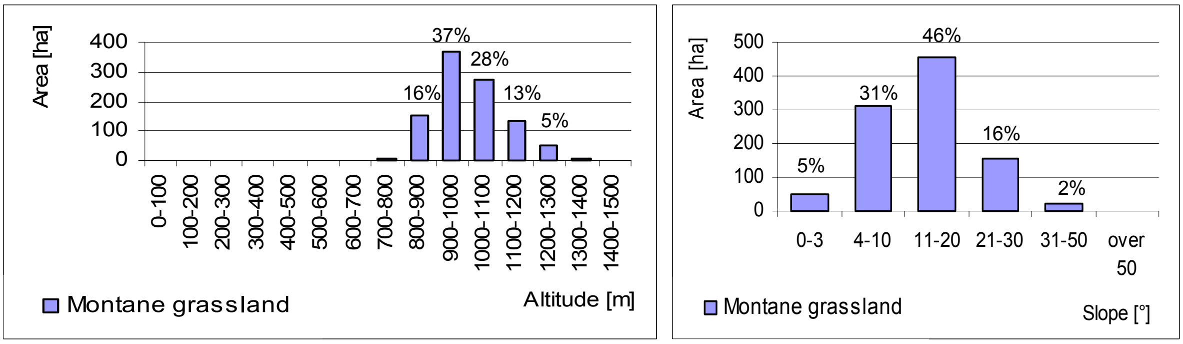


Fig. 49: Distribution of altitudes and slopes within the land-cover class 'Montane grassland'.

Parent rocks are rather uniform – about 90% consist of Riebeckit and the rest is formed by Dolomitic limestone and Calcareous sediment (i.e. edge of the highest parts of the Diksam plateau in the south-eastern -Teirebeh area; see Fig. 75 and appendix No. 6.).

The montaneous grasslands are to a large extent composed of *Themeda quadrivalvis*, *Hyparhenia hirta* and *Arthraxon lancifolius* (POPOV 1957) and herbs such as *Craterostigma pumilum, Helichrysum balfourii, Anagalis arvensis,* etc. (HABROVÁ 2004); isolated shrubs also occur (e.g. *Rhus thyrsiflora, Allophylus rubifolius, Euryops arabicus, Cocculus balfourii* etc.). In the biotope classification of HABROVÁ (2004) it directly corresponds to G.1. – Cleared pastures on granite (*kozoho*); some edges, small patches or sparse growths of S.3.5. – Dwarf montane shrubland with Hypericum scopulorum (*chirebebjehan*) might be also included in this LC class.

According to the LCCS it is classified as: Continuous Open ((70-60) - 40%) Short Grassland; Major Landclass: Sloping Land, Slopeclass: Hilly; Lithology: Igneous plutonic rock - Granodiorite; Soils: Soil Surface, Stony (5 - 40 %), Subsurface: Ferralsols; Climate: Subtropics Winter Rainfall - Moist semi-arid; Altitude: 1000 -1500 m; Erosion: Water Erosion – Rill. LCC Level: A6A11B4C1-A12B13-L2L8M112N2N4N1109O3O12P10 Q7.

Seasonal dynamics of montane vegetation types is depicetd and described in the chapter 4.7.3 (Fig. 114).

(17) '<u>Montane mosaic</u>' is the second and the most spread montaneous class on the island. Since it was not possible to distinguish between rather small but dense patches of diverse bushes and thickets of various heights, the unifying, relatively wide landcover class was established. In consequence, 'Montane mosaic' forms a matrix containing separate patches of other two montaneous classes: Montane grassland (above) and Montane forest (below).

The class occupies most of the higher parts of Haggeher mountains, in the southeast reaching the summits of adjoining Dixam plateau (Fig. 51). It occurs on an approximate area of about 4 600ha at altitudes mostly over 700 m with the centre of occurrence between 800 and 1100m alt. (approx. mean altitude 980m). The slopes are considerably higher than on Montane grassland (slopes over 20° preponderate, see Fig. 52) with the mean slope reaching a value of 24°. The class belongs to both the 4th and the 5th altitudinal vegetation zones (see Fig.

82). Since the area of the 4th AVZ is markedly larger, majority of the class lies in the 4th AVZ (see Fig. 83).

Fig. 50: Montane mosaic.

A bedrock is almost completely created by Riebeckit (see Fig. 75).

More biotope types of HABROVÁ (2004) can be attributed to this landcover class. The best-preserved parts belong to the biotope W.3. – Montane woodland (*shirmihin min haggeher*) composed by trees such as *Pittosporum viridiflorum, Dracaena cinnabari, Spiniluma discolor, Euphorbia socotrana, Euclea divinorum*, *Sideroxylon fimbriatum* and *Commiphora planifrons* and by shrubs such as *Croton sulcifructus, Cephalocroton socotranus Dirachma socotrana, Pulicaria lanata, Carphalea obovata, Hibiscus scottii, Rhus thyrsiflora, Allophylus rubifolius, Osyris quadripartita, Clerodendrum galeatum* etc. In the undergrowth *Pteridium aquilinum* and *Begonia socotrana* occur (HABROVÁ 2004). However, although this biotope was from the beginning considered as a part of 'Montane mosaic', from the final field-trip it follows that it partly corresponds rather to the following class –'Montane forest' (more below).

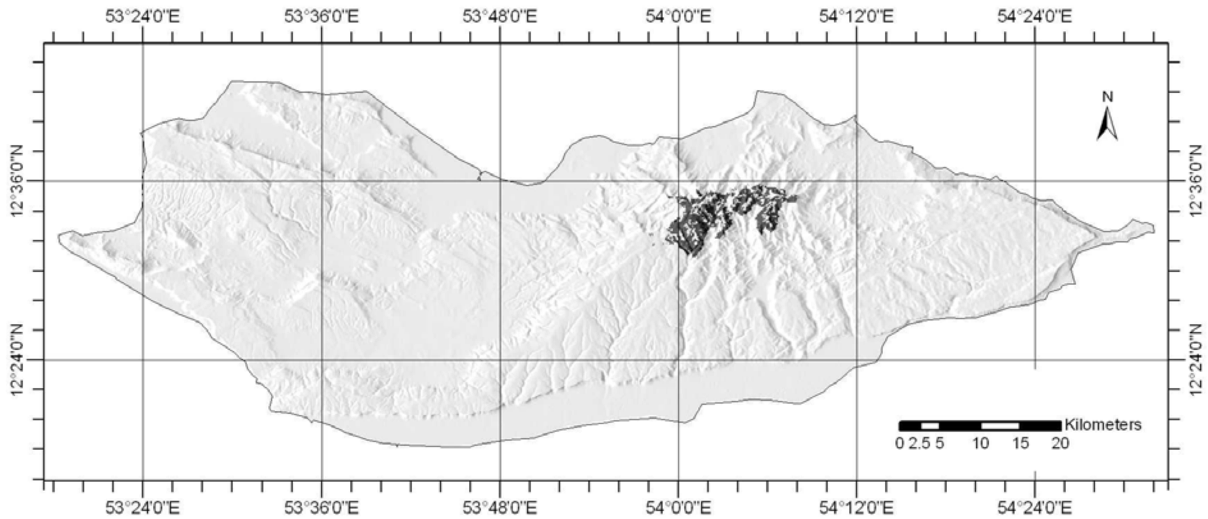
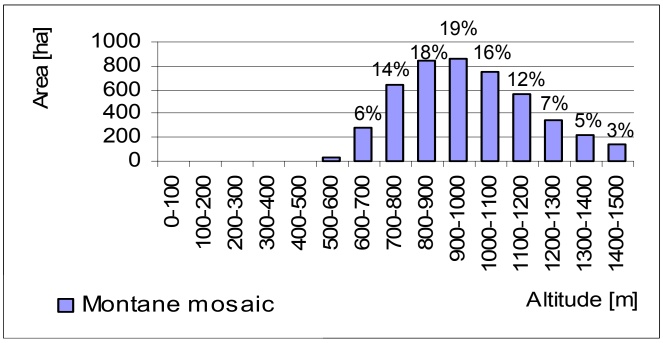


Fig. 51: Spatial distribution of 'Montane mosaic' on Socotra.

Areas without or with only emergent trees appertain fairly to the biotop S.1.1. – Evergreen montane shrubland (*shirmihin yezler*). The shrub layer is to a large extent composed of above-mentioned species. In addition there are shrubs such as *Hypericum scopulorum, Cocculus balfourii, Euryops arabicus, Graderia fruticosa, Ruellia insignis, Coelocarpum haggierensis* and *Vernonia unicata* (HABROVÁ 2004).

Finally, degraded sites (mostly probably former pastures) overgrown by *Hypericum scopulorum* belongs to the biotope S.3.5. - Dwarf montane shrubland with Hypericum scopulorum (*chirebebjehan*).



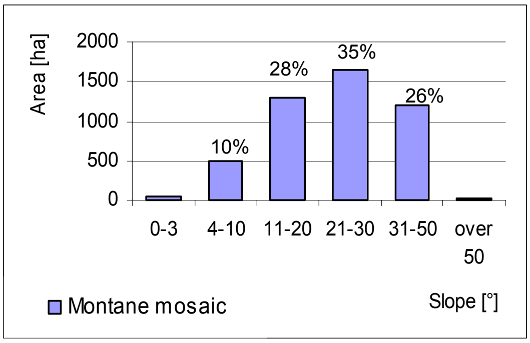


Fig. 52: Distribution of altitudes and slopes within the land-cover class 'Montane mosaic'.

The class is accorging LCCS labelled as: Semi-Evergreen Fragmented (Striped) ((70-60) - 40%) Woodland With Sparse Medium High Shrubs; Major Landclass: Steep Land, High-Gradient Mountain; Climate: Subtropics Winter Rainfall - Dry semi-arid; Altitude: 1000 -1500 m; Erosion: Water Erosion - Rill; Floristic Aspect: Hypericum, Euphorbia, Pittosporum, etc. / Semi-Deciduous Open (40 - (20-10)%) Woody Fragmented (Striped) Vegetation With Medium High Emergents. The LCC Level is: A3A11B2C2D1E2F2F6F10G3 -A12B7C4E4G9-L31O3O11P10Q7Z t17 / A1A11B1C2D1 E2 F2F5F10G2-A13C4E4G6.

(18) '<u>Montane forest</u>' is the last and the least class of the three montaneous land-cover classes. It occurs at the highest locations of Haggeher Mts., particularly in the western part – Bithagger (Scand), small patches may occur elsewhere (Fig. 54). In total it covers area of about 820ha.

Fig. 53: Montane forest.

The class occupies the steepest slopes (excluding cliffs) of Haggeher, particularly above 700m a.s.l.. Thus, the value of mean slope amounts to 25°. As evident from the figure 55, the distribution of altitudes within this class exhibit a depression around the value 1100m. In this altitudinal range namely gentler slopes covered by montane grasslands predominate. The mean altitude of occurrence of montane forests is approximately 1055m above sea level.

The class belongs to both the 4th and the 5th altitudinal vegetation zones (see Fig. 83). Bedrock is completely created by riebeckit.

The tree layer (higher than [4]5m and with canopy closure at least 30%) is to a large extent composed of *Pittosporum viridiflorum, Dracaena cinnabari, Spiniluma discolor,* *Euphorbia socotrana, Euclea divinorum* and *Sideroxylon fimbriatum.* The shrub layer is formed by *Croton sulcifructus, Cephalocroton socotranus,Carphalea obovata, Hibiscus scottii, Rhus thyrsiflora, Allophylus rubifolius, Osyris quadripartita, Clerodendrum galeatum* etc. In the undergrowth *Pteridium aquilinum* is frequent (HABROVÁ 2004).

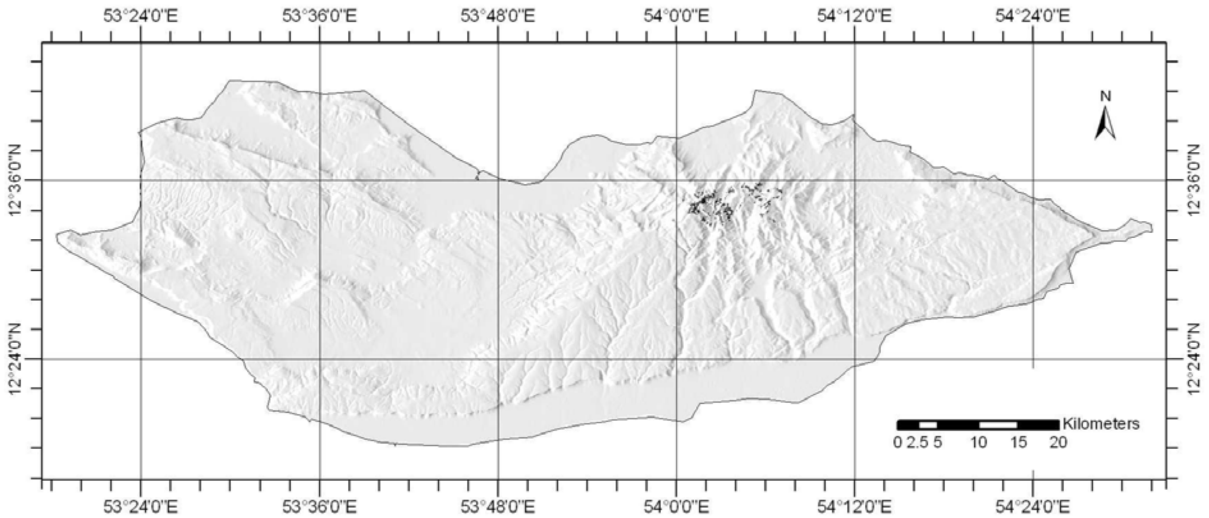


Fig. 54: Spatial distribution of 'Montane forest' on Socotra.

This class is a direct counterpart of biotope type F.4. – Montane forest - *shirmihin min haggeher* (HABROVÁ 2004). Nevertheless, according to the latest ground truth, it is likely that considerable part of the class (particularly in the east of Haggeher Mts.) refers rather to the biotope W.3. – Montane woodland (canopy closure of trees 5-30%). This discordance might be caused by sole NDVI threshold value that was used for the distinction between woodlands and forests all over Socotra (see chapter 3.4.). This NDVI threshold fitted well for the distinction of Frankincense woodlands and forests, however, was too low to safely discriminate between Montane woodlands and forests. In consequence, the class 'Montane forest' should be rather called 'Montane forest and woodland'.

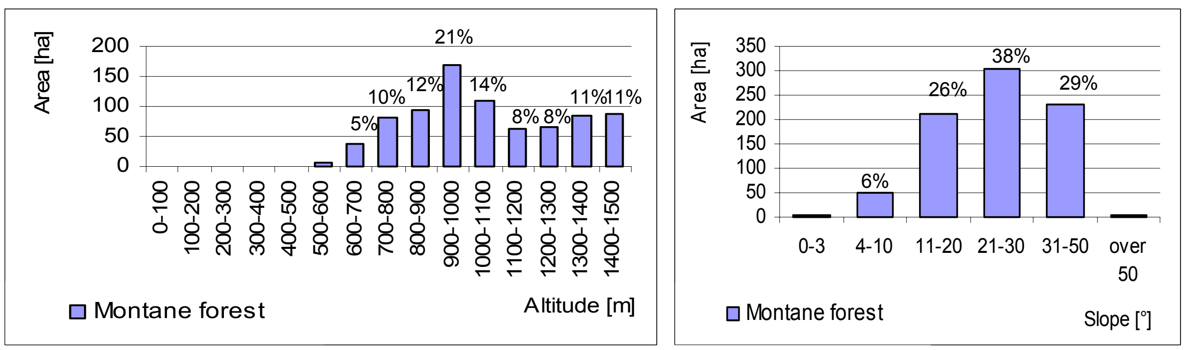


Fig. 55: Distribution of altitudes and slopes within the land-cover class 'Montane forest'.

The LCC Label of the class is as follows: Broadleaved Evergreen Fragmented (Cellular) ((70-60) - 40%) Woodland; Lithology: Igneous plutonic rock - Granite; Soils: Soil Surface, Stony (5 - 40 %), Subsurface: Ferralsols; Climate: Subtropics Winter Rainfall - Moist semi-arid; Altitude: 800 -1500 m; Erosion: Water Erosion - Gully / Closed Medium High Shrubland (Thicket). The LCC Level: A3A11B2C2D1E1-A12B6C5M111N2N4N1109O3 O12P10Q8 / A4A10B3-B9

The class (19) 'Sedimentary rocks' was distinguished and mapped by means of SRTM – DEM and GIS layer of geology. Only slopes over 50° occurring on sedimentary parent rock were automatically included in this class. The spatial resolution of the DEM (90m) allowed mapping of only large reefs, cliffs and escarpments. Local, limited rock outcrops could not be recognised by this approach.

Fig. 56: Sedimentary rocks

As apparent from the figure 57, most of the class is formed by long cliffs and escarpments separating limestone plateaus from coastal (and inland) plains. It refers particularly to edges of limestone plateaus of Keyrakh and Quatariyah in the south, Falang plateau in the southeast, Momi plateau in the northeast and Khaidhehd'e plateau in the northwest of Socotra. Total area of the class, as mapped by the 90m resolution DEM, amounts to cca 1100ha.

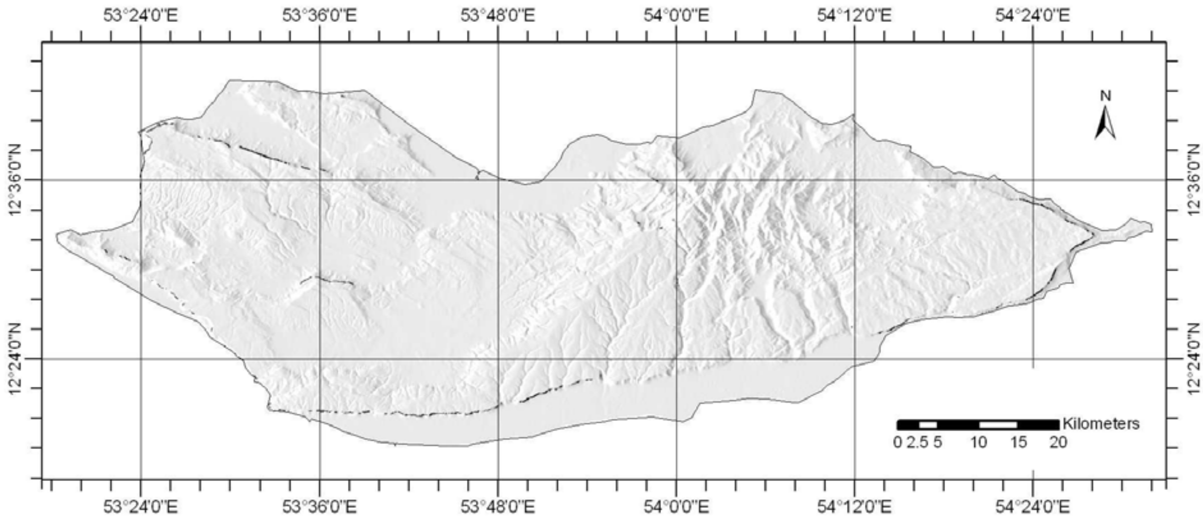


Fig. 57: Spatial distribution of 'Sedimentary rocks' on Socotra.

Distribution of slopes within the class (see Fig. 58) shows that some slopes lower than 50° occur. This is caused by generalization of the final map output, which was performed by majority filtering using mowing window of 5x5 pixels (see chapter 3.4.). The mean calculated slope is approximately 54°.

Majority of the cliffs occur in lower elevations, as their foothills mostly lie on coastal plains. Thus the altitudes range from about (50)100 to 700m above sea level (see Fig. 58). The average altitude of its occurrence is approximately 390 m (Tab. 5).

Accordingly, most of the class (over 70%) lies in the 2nd altitudinal vegetation zone, the highest parts belongs to the 3rd AVZ.

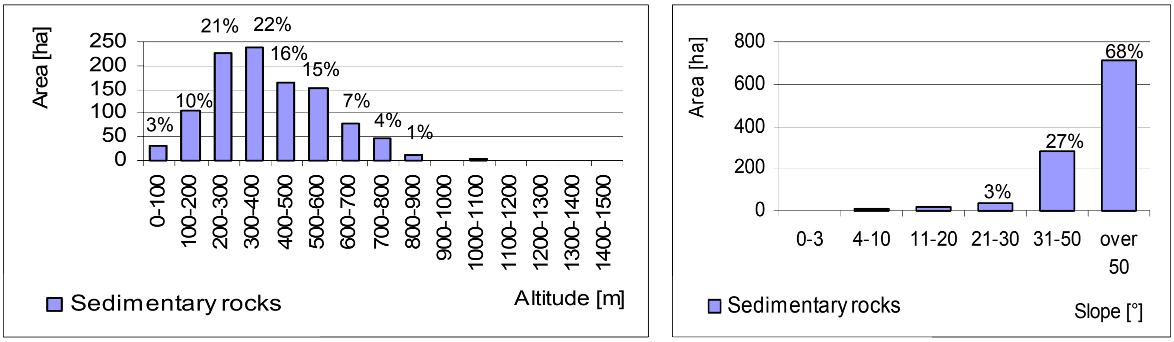


Fig. 58: Distribution of altitudes and slopes within the land-cover class 'Sedimentary rocks'.

As most of the sharp plateau edges are formed by older (Jurasic) Calcareous sediments, this rather less freqent bedrock constitute better part of the class (over 70%); the rest is formed by Dolomitic limestone (see Fig. 75).

The vegetation of sedimentary rocks is characterised by such species as *Boswellia dioscorides, Boswellia bullata, Boswellia popoviana, Boswellia nana, Dorstenia gigas, Adenium obesum* ssp. *sokotranum*, ocassionaly also by *Dracaena cinnabari* and *Jatropha unicostata*. Herbs are represented e.g. by *Kalanchoe farinacea* (HABROVÁ 2004).

This landcover class can be truly ascribed to biotope type R.1. – Limestone rocks (*toyo*) of HABROVÁ (2004).

The LCC Label of the class is: Bare Rock and/or Coarse Fragments; Major Landclass: Steep Land, High-Gradient Escarpment Zone, Slopeclass: Steeply Dissected to Mountainous; Lithology: Calcareous rock - Algal/reefal limestone; Altitude: 100 - 800 m. LCC Level: A3-L33L9M235P9.

The class (20) 'Basement rocks' is analogical to the previous, nevertheless, confined to igneous and metamorphic rocks. Similarly as in the case of Sedimentary rocks, only major cliffs and rocks could be delineated by means of the DEM. The class covers an approximate area of 150ha.

Fig. 59: Basement rocks

As shows the figure 60, the pattern of occurrence is quite different in comparison with the previous class. It occurs in form of small patches only in central Haggeher Mts.

The distribution of altitudes, as displayed in the figure 61, is apparently bimodal. The first peak between 200 and 300m reflects rocks and cliffs rising from low rolling hills, which are found at the foothills of Haggeher Mts. The second peak falling in the range of altitudes from 800 to 1100m a.s.l. corresponds to a series of characteristic pinnacles of Haggeher Mts. (see Fig. 59). The mean attitude of the class is cca 730m, high value of standard deviation points at wide range and high variability of incident altitudes (see Tab. 5).

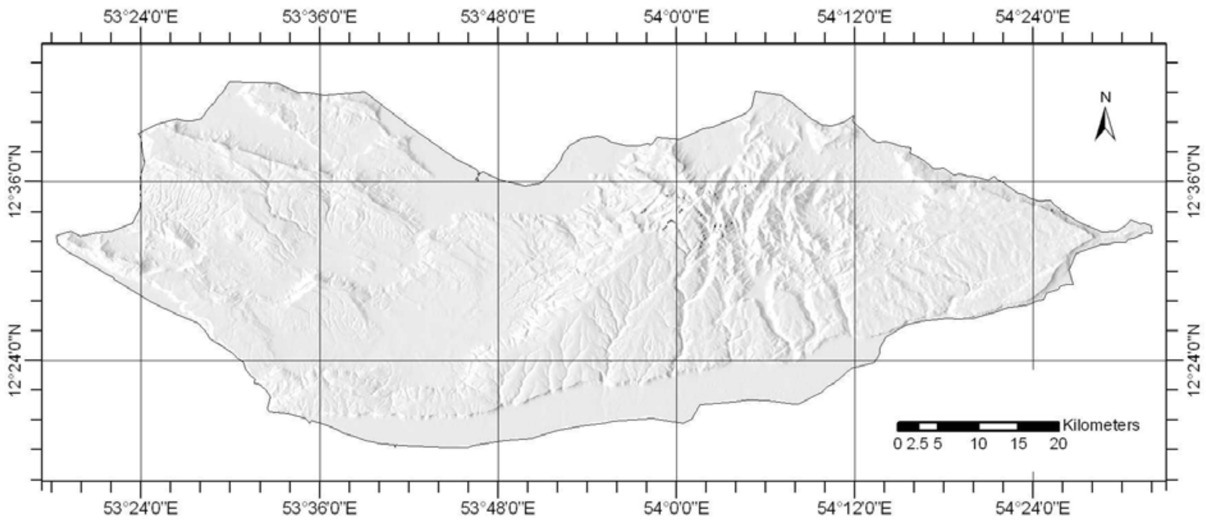


Fig. 60: Spatial distribution of 'Basement rocks' on Socotra.

Consequently, basement rocks occur in all altitudinal vegetation zones of Socotra, though, in particular in the 2nd, the 3rd and the 4th AVZ (see Fig. 83).

Representation of parent rocks is rather uniform – about 90% consist of Riebeckit; the rest is formed by Schist, Gneiss and Andesite.

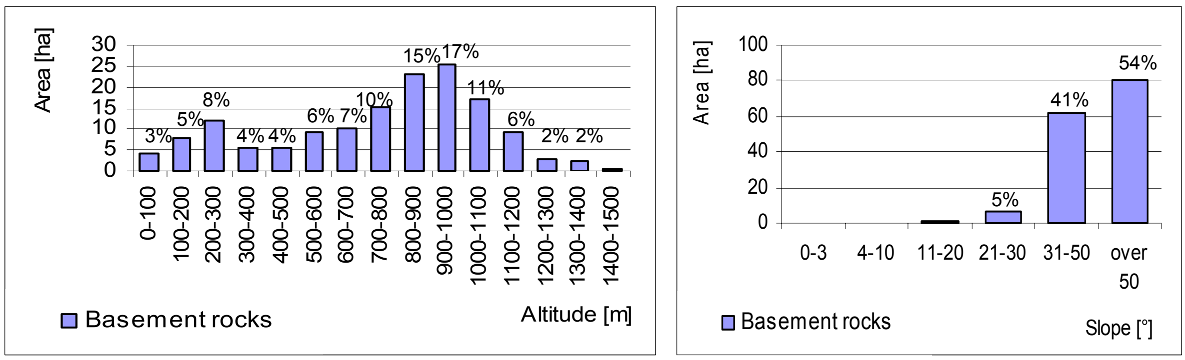


Fig. 61: Distribution of altitudes and slopes within the land-cover class 'Basement rocks'.

The vegetation of basement rocks was described by POPOV (1957) as follows: The rock vegetation does not reach the same development on granites, as on the limestone. The surface of rocks is covered with lichens so thickly that the naturally pink granite appears grey from a distance. The higher forms of flora, however, are restricted to the occasional fissures, where succulents such as *Kalanchoe farinacea, K. rotundifolia, Aloe perryi,* and some herbs such as *Exacum affine, E. caeruleum* and *Begonia socotrana* find a foothold. HABROVÁ (2004) in addition indicates *Dorstenia gigas*, *Adenium obesum* ssp. *sokotranum*, occasionally juveniles of *Dracaena cinnabari* and cushion vegetation such as *Helichrysum rosulatum, H. aciculare, Nirarathamnos asarifolius, Hemicrambe fruticosa,* etc.

The class 'Basement rocks' can be directly ascribed to biotope type R.2. – Granite rocks (*toyo*) of HABROVÁ (2004).

According LCCS it is labelled as: Bare Rock(s); Major Landclass: Steep Land, High-Gradient Mountain, Slopeclass: Steeply Dissected to Mountainous; Lithology: Igneous rock; Altitude: 500 -1500 m. LCC Level: A3-A7-L31L9M1P10.

The date palm (*Phoenix dactylifera*) is the main cultivated plant on the island. The (21) 'Date palm plantations' are present over small areas along the most of the wadis and coastal lagoons. They occur in particular along streams north and south of Haggeher mountains, which are receiving a water supply from relatively humid mountains (Fig. 62 and 63). While the wadis running south are usually bordered only by narrow strip of date palms, the wadis north of Haggeher support relatively extensive areas of date palm plantations, in particular on the Hadiboh plain. It naturally corresponds with increased planting effort at the most populated site of the island. Major date palm plantations occur also on the southern seashore in the western part of Noged plain, in the east at Shu'ub and in the northeast in the wadi in Qalansiyah and near Qeyson village (approximately 5km southwest of Qalansiyah), where a brook originating in Ma'aleh karst area stems. A total area of date palm plantations, as mapped according to Landsat ETM imagery, amounts to 1620ha.

Fig. 62: Date palm plantations.

As evident from the figures 63 and 64, date palm are planted in particular on flat lowlands (more than 70% grows at altitudes not exceeding 100m and about 65% on slopes lower than 3°). However, where water-table level is high and soil permits this, they are planted even at heights above 400m (and probably higher) on slopes steeper than 10° (reported for example on Firmihin). The mean attitude of its occurrence is about 80m above sea level, the mean slope is around 4°.

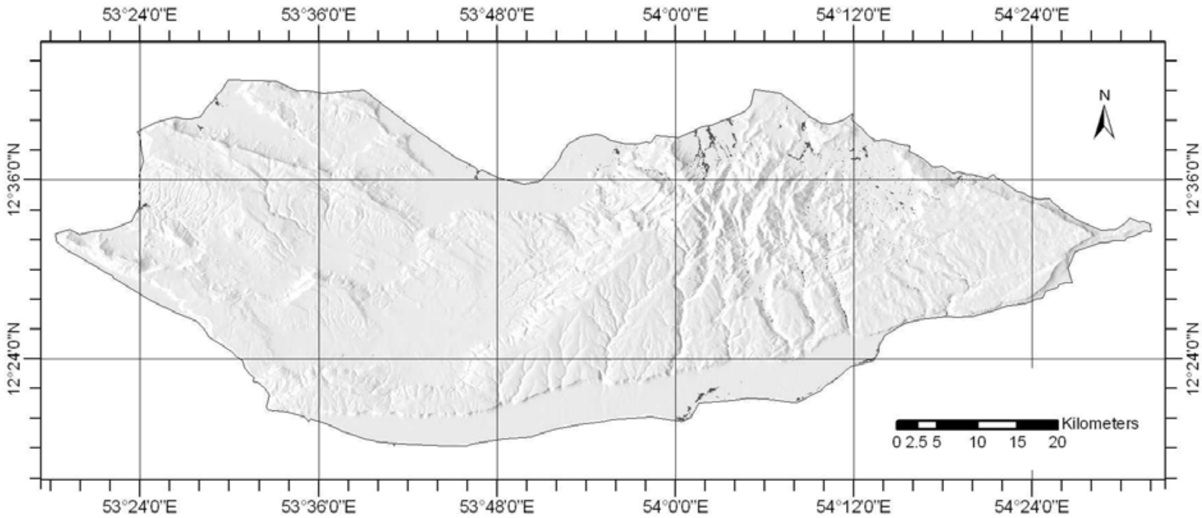
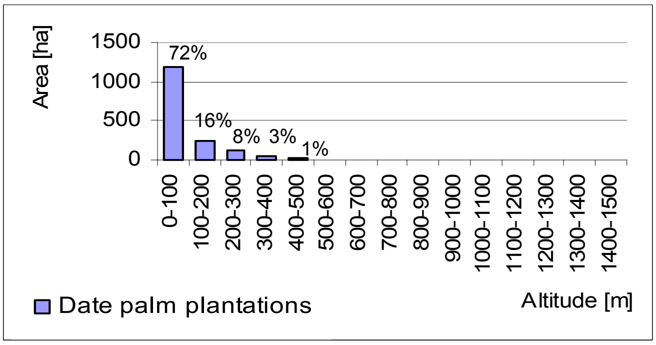


Fig. 63: Spatial distribution of 'Date palm plantations' on Socotra.

As for altitudinal vegetation zones, date palms are planted mainly in the first and partly in the second AVZ (occurrence in further AVZ's is quite marginal).

Concerning bedrocks, date palms are planted preferably on Quaternary sediments (about 50%), Dolomitic limestones and Calcareous sediments form about 15% of the parent rocks, about 14% is formed by Biotite granite and the rest are other igneous and metamorphic rocks (see figure 75).



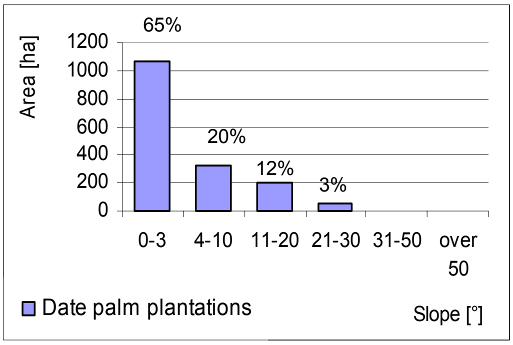


Fig. 64: Distribution of altitudes and slopes within the land-cover class 'Date palm plantations'.

The landcover class 'Date palm plantations' directly corresponds to the biotope type DP. – Date palm plantations (*hed'ob*) of HABROVÁ (2004).

The LCC Label of the class is: Monoculture of Continuous Large To Medium Sized Field(s) Of Needle-leaved Evergreen Tree Crop(s); LCC Level: A1B1B5C1-A8A9.

The (22) 'Urban' land is more or less restricted to two major sites on the northern coast: Hadiboh (and surrounding villages) in central part and Qalansiyah in the northwest. The Mouri Airport and some surrounding villages were recognised as well (see Fig. 66). The total area of the built-up land, as distinguished by means of Landsat ETM image and its classification, is about 440ha.

As evident from the figure 66, the major settlements are strongly associated with the northern coast. The reason is probably better water supply and more direct historical access to the adjacent Yemen mainland.

Fig. 65: Urban

Considering the occurrence, characteristic altitudes and slopes of this landcover class are very low (see Fig. 67). The mean altitude is about 17m above sea level and the mean slope is approximately 2°. Accordingly, the urban land lies principally in the 1st altitudinal vegetation zone (about 90%), marginally in the 2nd AVZ, and the bedrock is formed for the most part by Quaternary sediments (see figures 83 and 75).

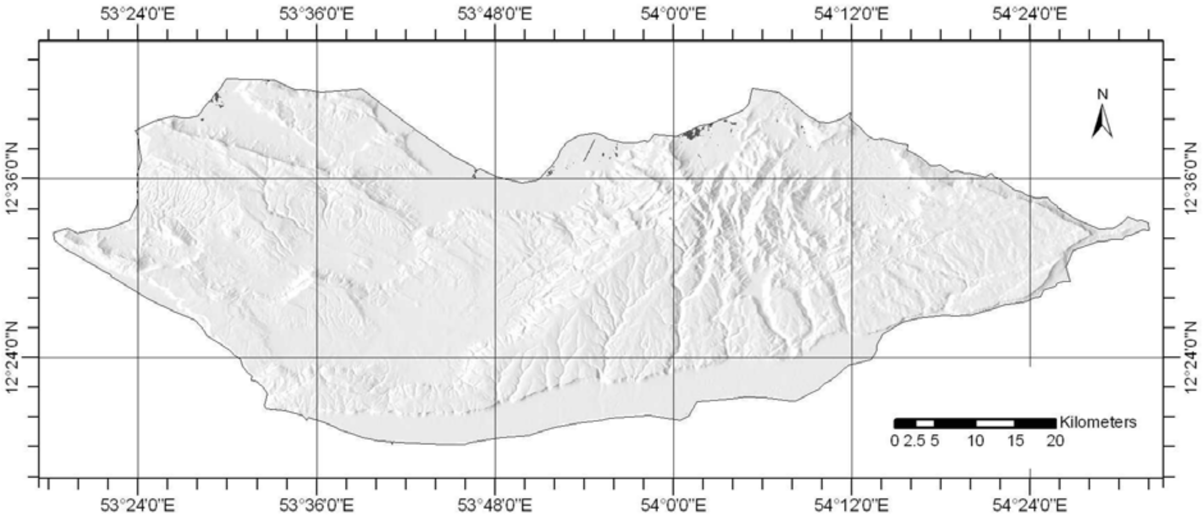
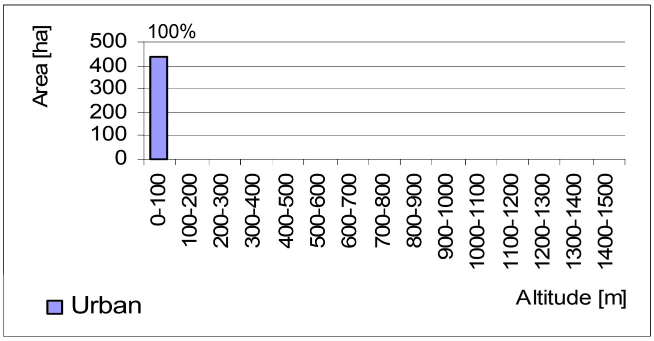


Fig. 66: Spatial distribution of 'Urban' land on Socotra.

Vegetation cover of the class is very scarce, for the main limited to some native and introduced tree species that are planted in small home gardens. In some enclosures various grasses and herbs occur and, if not grazed, they are capable to fruit (HABROVÁ 2004).



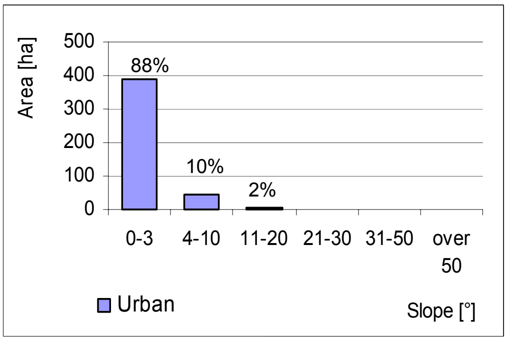


Fig. 67: Distribution of altitudes and slopes within the land-cover class 'Urban' land.

As for the biotope classification of HABROVÁ (2004), the class can be in a straight-line ascribed to the biotope type U. – Built-up land (*kajher*).

In the LCCS it would be labeled as: Urban Area(s); LCC Level: A4-A13.

The class (23) 'Savanna woodland' was not distinguishable by means of satellite imagery classification and thus, it was mapped additionally in the field during the last ground-truth in October 2004 using the global positioning system. This is also the reason, why it is described at last.

Manual interpretation of some vegetation types is in land-cover mapping practice still common, particularly in complex tropical areas (e.g. HELMER et al. 2002). The field knowledge was partly used also for final mapping of areas that were in the used Landsat ETM imagery affected by a cloud cover.

This for Socotra extraordinary vegetation type (Fig. 68) occupies solely limited area (approximately 900ha) of the Qa'arah plain in the south (see Fig. 69). As it develops (in contrast to the Frankincense woodland) only on the coastal plain, the topography is formed by altitudes ranging from 10 to 50m in elevation, while the slopes are not exceeding 3° (see also Fig. 70).

Fig. 68: Savanna woodland

Subsequently, the class is situated in the 1st altitudinal vegetation zone and the bedrock is formed only by Quaternary sediments – in this case loess.

In spite of the location on the southern coast, according to NDVI Time Series Analysis (see chapter 4.7.1.) the site seems to be quite atypically affected also by the winter monsoon (see figures 91 and 94). It may suggest a hypothesis, that the locality has specific environmental conditions formed most likely also by NE winter winds. The effect is probably allowed by unique topography of the site, where no barriers north and northeast of Keyrakh plateau occur and a depression between Keyrakh and Qatariyah plateaus (at 53° 41’ E) possibly allows a penetration of wet NE winds also to Qa’arah plain (CULEK in litt.). This phenomenon was observed and described also at the profile No. 3 in the chapter 4.7.2. (see figures 103 and 104).

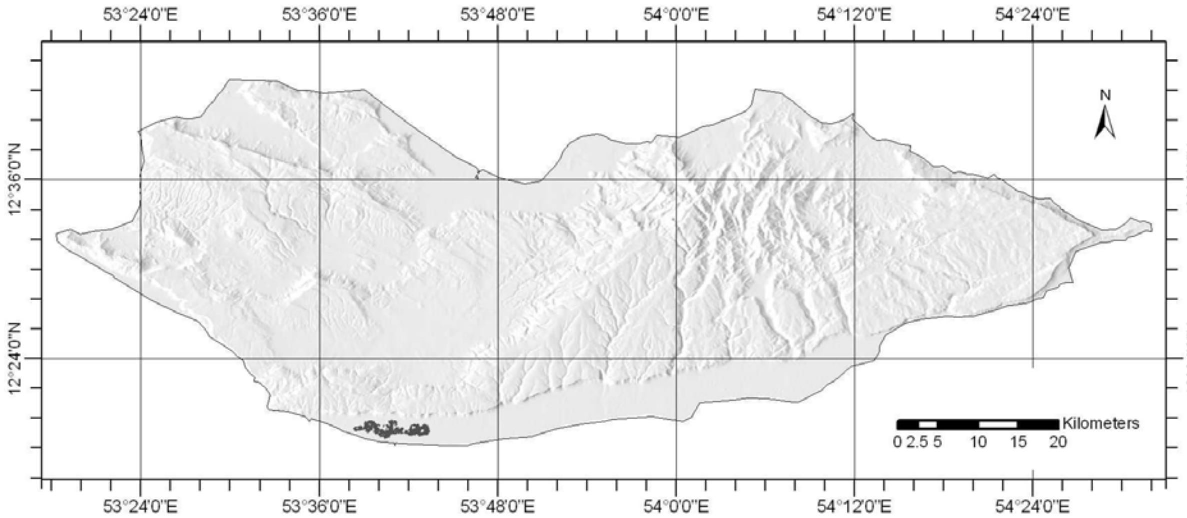
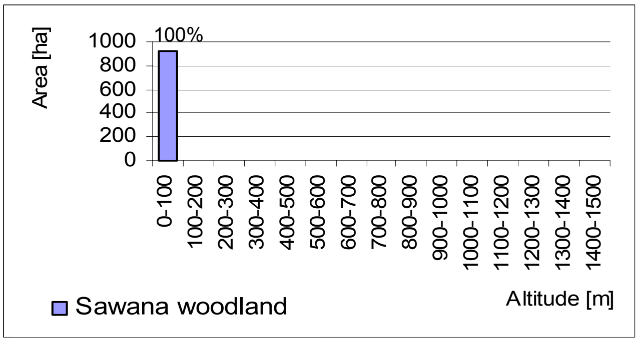


Fig. 69: Spatial distribution of ‘Savanna woodland’ on Socotra.

A sparse tree layer of the deciduous woodland (canopy about 5%) is dominated by *Commiphora ornifolia* and *Maerua angolensis* var. *socotrana*, occasionally *Dendrosicyos socotrana* and *Euphorbia arbuscula*. The shrub layer is composed of common species of coastal plains such as *Croton socotranus, Jatropha unicostata, Cissus subaphylla*, etc. (HABROVÁ 2004).

Concerning biotope types described by HABROVÁ (2004), the class has a direct counterpart in the biotope W.4. – Savanna woodland (*ekeshi-ejhahab*).



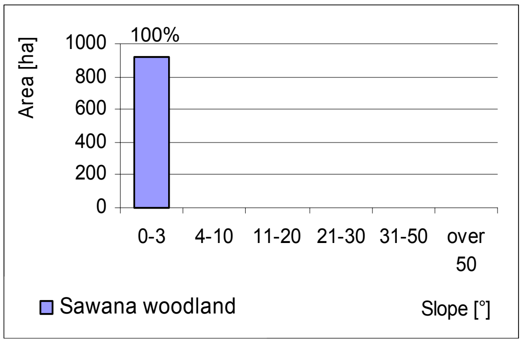


Fig. 70: Distribution of altitudes and slopes within the land-cover class 'Savanna woodland'.

The LCC label of the class is: Semi-Deciduous (40 - (20-10)%) Woodland With Open Medium High Shrubs; Major Landclass: Level Land, Plain, Slopeclass: Flat to Almost Flat; Lithology: Sedimentary rock; Climate: Tropics - Dry semi-arid; Altitude: < 50 m; Erosion: Visible Evidence of Erosion; Floristic Aspect: *Commiphora ornifolia*; LCC level A3A11B2C1D1E2F2F6F7G3F1-A13B7E4F9G9-L11L5M2N1128O1O1 1P5Q2Zt22.

No.	Land-Cover class (KRÁL 2004)	Biotope code	Biotope Type (HABROVÁ 2004)
1	Sea	-	-
2	Mangroves	F.2.	Mangrove forest
3	Coastal salted desert	DS.2.	Salted desert
4	Wetlands	Wt.	Coastal lagoons
5	Wadi	Wa.	River beds
		W.5.	Riverine woodland *(ocassionally in wadi beds)
		S.1.2.	Ficus Shrubland *(ocassionally in wadi beds)
6	Sand dunes	DS.1.	Sand dunes
		S.2.6.	Tamarix shrubland *(marginally on Noged plain)
7	Sparse dwarf shrubland	S.3.1.	Dwarf shrubland from lowland and low highland
		S.3.3.	Dwarf coastal shrubland *(Noged, Neet)
		S.2.7.	Low coastal shrubland *(Neet, Shu'ub - sparse form only)
		D.1.	Degraded land *(surroundings of Hadiboh)
		S.2.1.	Croton shrubland *(sparse form)
8	Low Croton-Jatropha shrubland	S.2.1.	Croton shrubland
		S.2.2.	Jatropha shrubland
		S.2.3.	Mixed deciduous shrubland
		S.2.7.	Low coastal shrubland *(Neet, Shu'ub)
		S.1.4.	Myrrh tree shrubland *(only in the 2nd AVZ)
9	High shrubland with succulents	S.1.3.	Succulent shrubland
		S.2.2.	Jatropha shrubland
		S.2.3.	Mixed deciduous shrubland *(marginally)
		S.1.4.	Myrrh tree shrubland *(marginally)
10	Frankincense woodland	W.2.	Deciduous frankincense woodland
		W.6.	Debris woodland
11	Frankincense forest	F.3.	Deciduous frankincense forest
		F.5.	Debris forest
12	Dracaena woodland	W.1.	Dragon's blood tree woodland
		S.2.4.	Low shrub. with Croton soc. "B" and/or Buxantus pedicelatus *(marginally)
13	Dracaena forest	F.1.	Dragon's blood tree forest
14	Submontane grassland and dwarf shrubland	G.2.	Pastures on limestone plateaus
		S.3.2.	Dwarf shrubland from highland *(sparse form)
		S.3.4.	Eolic dwarf shrubland *(particularly at Ma'aleh)
15	Submontane shrubland	S.2.4.	Low shrubland with Croton socotranus "B" and/or Buxantus pedicelatus
		S.2.5.	Lycium shrubland *(Ma'alah)
		S.3.2.	Dwarf shrubland from highland
16	Montane grassland	G.1.	Cleared pastures on granite
		S.3.5.	Dwarf montane shrubland with Hypericum scopulorum *(sparse form)
17	Montane mosaic	S.3.5.	Dwarf montane shrubland with Hypericum scopulorum
		S.1.1.	Evergreen montane shrubland
		W.3.	Montane woodland
18	Montane forest	F.4.	Montane forest
		W.3.	Montane woodland *(marginally)
19	Sedimentary rocks	R1	Limestone rocks
20	Basement rocks	R2	Granite rocks
21	Date palm plantations	DP.	Date palm plantations
22	Urban	U.	Build-up land
23	Savanna woodland	W.4.	Savanna woodland

Tab. 4: A conversion table between land-cover classes and biotope types recognised and described by HABROVÁ (2004), * note specifying a range of occurrence.

4.3. Summarized ecotope and landcover characteristics of the island

Overall terrain characteristics of Socotra are based on DEM coming from the Shuttle Radar Topography Mission (SRTM) and having spatial resolution 90m. Approximation of an area of altitudinal belts (the ranges of altitude are 100m) is presented in the figure 71. Similar approximation was introduced by MIES et BEYHL (1996), though distinguishing only 4 major altitudinal regions (vs. 15 altitudinal belts of this analysis). The improvement of the analysis was possible thanks to sufficient resolution of the SRTM DEM data, which are recently disposable worldwide free of charge.

Os one can observe, the altitudinal range 0-100m a.s.l. is dominating on Socotra (area more than 80 000ha) comprising low coastal plains, which occur on both, southern and northern shores of the island (see also a hypsography map in appendix No. 3). The distribution of altitudes reveals a secondary peak around the range of elevation 300-400m a.s.l. that is formed by wide-spread limestone plateaus (area of this range is about 50 000ha; a combined area of the altitudinal range 300-600m a.s.l. is more than 120 000ha). From that point the areas of higher altitudes are sharply decreasing. Not more than 4000ha range above 1000m a.s.l. and only 1000ha above 1200m a.s.l.

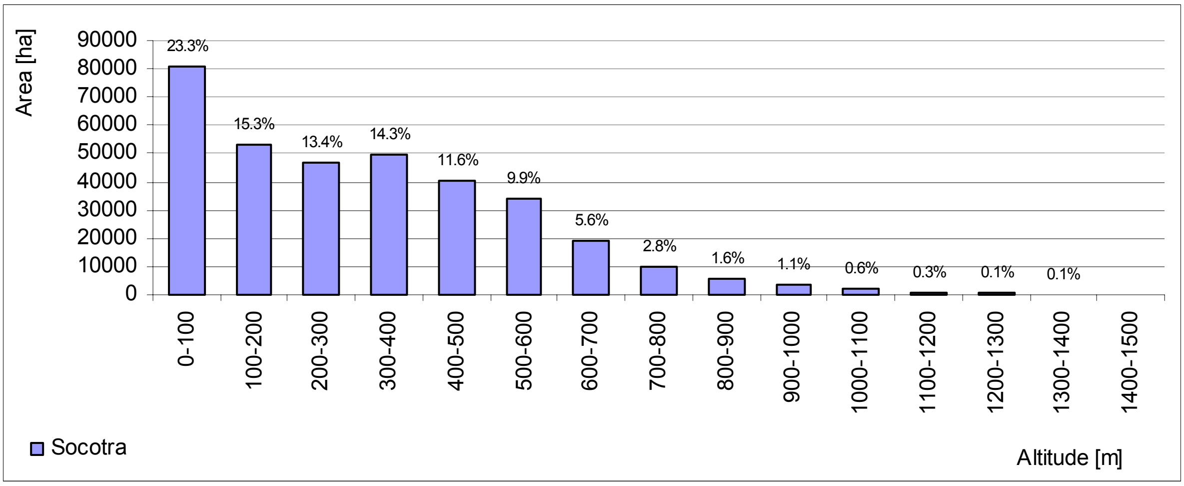


Fig. 71: Distribution of terrain altitudes within the island.

Analogical analysis was newly carried out also for slope classes. Not surprisingly the flat terrain predominates, as better part of the island falls either within coastal /inland lowlands or limestone plateaus (see figure 72 and appendix No. 4 – map of slopes). Accordingly, both slope classes 0-3° and 4-10° cover an estimated area exceeding 115 000ha (33%) per each. While the former class can be largely associated with costal and inland plains, the latter is mostly pertinent to limestone plateaus. The slopes of the range 11-20° are affecting on estimated area 65 000ha (19% of the area of the island). This is often the question of valleys of sporadic watercourses either on limestone plateau or basement rocks. Steeper part of low rolling hills which often makes a transition between lowlands and both limestone plateaus and Haggeher Mts. falls within this slope class as well. These slopes occur also in Haggeher Mts. particularly on localities of 'Montane grassland'. The class representing a range of slopes from 21 to 30° cover an approximate area of 34 000ha (10% of total area). It affects in deep wadi canyons on limestone plateaus (e.g. Darho, Esgego, Azrho, Farho, Ohgash, etc.) and particularly in Haggeher Mts, where it predominates (see also appendix No. 5). The slope class 31-50° (more than 14 000ha and 4% of total area) occur especially in western (and the most elevated) part of the Haggeher Mts and similarly as the previous class it covers steep slopes of wadi canyons. Together with the steepest slope class (slopes over 50° - i.e. 1000ha and 0,3% of total area) it represents cliffs, which often separate the limestone plateaus from the coastal plains e.g. Noged plain on the south and similarly the Khaidhede plateau from Djaahel plain on the west. It also encloses Momi and Falang plateaus on the southeast and Beghihem and Ajdhedjo plateaus on the southwest (i.e. mostly the land-cover class 'Sedimentary rocks'). The 'Basement rocks' of Haggeher Mts. of course fall in the latter slope class as well.

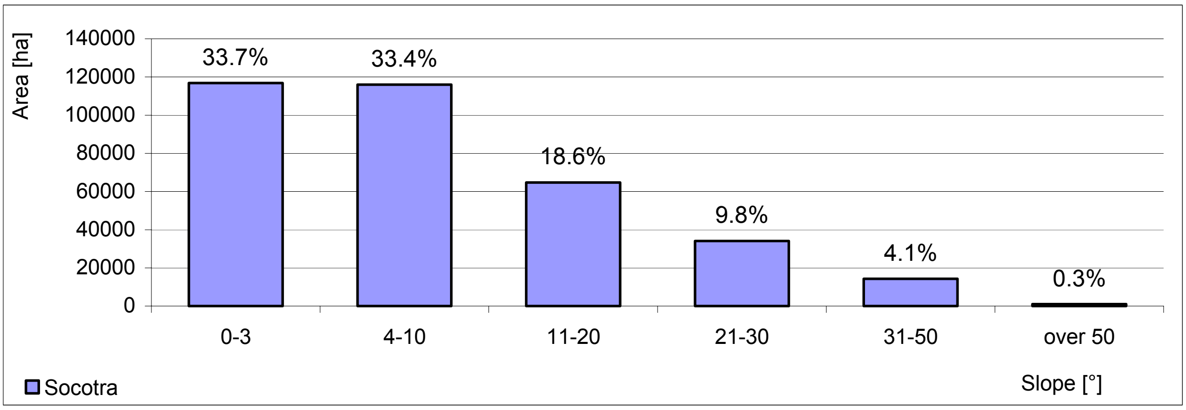


Fig. 72: Distribution of slopes within the island.

The distribution of slopes, as depicted using SRTM DEM, is probably slightly shifted in lower values thanks to resolution of the DEM. In other words, real slopes of particular sites are almost certainly a bit higher (i.e. smoothing effect of a lower spatial resolution).

As it evolved from the description of particular land-cover classes in previous subchapter (No. 4.2.), most of the classes have specific pattern of occurrence concerning the elevation and steepness of slopes. These typical terrain characteristics are summarised in different form in the table 5. A mean altitude and a mean slope demonstrate a general level of topography conditions, while the values of standard deviations of both statistics uncover possible variability of those conditions. The minimum and maximum values were found inadequate for similar purpose, since they represent extreme values, which often correspond to misclassified pixels. The extreme values may also be affected by miss-overlays of GIS layers with diverse spatial resolution (e.g. 30m of land-cover vs. 90m of DEM). Analogical statistical analysis was used for example by KIMBALL et WEIHRAUCH (2000) evaluating topography conditions of alpine vegetation communities in New England.

Estimates of the area and degree of coverage of particular land-cover classes within Socotra Island are summarised in figure 73 and listed also in table 6. As one can observe, five major land-cover classes cover more than 88% of total area of the island. The flat lowlands are to a large extend covered by 'Sparse dwarf shrubland' (cca 14% of total area) and 'Low Croton-Jatropha shrubland' (cca 32% of total area of the island). The slopes of low and middle elevations are mostly covered by 'High shrubland with succulents' (14% of total area). The last two principal land-cover classes 'Submontane grassland and dwarf shrubland' and 'Submontane shrubland' are closely associated with limestone plateaus. They cover cca 20% and 9% of the total area respectively.

A combined area of all woodlands and forests of the island (all vegetation formations that are determined by a tree cover with min. canopy closure 5%, though with exclusion of 'Date palm plantations') is about 19 400ha (i.e. 5.5% of total area).

Built-up land together with the Date palm plantations occupy less than 1% of the total land area. The figure is lower than the estimate of MIES and BEYHL (1996), who assumed that the settlement areas and plantations (including date-palm grows and small gardens) take up less than 2% of the land area.

No.	Land-cover class	Mean Altitude [m]	Mean Slope [°]	Stand. Dev. Altitude	Stand. Dev. Slope
2.	Mangroves	0	0	-	-
3.	Coastal salted desert	5	1	2	2
4.	Wetlands	4	3	6	5
5.	Wadi	96	4	77	6
6.	Sand dunes	40	7	69	12
7.	Sparse dwarf shrubland	85	4	92	6
8.	Low Croton-Jatropha shrubland	184	7	125	7
9.	High shrubland with suculents	322	19	150	11
10.	Frankincense woodland	507	22	207	10
11.	Frankincense forest	633	25	205	9
12.	Dracaena woodland	624	15	206	9
13.	Dracaena forest	647	12	54	7
14.	Submontane grassland and dwarf shrubland	481	8	140	6
15.	Submontane shrubland	606	8	147	6
16.	Montane grassland	1010	13	109	7
17.	Montane mosaic	981	24	197	10
18.	Montane forest	1055	25	241	10
19.	Sedimentary rocks	391	54	166	6
20.	Basement rocks	733	53	309	5
21.	Date palm plantations	79	4	104	5
22.	Urban	17	2	16	3
23.	Savanna woodland	26	1	7	1

Tab. 5: Topography statistics of particular land-cover classes.

A total area of the island as calculated according to the land-cover map is 350 490ha. This figure is somewhat lower than the area usually quoted in literature (over 360 000ha). The disagreement might be caused either by misclassification of mixed edge pixels on the coastline (sea / land confusion) or by insufficient geocoding of the input Landsat image. Particularly in the southern part of the island there is a lack of natural distinct land-shapes that could be used as ground control points.

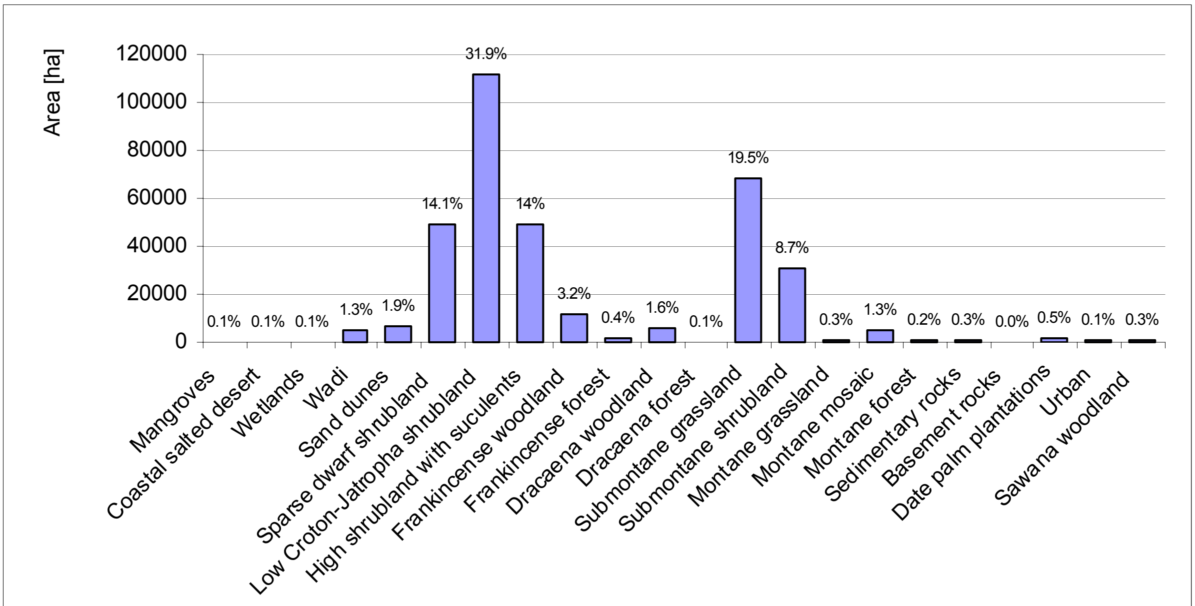


Fig. 73: Approximate area of particular land-cover classes and their proportion in the total area of the island.

No.	Land-cover class	Area [ha]	% of Total
2.	Mangroves	177	0.1%
3.	Coastal salted desert	243	0.1%
4.	Wetlands	390	0.1%
5.	Wadi	4699	1.3%
6.	Sand dunes	6606	1.9%
7.	Sparse dwarf shrubland	49574	14.1%
8.	Low Croton-Jatropha shrubland	111638	31.9%
9.	High shrubland with suculents	48911	14.0%
10.	Frankincense woodland	11359	3.2%
11.	Frankincense forest	1258	0.4%
12.	Dracaena woodland	5765	1.6%
13.	Dracaena forest	234	0.1%
14.	Submontane grassland and dwarf shrubland	68409	19.5%
15.	Submontane shrubland	30535	8.7%
16.	Montane grassland	1012	0.3%
17.	Montane mosaic	4586	1.3%
18.	Montane forest	822	0.2%
19.	Sedimentary rocks	1141	0.3%
20.	Basement rocks	150	0.0%
21.	Date palm plantations	1619	0.5%
22.	Urban	440	0.1%
23.	Savanna woodland	925	0.3%
	TOTAL	**350490**	**100.0%**

Tab. 6: Area and proportion of particular land-cover classes on Socotra Island.

Figure 74 shows proportions of main geological units on Socotra as calculated from the geology map (ANON. 1990). One can observe that more than 50% of the parent rock of Socotra is shaped by Tertiary dolomitic limestone, 7% by Jurassic calcareous sediments and 22% is formed by Quaternary sediments. Among the basement rocks the Peralkine granite (Riebeckit) prevails (7% of total area) as the main parent rock of the Haggeher Mts.

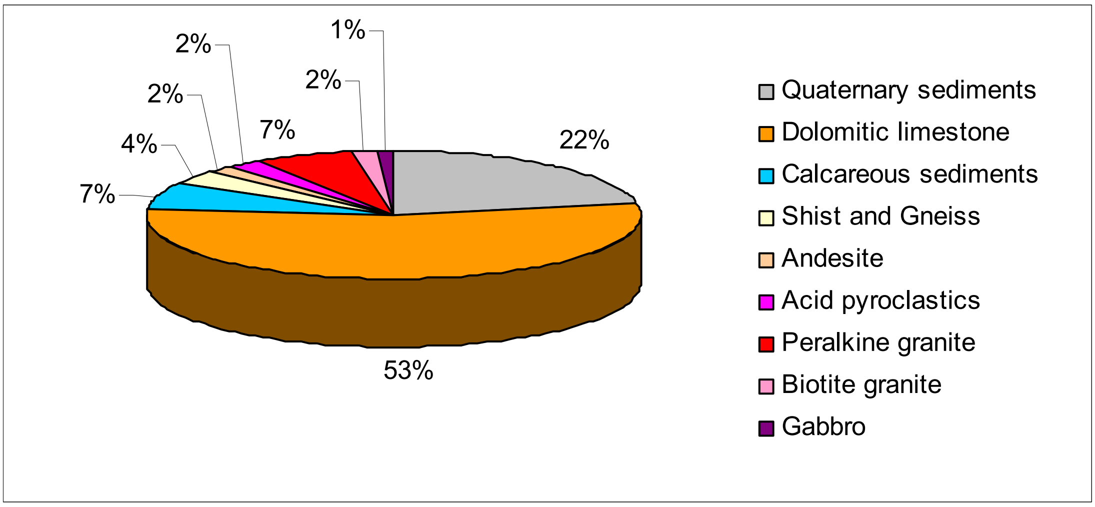


Fig. 74: Proportion of main bedrocks in the total area of Socotra Island.

A relation between geological units and land-cover classes is demonstrated in the figure 75. Some land-covers exhibit strong fidelity to the particular parent rock, nevertheless, in most cases it is rather the question of a coincidence with major physiographic zones of characteristic topography and altitudinal range (low costal plains – quaternary sediments; elevated limestone plateaus – dolomitic limestone and calcareous sediments; upland Haggeher – igneous and metamorphic rocks).

Moreover, the disposable GIS layer of geology was obviously spatially inaccurate at some places and therefore some mis-overlaps might occur. This is for example the question of 'Coastal salted desert' and 'Wetlands', which actually probably completely lie on quaternary sediments, although in the figure 75 appear to encroach other bedrocks.

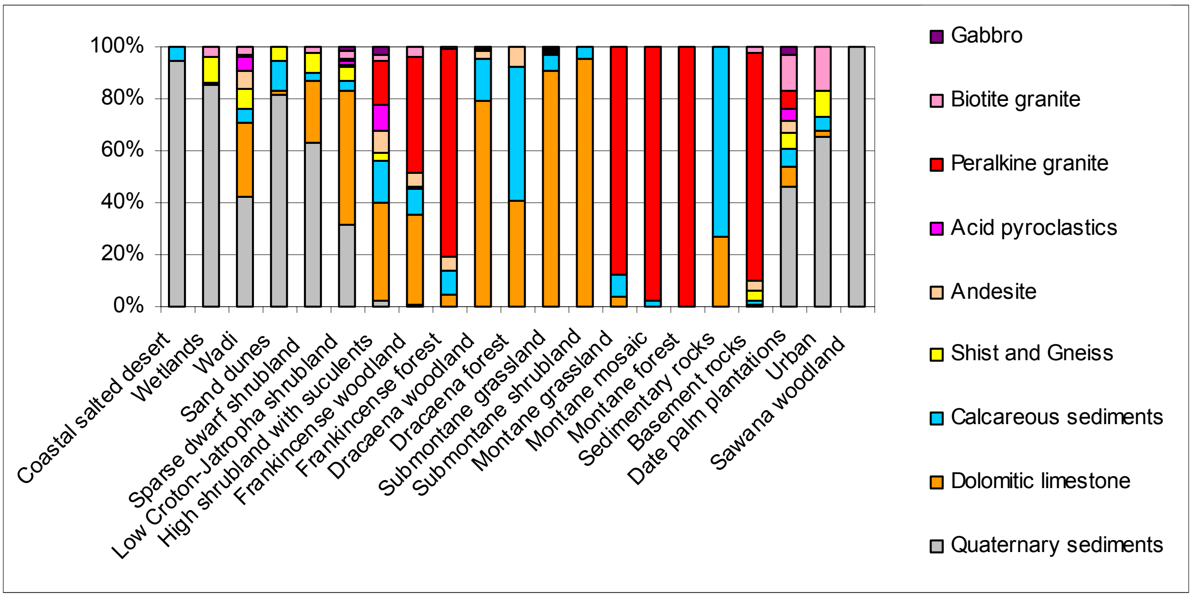


Fig. 75: Cross-tabulation of terrestrial land-cover classes (X axis) and geological units(Y axis).

4.4. Comparison of the land-cover map with historical and current vegetation maps

4.4.1. Tentative vegetation map of GWYNNE (1968)

The Gwynne's map (GWYNNE 1968) was very simple and distinguished only six major vegetation types (see figure 76). Its major importance is given by the fact that it is the first known vegetation map of Socotra. Due to its simplicity any comparison with later maps may be only approximate.

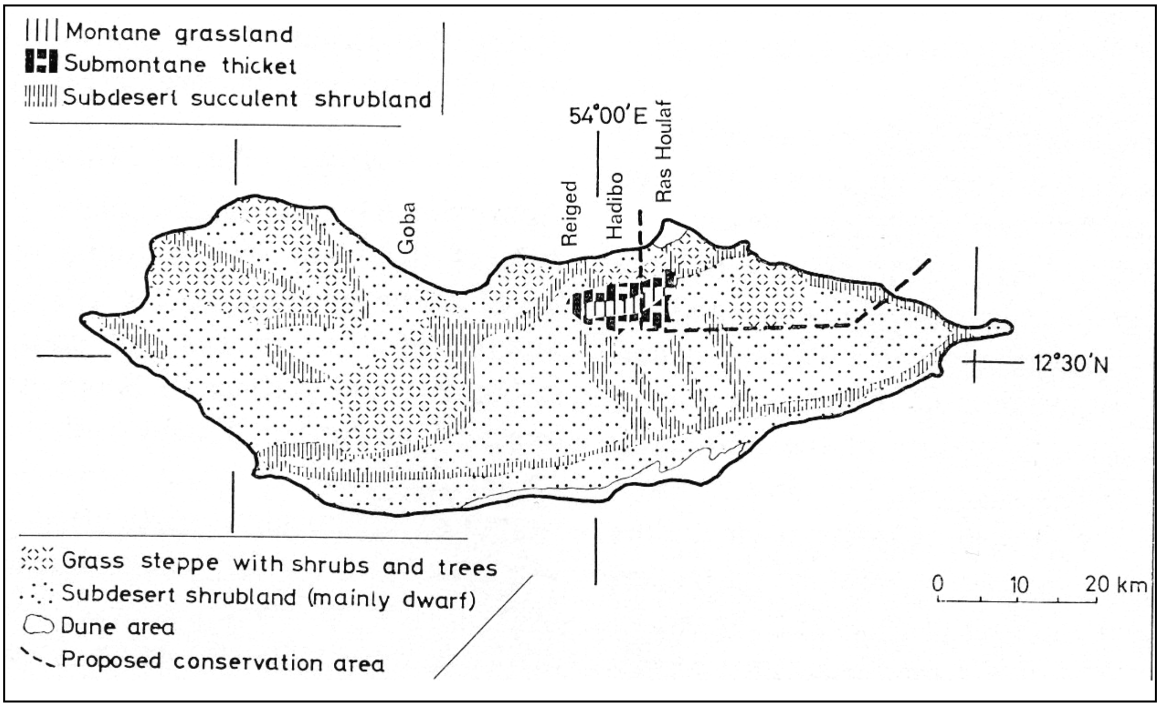


Fig. 76: Tentative vegetation map of Socotra. The map is based on personal observations, the published account of POPOV (1957) and on topographic and vegetational detail obtained from a near vertical space photograph. This map does not show the Herbaceous Halophylous Plant formations of the coast, Mangrove, Lowland Thicket and Fresh Water Swamp Formations (GWYNNE 1968).

Appropriate land-cover classes are roughly ascribed to the six Gwynne's general vegetation types as follows:

(1) 'Montane grassland' and evergreen (2) 'Submontane thicket' after Gwynne ocupy the highest locations of the Haggeher. The montaneous land-cover classes (i.e.'Montane grassland', 'Montane mosaic' and 'Montane forest') may be more or less directly ascribed to those two Gwynne's vegetation types.

(3) 'Subdesert succulent shrubland' occurs according to Gwynne on similar sites as the LC class 'High shrubland with succulents'. It covers steep slopes and hill-sides and mostly remains dominant there. Nevertheless, it was mapped in a lesser extend that the current land-cover class.

(4) 'Grass steppe with shrubs and trees' is rather a general vegetation type. According to Gwynne's map it covers some of the northern coastal plains such as Karma and Lhasi and the inland basin the Zahr as well as the Ma'alah limestone plateau. The recognition of this vegetation type remains unclear, as it generally matches the same land-cover classes as the following Gwynne's vegetation type (5). In addition, any marked presence of trees is not recently known from concerned sites, except rare riwerine woodlands, which occasionally border some of the wadi beds in coastal plains.

(5) 'Subdesert dwarf shrubland' is again rather ambiguous vegetation type comprising most of the coastal plains and limestone plateaus. The major land-cover classes of lowlands and plateaus such as 'Sparse dwarf shrubland'; 'Low Croton-Jatropha shrubland';

'Submontane grassland and dwarf shrubland' and 'Submontane shrubland' might be attributed to this Gwynne's vegetation type.

(6) 'Dune area' was mapped relatively very precisely. Major 'Sand dunes' distinguished by the classification of Landsat ETM image on Howlef and Noged look a lot like those in the map of Gwynne.

4.4.2. Map of principal vegetation types (MILLER et MORRIS 2000; 2004)

Relatively recent vegetation map (appendix No. 7) was introduced by MILLER and MORRIS (2000; 2004). The authors themselves admitted that the description of vegetation presented problems (MILLER et MORRIS 2004): "There is some altitudinal zonation, but over most of the island there is a mosaic of related vegetation types, which although floristically related can be physiognomycally very distinct. The system below is based on physiognomy, but reflects floristic differences as far as possible".

They have recognised six principal vegetation types on Socotra (in fact seven, but the first one – 'Coastal vegetation' - was reportedly too narrow to be mapped). A brief description of Miller's vegetation types as well as an approximate comparison with new land-cover classes is presented below. Terrestrial classes distinguished in both map concepts were cross-tabulated using the GIS overlay. The results are shown in figures 77 and 78 (see also the Appendices No. 2 and 7).

(1) Coastal vegetation:

a. Mangroves: Mangrove thicket [<5m] Dominants: *Avicennia marina*.

This vegetation type can be truly ascribed to the land-cover class 'Mangroves'.

b. Coastal plains: Mosaic of low succulent shrubs [<1.5m] and woody-based herbs [<0.5m] and patches of shrubland [<3m]. Dominants: various, including *Limonium sp.*, *Tamarix nilotica, Suaeda* sp. and *Atriplex* sp.

Although this vegetation type was according to Miller and Morris rather marginal, new land-cover map distinguish similar class 'Sparse dwarf shrubland' on relatively large areas on coastal and inland plains. Nevertheless, the latter class is based more on physiognomy and degree of coverage than on floristic differences and therefore it is not restricted only to halophytic coastal communities.

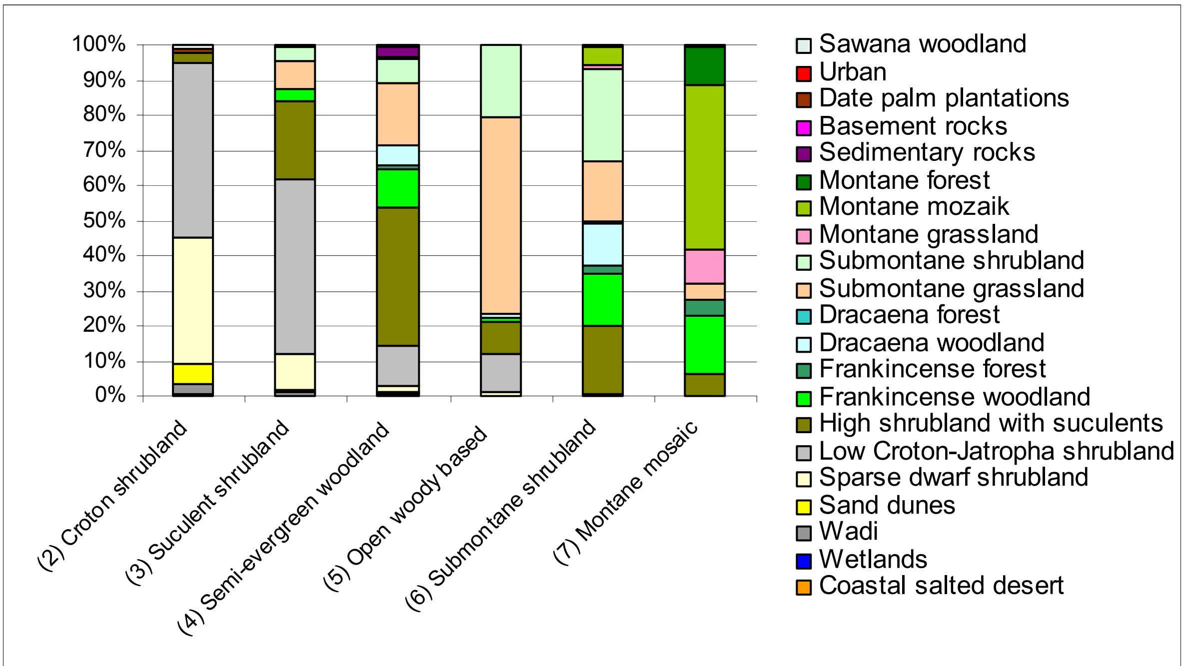


Fig. 77: Proportion of various land-cover classes (Y axis) within particular vegetation types of MILLER and MORRIS (X axis).

(2) Croton shrubland: Deciduous shrubland [<2.5m] with scattered emergents [<5m] and open dwarf shrub layer [<1m] below. Dominated by *Croton socotranus*. If heavily grazed the herb cover is dominated by *Cassia holosericea* and *Tephrosila apollinea*.

This vegetation type the most directly corresponds to the class 'Low Croton-Jatropha shrubland', although also big part of 'Sparse dwarf shrubland' falls in this vegetation type (see figure 77). On the other hand, the land-cover class 'Low Croton-Jatropha shrubland' covers to a large extend not only flat lowlands (as in the concept of Miller and Morris) but frequently encroaches on the hill-sides and sometimes remains dominant there, although these sites are according to Miller mapped as the following vegetation type - (3) Succulent shrubland. It reveals that the perception of Croton shrublads is in both map concepts slightly different (shifted). The figure 78 shows, that many other small land-cover classes fall in particular within the Miller's vegetation type (2) Croton shrubland. This is for example the question of 'Coastal salted desert'; 'Wetlands'; 'Wadi'; 'Sand dunes'; 'Date palm plantations'; 'Urban' and 'Savanna woodland'.

(3) Succulent shrubland: Open deciduous succulent shrubland [<4m] with emergent trees [<6m] and a lower layer [<1m] of cushion vegetation and subshrubs. Dominants: *Jatropha unicostata* and *Croton socotranus* with *Euphorbia arbuscu!a*, *Adenium obesum* and *Tephrosia apollinea.*

This vegetation type has according its description again quite direct counterpart among land-cover classes (i.e. 'High shrubland with succulents'). However, comparing the maps, the occurrence of both classes is slightly shifted. Although 'High shrubland with succulents' covers an important part of appropriate areas, another half is covered by 'Low Croton-Jatropha shrubland'. This discordance was partly described above. Moreover, also the land-cover classes confined to the limestone plateaus should according to GIS overlay fall in this vegetation type. It shows that the general map of vegetation types is locally inaccurate.

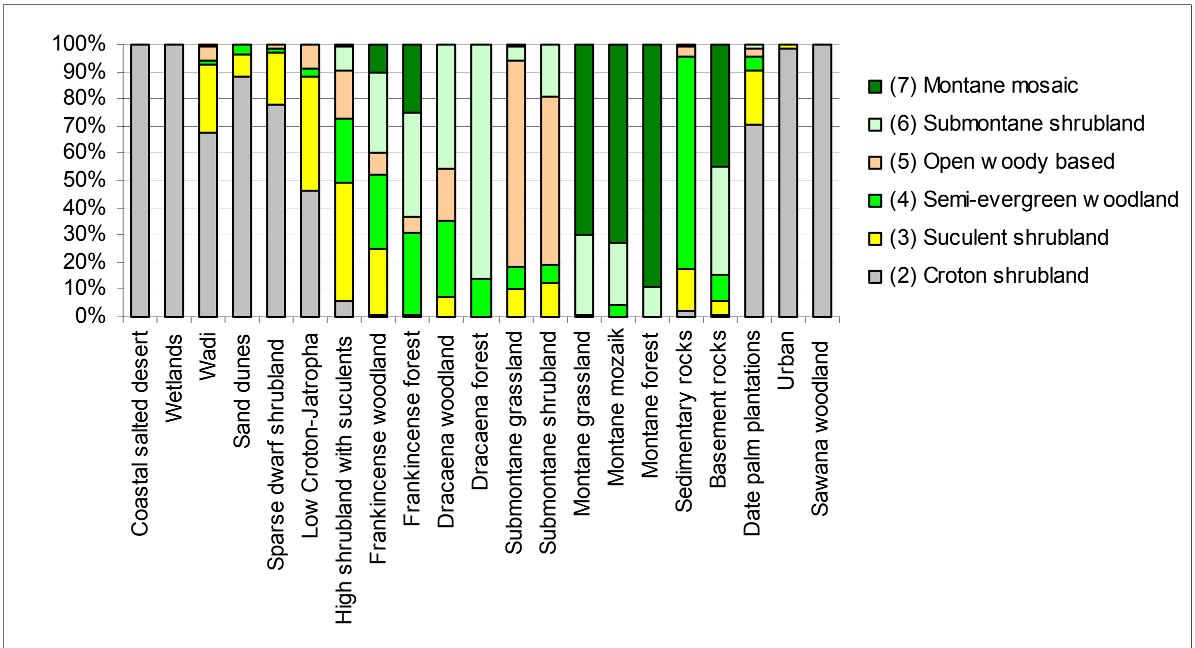


Fig. 78: Proportion of vegetation types of MILLER and MORRIS (Y axis) within particular land-cover classes (X axis).

(4) Semi-evergreen woodland: Semi-deciduous thicket [<5m] with emergent trees [<8m] Dominants: *Rhus thyrsiflora, Buxanthus pedicellatus, Carphalea obovata, Sterculia africana*.

In the map of Miller and Morris it forms relatively narrow transitional belt separating Suculent shrubland and “higher” vegetation types pertinent either to limestone plateaus or Haggeher mountains (see appendix No. 7). Hence, although it should correspond mainly to land-cover classes ‘Frankincense woodland’ and ‘Frankincense forest’, in fact it is the vegetation type without any clear counterpart in the land-cover map (see figure77).

(5) Open and woody-based herb communities: Mosaic of woody-based herb communities [<0.5m], cleared grassland and dwarf shrubland [<2m]. Relict woodlands, typically with *Dracaena cinnabari* and *Boswellia elongata*, are also occasionally found in this zone. Dominants: *Jatropha unicostata, Lycium sokotranum, Gnidia socotrana, Buxanthus pedicellatus, Croton socotranus, Leucas virgata* and *Cissus hamaderohensis*.

This vegetation type may be ascribed particularly to the land-cover class ‘Submontane grassland and dwarf shrubland’ (more than 55%), more elevated parts than to the ‘Submontane shrubland’ (cca 20%, see figures 77 and 78).

(6) Submontane shrubland: Semi-deciduous shrubland [<5m] with emergent *Dracaena* [<8m] and cleared grassland. Dominants: *Dracaena cinnabari, Rhus fhyrsiflora, Euryops arabicus, Buxanthus pedicellatus, Gnidia socotrana* and *Cocculus balfourii*.

It is again rather dichotomous vegetation type comprising higher parts of limestone plateaus as well as lower parts of Haggeher mountains (see the figure). Thus, in GIS overlay it overlaps with land-cover classes typical for limestone plateaus as ‘Submontane shrubland’ (cca 25%); ‘Submontane grassland and dwarf shrubland’ (cca 17%); ‘Dracaena woodland’ (cca 12%) and ‘Dracaena forest’ as well as with ‘High shrubland with succulents’ (cca 20%); ‘Frankincense woodland’ (cca 15%) and ‘Frankincense forest’ (see figures 77 and 78).

(7) Montane mosaic of evergreen woodland, grassland, dwarf shrubland and cushion vegetation: Mosaic of dense evergreen woodland and thicket [<5m], patches of cleared grassland, dwarf shrubland [<1.5m] and cushion vegetation on exposed summits. Dominants: *Dracaena cinnabari, Rhus thyrsiflora, Hypericum* sp., *Helichrysum* sp. and *Euryops arabicus*.

In this case the both maps are fairly coherent. When compared with the land-cover map, about 70% of this vegetation type is covered by montaneous land-cover classes as ‘Montane grassland’ (cca 10); ‘Montane mosaic’ (almost 50%) and ‘Montane forest’ (cca 10%, see figure 77). Additional land-cover classes falling partly in this vegetation type are ‘Basement rocks’; ‘Frankincense woodland’ and ‘Frankincense forest’ (see figure 78).

On the basis of the comparison presented above, one can conclude that:

- The map of six (seven) vegetation types presented by MILLER and MORRIS (2000, 2004) is rather general and could serve only for overall information about spatial distribution of various vegetation types over the island whereas the new land-cover map gives sufficient information even on the local level.
- The new land-cover map distinguishing 22 classes (unlike the map of principal vegetation types) reflects also spatially restricted but environmentally significant classes as ‘Wetlands’; ‘Wadi’; ‘Sand dunes’; ‘Savanna woodland’; etc.).
- In most cases there is more or less clear relation between Miller’s principal vegetation type and appropriate landcovers (e.g. types [5] Open and woody-based herb communities or [7] Montane mosaic), nevertheless a perception of some vegetation types may be sometimes in the two map concepts slightly ‘shifted’ (e.g. types [2] Croton shrubland and [3] Succulent shrubland).

- Some of the vegetation types, as mapped by Miller and Morris (e.g. [4] Semi-evergreen woodland and [6] Submontane shrubland), are rather dichotomous without any clear counterpart or group of related counterparts among land-cover classes.

4.5. Altitudinal vegetation zones

As explained in chapter 3.6., Altitudinal Vegetation Zones (vegetation tiers) express the connection of the sequence of differences in vegetation with the sequence of differences in altitudinal and exposure climate (ZLATNÍK 1956). By means of the computer image analysis of multitemporal data of the MODIS satellite, all five altitudinal vegetation zones (AVZ) occurring on Socotra were generally mapped. These zones were distinguished and described in the course of field operations in 1999 to 2004 by Buček and Habrová (BUČEK in PAVLIŠ 2002; HABROVÁ 2004; PAVLIŠ et HABROVÁ 2005). The overall accuracy of a resultant map was approximately determined by means of an error matrix to be circa 87%. Although the evaluation points used are not identical with training fields used for the creation of spectral signatures, they occur in their immediate proximity and thus, they are not independent. Therefore, it is necessary to take calculated indicators of accuracy as preliminary ones (with the independent set of reference data the calculated accuracy is usually a little lower).

According to the error matrix (Tab. 7), all altitudinal vegetation zones were mapped with an acceptable accuracy. The producer's accuracy and the user's accuracy range between 83 and 93%. The 1st AVZ makes an exception when the producer's accuracy amounts to only 73% (on several places, the zone was mapped as the 2nd VZ). However, it is debatable if rather inaccurate determination of the AVZ at some reference points did not occur.

		Reference Data					Classified Totals	Producer's accuracy	User's accuracy
		1st AVZ	2nd AVZ	3rd AVZ	4th AVZ	5th AVZ			
Classification data	1st AVZ	46	4	0	0	0	**50**	*73.0%*	*92.0%*
	2nd AVZ	17	115	4	0	0	**136**	*91.3%*	*84.6%*
	3rd AVZ	0	7	62	3	1	**73**	*92.5%*	*84.9%*
	4th AVZ	0	0	1	25	2	**28**	*83.3%*	*89.3%*
	5th AVZ	0	0	0	2	31	**33**	*91.2%*	*93.9%*
Reference Totals		**63**	**126**	**67**	**30**	**34**	**320**	Overall acc. 87.2 %	

Tab. 7: Error matrix for the map of altitudinal vegetation zones.

By means of GIS analyses, synoptic data were extracted from related data layers (e.g. DEM, geological map, land-cover map, map of monsoon effects etc.) for particular altitudinal vegetation zones. These data presented also in the form of tables and charts are used for the description of particular AVZ as follows:

First altitudinal vegetation zone: *planar,* (*meterhel*)

As evident from the resultant map (appendix No. 8), all coastal and mostly also inland plains rank among the 1st altitudinal vegetation zone. In the north, it refers particularly to plains Haďale, Karma, large part of the Hadibo plain, Ras Howlef and considerable part of the Dibean plain. In the east, the 1st AVZ consists of the Ras Momi, in the south it refers to plains Noged and Qa'arah, in the southwest it is the plain of Neet and in the northwest the plain of Dikat. In the inland, it refers to plains Menihd'he, Zahr and large parts of plains Sikho and Osmariah. As in the case of land-cover classes, the description of occurrence uses the orographical division of the island according to CULEK (in PAVLIŠ et HABROVÁ 2005; see also appendix No. 5).

There are no permanent watercourses in this AVZ, water flows only episodically in rain season. This AVZ exhibits the highest density of settlements.

According to Fig. 79, it is evident that more than 70% of the 1st AVZ is situated at an altitude not exceeding 100 m. The remainder (about 25%) is formed by altitudes ranging from 100 to 200m (inland plains and adjoining slopes). The minimum proportion of altitudes over 200m showed in Fig. 79 can be regarded as an error caused by the low spatial resolution of the MODIS satellite (250 m), which was used for the delimitation of altitudinal vegetation zones.

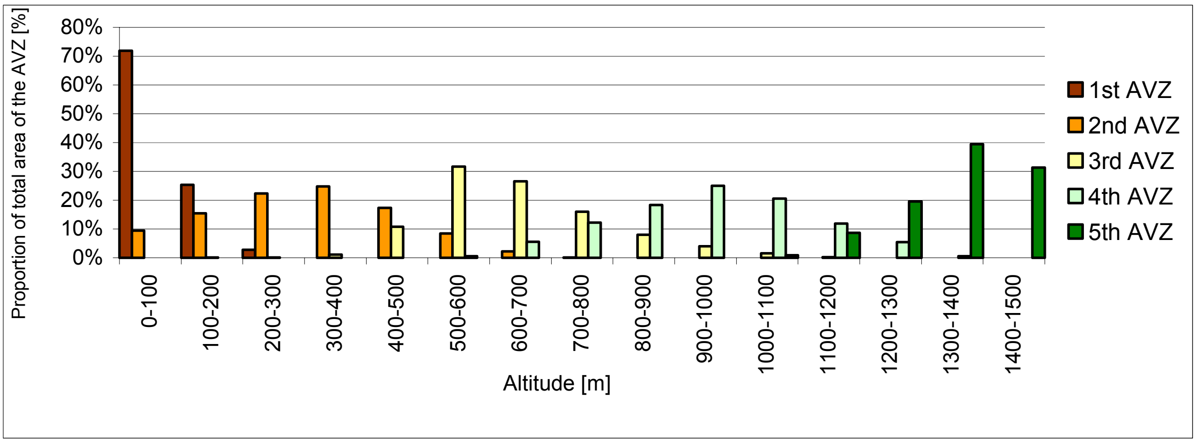


Fig. 79: Distribution of altitudes within particular AVZ.

With respect to the occurrence of the 1st AVZ described above, data on the characteristic distribution of slope inclination are not surprising (see Fig. 80). About 75% of the area do not exceed 3° and on about 20% of the area the inclination ranges between 4 and 10%. Where the 1st AVZ reaches the connecting slopes, the inclination can achieve even higher values. Topography conditions of the 1st AVZ are also described in the table 8. The mean calculated altitude of the AVZ amounts to 67 m and mean inclination 3°. Low standard deviations relating to the values also indicate low variability of data, i.e. not very rugged topography in the region (as mentioned in chapter 4.3., since the spatial resolution of the DEM used is 90m, real average inclinations are probably higher – lower resolution of DEM exhibits "smoothing effect").

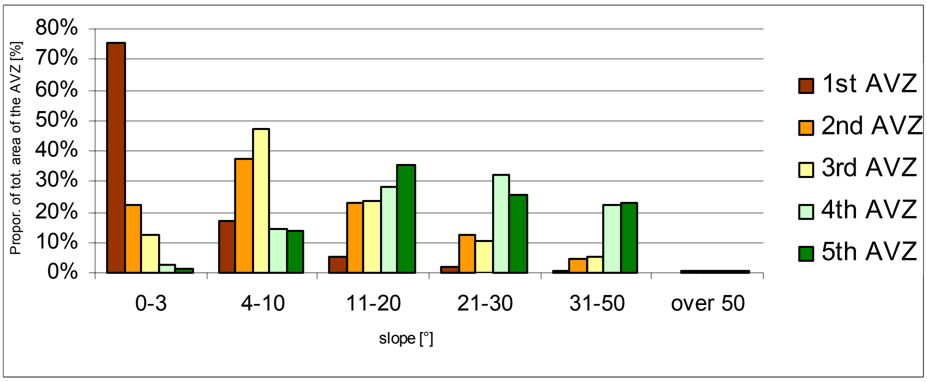


Fig. 80: Distribution of slopes within particular AVZ.

Generally, the 1st AVZ can be considered to be rather homogeneous also with respect to other properties of the ecotope. It is also corroborated by Fig. 81, which demonstrates the proportion of various bedrocks within particular AVZ. The 1st AVZ is created from about 70% by Quaternary sediments, 20% are Dolomitic limestones and Calcareous sediments and only 10% are igneous and metamorphic rocks. Types of the vegetation cover are also rather uniform (Fig. 82). Roughly on 45% area, 'Low Croton-Jatropha shrubland' occur, about on 42% there is 'Sparse dwarf shrublad', the proportion of 'Sand dunes' (cca 6%) and riverbeds of 'Wadi' (cca 3%) is also significant. The remaining part is occupied by other landcover classes typical of the 1st AVZ (see Fig. 83).

As for climate, the major part (cca 60%) of the 1st AVZ is affected by winter monsoons (Fig. 84). However, according to the results of phenological analyses, effects of monsoons are not so intense there as in higher situated parts of the island. The vegetation phenology of the first altitudinal vegetation zone, as depicted by time series of MODIS NDVI images, is presented in figures 108 and 109 in the chapter 4.7.3.

No.	Altitudinal Vegetation Zone	Mean Altitude [m]	Mean Slope [°]	Stand. Dev. of Altitudes	Stand. Dev. of Slopes
1st	planar (*meterhel*)	67	3	59	5
2nd	collinean (*emhar*)	310	11	148	10
3rd	submontane (*ariob*)	645	12	138	10
4th	montane (*dagash*)	954	22	156	11
5th	alto-montane (*azabzabahan*)	1345	23	89	11

Tab. 8: Topography statistics of altitudinal vegetation zones.

Second altitudinal vegetation zone: *collinean*, (*emhar*)

The second AVZ as compared with the first AVZ is much more heterogeneous nearly in all aspects. It also refers to the most distributed AVZ at all on the island (it covers more than 50% area of the island – see Fig. 85 and Tab. 9). The 2nd AVZ occupies areas of the highest parts of plains (foothills) such as Hadiboh, Lhasi and Zahr, adjoining gentle limestone slopes and low rolling hills as well as steep cliffs (Zhodhole, Shebhere), large parts of lower limestone plateaux (e.g. Katdkh, Dyfshe, Kileem, Serbe, Serhan, Sheezeb, Falang, Momi etc.) and also the majority of inland valleys on igneous rocks (e.g. Tsidet, Diasmu, Dishten, Salhoan, Teida, etc.; see appendices No. 8 and 5).

Watercourses hold running water mainly in the rain season. The density of settlements is relatively high.

The scope of altitudes of the AVZ occurrence corresponds also to the broad distribution. It ranges from about 50 to 600m alt. However, as evident from Fig. 79, the centre of occurrence is narrower (nearly half of the area lies between 200 and 400m alt.). The average altitude of its occurrence is 310m (Tab. 8).

As for slopes, these are markedly higher than in the first AVZ. The largest part (about 40%) belongs to the category of slopes 4-10°, but more than 20% belong also to categories 0-3° and 11-20°. Larger slopes occur rather marginally (e.g. limestone cliffs above the Noged plain). The average inclination of topography in the second AVZ is about 11°.

Characteristic bedrock (Fig. 81) corresponds also to the distribution of the second AVZ. About 8% are Quaternary sediments, 65% are Dolomitic limestones, 10% Calcareous sediments, 5% Riebeckit and the rest consists of other igneous and metamorphic rocks.

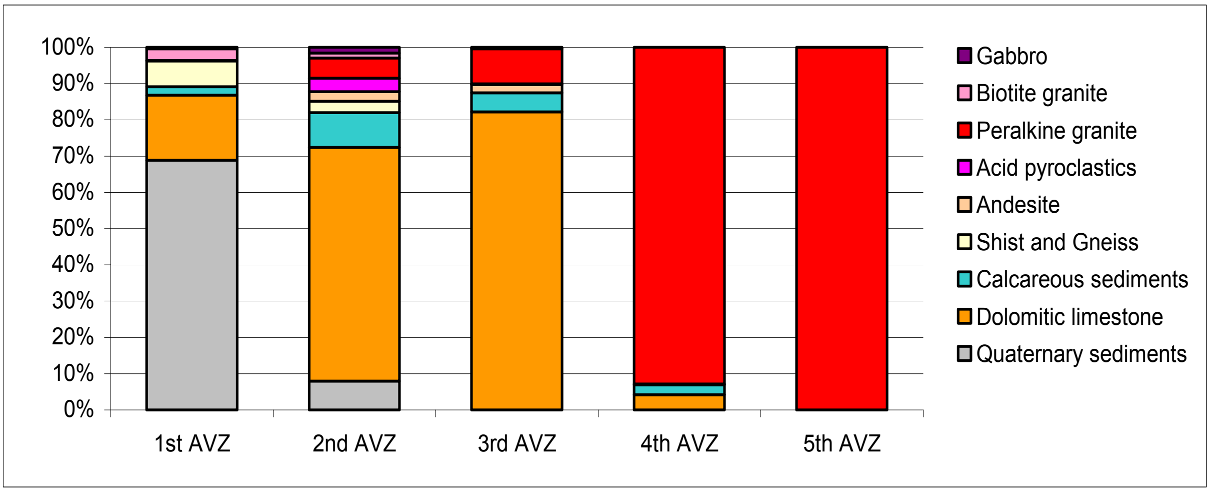


Fig. 81: Proportion of the bedrocks (Y axis) within particular AVZ (X axis) determined by an overlap of map layers.

As for the characteristic landcover and vegetation cover, the occurrence of 'Sparse dwarf shrubland' ceases and the dominant occurrence of 'Low Croton-Jatropha shrubland' continues (cca 35%) on gentle slopes. In contrast to the 1st AVZ, a low arborescent species *Commiphora socotrana* very abundantly occurs in the latter landcover class. On steep slopes, 'High shrubland with succulents' develops (cca 22%), in lower parts of limestone plateaus 'Submontane grassland and dwarf shrubland' (24%) and 'Submontane shrubland' (6%) occur (see Fig. 82).

With respect to the effect of monsoons, the 2nd AVZ falls into the both 'northern' side influenced in particular by the winter monsoon and 'southern' side of the island affected mainly by the summer monsoon (Fig. 84). The impact of monsoons on phenology of the vegetation of this AVZ is depicted in the figure 110 (chapter 4.7.3.) using NDVI time profile of 'High shrubland with succulents'.

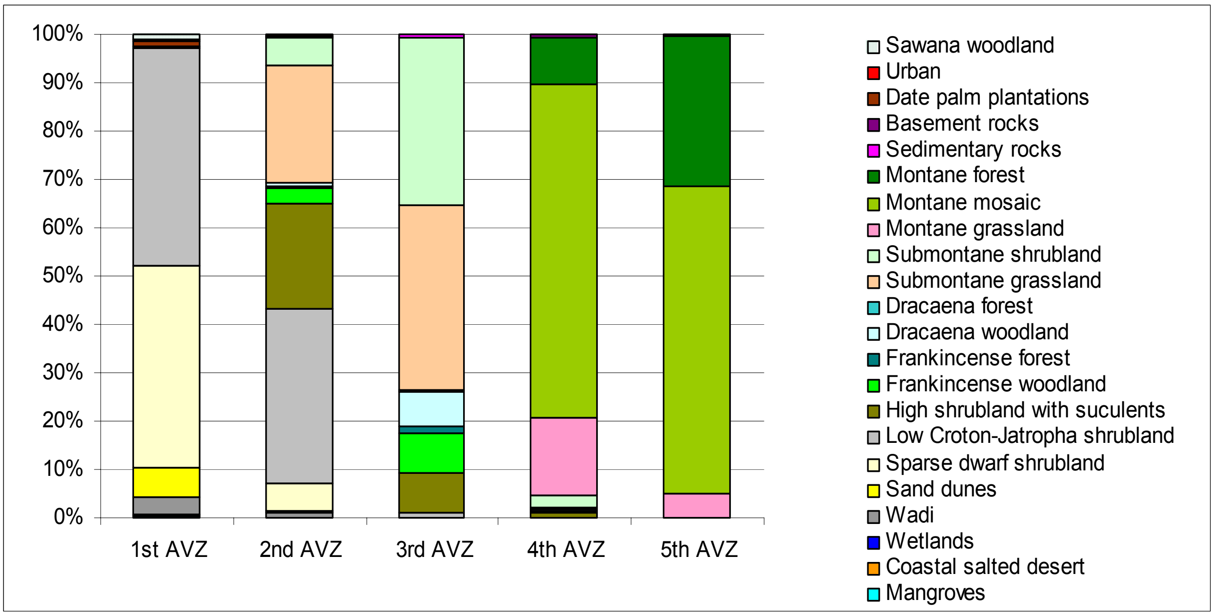


Fig. 82: Proportion of land-cover classes (Y axis) within particular AVZ (X axis).

Third altitudinal vegetation zone: *submontane, (ariob)*

The third vegetation zone occupying about 16% of the island area is typical for higher limestone plateaux, e.g. Khaidhedhe (Ma'alah) in the west; Keyrakh and Qatariyah in the south; Khod'olhei, Diksam and Shibehon in the middle of the island and the highest part of Momi in the NE of the island. Marginally, the foothill of the Haggeher central mountain range with sheltered walleyes belongs also to the zone (see appendices No. 8 and 5).

Influence of horizontal precipitation starts to be noticeable in this AVZ. They are significant in particular during the summer monsoon. The density of settlements is low.

Altitudes within the 3rd AVZ range from 400 to 900m while nearly 60% lie between 500 and 700m (Fig. 79). The mean altitude of the 3rd AVZ is 645m. The distribution of terrain slopes is similar as that in the 2nd AVZ being, however, a little shifted towards higher values (see Fig. 80). Also a mean slope is slightly higher (cca 12°).

A fact that the 3rd AVZ is typical of limestone plateaux is also corroborated by the occurrence of bedrocks (Fig. 81) nearly of 90% formed by limestone and calcareous sediments. The remainder (cca 10%) consists of Riebeckit (foothills of the Haggeher Mts.). The vegetation cover is also dominated by classes related to the limestone plateaux (see Fig. 82) such as 'Submontane grassland and dwarf shrubland' (cca 38%) and 'Submontane shrubland' (35%) completed by 'Dracaena woodland and forest' (cca 8%); on slopes, there is

'High shrubland with succulents' (cca 8%) and 'Frankincense woodland and forest' (cca 10%).

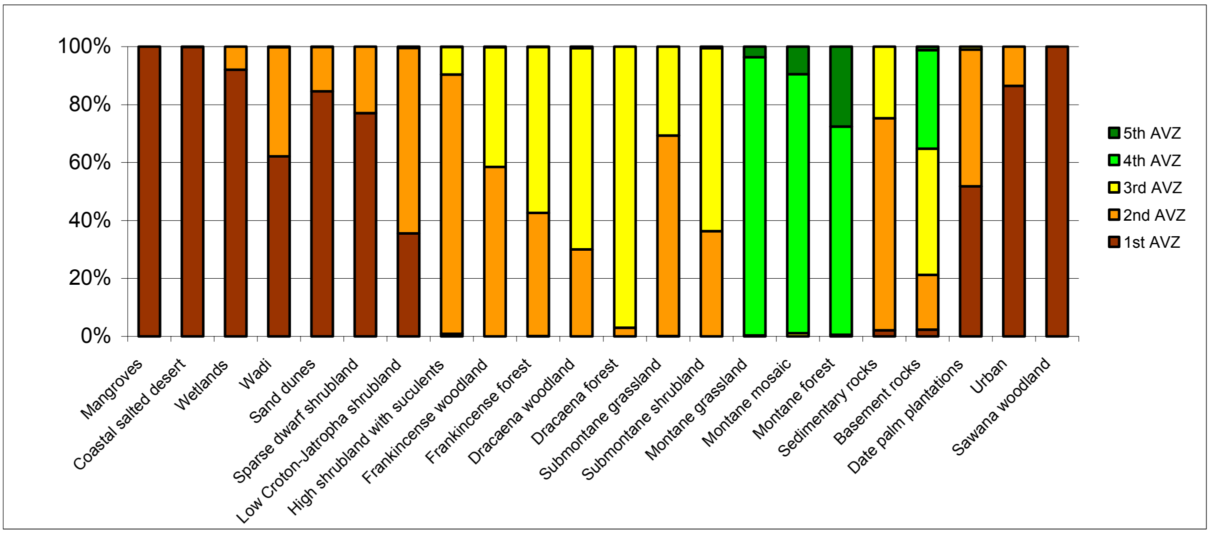


Fig. 83: Proportion of AVZ's (Y axis) within particular land-cover classes (X axis).

With respect to orography, effects of summer SW monsoon predominate there (62%). Some parts, e.g. Khaidhedhe (Ma'alah) in the north-west and the highest part of Momi in the north-east of the island are under the influence of winter monsoon (see Fig. 84 and 91). Differences between vegetation phenology of both sides are exemplified in figure 113 (chapter 4.7.3.) by means of NDVI temporal profile of 'Submontane shrubland'.

Fourth altitudinal vegetation zone: *montane, (dagash)*

Mountain vegetation zones occur in limited areas only in the central range of the Haggeher Mts. (see Tab. 9 and appendix No. 8). The 4th AVZ occurs at an altitudinal range of 700–1200 (1300)m however, it is typical between 800 and 1200m a.s.l. (Fig. 79); the average altitude of its occurrence is 954m. Since it refers to the typical mountain environment, slope inclinations are markedly higher than in the previous vegetation zones. Slopes 21-30° predominate (cca 32%), slopes 11–20° and 31-50° occur also more frequently (over 20%); the average inclination of slopes is about 22° (Tab. 8). The standard deviation value (11) gives evidence on the high variability of slopes (relatively flat areas of 'Mountain pastures' also occur).

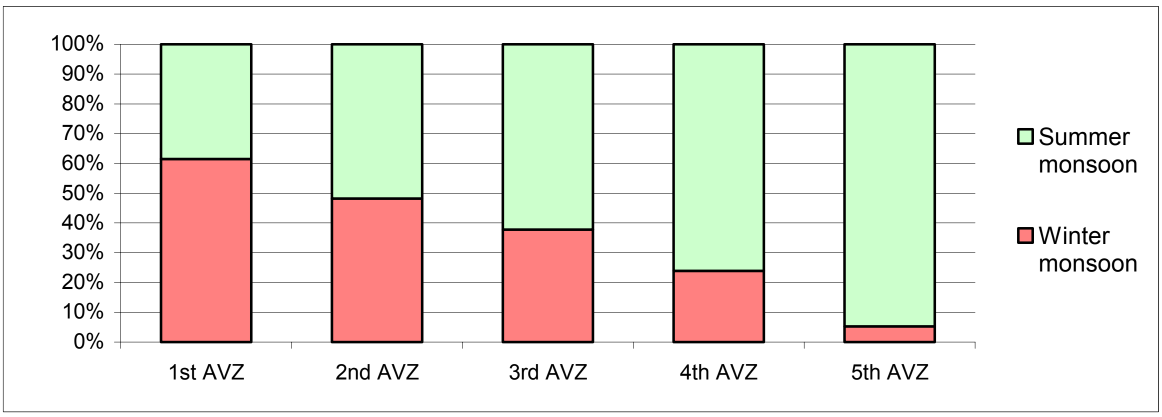


Fig. 84: Predominating impact of monsoons on phytophenology of particular AVZ, as derived from the TSA analysis of MODIS NDVI time series.

The AVZ is relatively reach in precipitation, it shows marked signs of the influence of dew and mist during both monsoonal periods. According to Time Series Analysis, effect of a summer monsoon predominates (see Fig. 84), nevertheless, based on NDVI time profiles of montane biotopes, it is evident that also regular precipitation occurs here both during summer and winter monsoons. Phytophenology of mountainous altitudinal vegetation zones is depicted in the figure 114. Plenty of small brooks and rivulets spring in this area. Watercourses are usually permanent.

Parent rocks are rather uniform – more than 90% consist of Riebeckit and the rest is formed by Dolomitic limestone (the highest parts of the Diksam plateau). The distribution of landcover classes is also rather simple. It refers to an archetype of pre-historical long-term cultivated pasture landscape with patches of cleared 'Montane grassland' on flat places and mild slopes (cca 16%). Remains of probably pre-islamic huge stone huts are present. Density of settlements is very sparse. On 70% of the area, the mosaic of montane shrubby biotopes predominates; steep slopes are sometimes occupied by 'Montane forest' (cca 10% of area of the AVZ).

Fifth altitudinal vegetation zone: *alto-montane*, (*azabzabahan*)

The ecotope of the 5th AVZ is very similar to that of the previous AVZ. It occurs at the highest locations of the Haggeher Mts. on an area of about 700ha at altitudes over (1100) 1200m with the centre of occurrence between 1300 and 1540m a.s.l. (mean altitude 1345m). The distribution of slopes is similar as that in the 4th AVZ, mean slope reaching a value of 23°.

The AVZ is characteristic by relatively humid climate, high precipitation and marked influence of horizontal precipitations (mist and dew). It is a spring area of several permanent watercourses. There is no permanent settlement in the AVZ, remains of probably pre-islamic huge stone huts still occur.

	1st AVZ	2nd AVZ	3rd AVZ	4th AVZ	5th AVZ	**Total**
Area [ha]	89810	198557	55788	6030	705	**350891**
Proportion of total area [%]	25.6%	56.6%	15.9%	1.7%	0.2%	**100.0%**

Tab. 9: Area and percentage of particular altitudinal vegetation zones on total area of the island.

A bedrock is completely created by Riebeckit. The vegetation cover of the zone is mainly formed by the mosaic of mountain biotopes (cca 63%) and 'Montane forest' (cca 30%). The rest consists of 'Montane grassland' (5%) and 'Basement rocks' (< 1%).

Similarly as in the 4th AVZ, according to Time Series Analysis the effect of a summer monsoon predominates, however, a winter monsoon participates very significantly in total precipitation at these locations. It is apparent also from the MODIS NDVI temporal profile of mountainous altitudinal vegetation zones (Fig. 114).

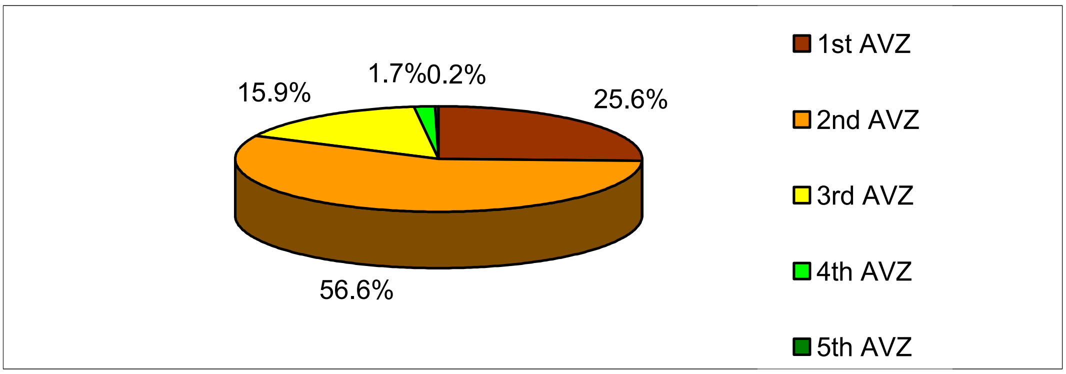


Fig. 85: Proportion of altitudinal vegetation zones in the total area of the island.

4.6. Comparison of AVZ's with other zonations of vegetation

4.6.1. Elevational belts of MIES and BEYHL (1996)

In 1996 Mies et Beyhl presented their suggestive "Vegetation ecology of Socotra". They introduced there, among others, inspirational classification of the plant communities based on elevation, prevailing ecological factors – in particular moisture – and physiognomy of the plants. The description of the 'elevational belts' is presented below (MIES et BEYHL 1996): 'Five zonal formations or belts can be distinguished. They are strongly influenced by the conditions of temperature and moisture. They extend in an orderly fashion, according to an environmental gradient, from the cost to the mountains; the natural vegetation cover is also mentioned':

1. Coastal / Arid (0-200m a.s.l.)
Sporadic, inconspicuous rainfall (< 200 mm), no fog or dew, high temperatures. The habitats are affected by salinity, crystallizing on the soil surface as water evaporates from the soil capillaries or by sea-borne salt deposited as an aerosol. Coastal lowlands and exposed xerothermic localities. Occurrence of xerophytes, succulents and halophytes.

2. Lowlands reaching lower hillsides / Semi-Arid (100-400m a.s.l.)
Little seasonal rainfall, mostly between December and January (< 400 mm), little dew-fall occurs in that period, high temperatures. Lower hill country up to 400m a.s.l. Xerophytes occur in open bushland and giant succulents are common.

3. Hillsides / Semi-Arid montane (400-700m a.s.l.)
Little seasonal rainfall in the winter half-year, dew, moderately high temperatures. Upper hill country and foothills of the Haggeher range between 400 to 700 (800)m a.s.l. Xerophytic bushland dominate, but there are local outskirts of the bushlands and forests.

4. Montane / Mesic montane (700-1200m a.s.l.)
Periodic rainfalls in two seasons, from November to January and a shorter one in April and May, heavy cloud formation in the monsoon period and at the time of the northeastern trade-winds, heavy dew and fog precipitation, moderate temperatures which drop during the night. Dense bushland or thickets and forests. The regular dew and fog leads to a dense cover of mosses and lichens as epiphytes on branches and rocks.

5. Subafroalpine / Mesic montane (> 1200m a.s.l.)
Periodic rainfall as before, heavy dew but less fog formation and precipitation, very high insolation, temperatures strongly diurnal, moderately warm during the day, but falling considerably at night. Strong winds. Peaks of the Haggeher Mts. (above 1200m a.s.l.). Typical of this belt are dwarf shrubs and cushion plants, which on exposed slopes occur at even lower altitudes. Conversely, dense bushlands can extend their range to higher altitudes than usual by inhabiting sheltered localities.

In fact it is the question of the first simple definition and description of altitudinal vegetation zones of Socotra. In general, the five elevational belts described above by Mies and Beyhl are more or less accordant with five altitudinal vegetation zones defined by Buček and Habrová (BUČEK in PAVLIŠ 2002; HABROVÁ 2004; PAVLIŠ et HABROVÁ 2005) and mapped by KRÁL (2002; HABROVÁ et KRÁL 2002; KRÁL in PAVLIŠ et HABROVÁ 2005). Nevertheless, there are several gaps in consistency in the description of elevational belts of Mies and Beyhl. Firstly, the ranges of elevation for particular belts are probably not so strictly separated. Actually, effective penetration between neighbouring AVZ often exists, so that higher AVZ can in some places occur in lower altitudes than a generally lower AVZ. The differences are caused by a complex topography of the island, various slope aspects, complex monsoon impact, etc. Secondly, the rainfall patterns described for particular belts are very inaccurate. Together with no specific mention of limestone plateaus it suggests an idea that the authors described in particular a vegetation zonality of the northern part of the island, which is considerably affected by winter monsoons (see chapter 4.7.1.). Since the elevational vegetation belts of Mies and Beyhl has never been mapped, a more detailed comparison with current altitudinal vegetation zones can not be presented.

4.6.2. Principal vegetation types of Socotra (MILLER et MORRIS 2000; 2004)

As evolved from the comparison of Miller's vegetation map (MILLER et MORRIS 2000; 2004) and the new land-cover map, the former is very simple (see appendix No.7). Although it was originally based on physiognomy (while reflecting floristic differences), the detailed cross-tabulation with the landcover map shows, that it depicts rather some general vegetation zones than concrete vegetation cover of particular sites. Therefore, it could be interesting to overlay and compare the Miller's vegetation map also with the new map of altitudinal vegetation zones.

Since the first principal vegetation type recognised by Miller (1) 'Coastal vegetation' was reportedly too narrow to map, the map overlay and consequent cross-tabulation concerns other vegetation types (see figures 86 and maps 87):

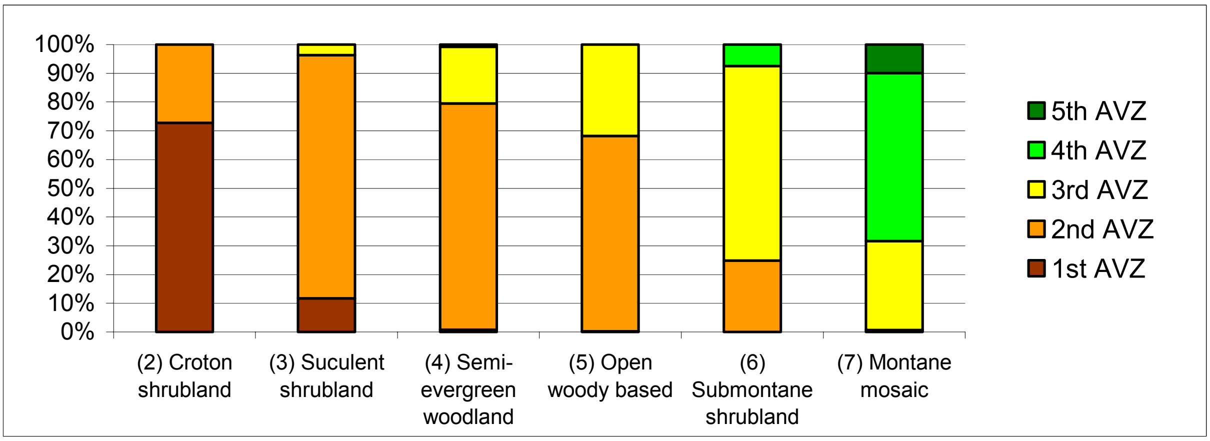


Fig. 86: Proportion of altitudinal vegetation zones (Y axis) within particular vegetation types of MILLER and MORRIS (X axis).

(2) 'Croton shrubland' closely resemble the 1st altitudinal vegetation zone, although some marginal overlaps with the 2nd AVZ occur.

(3) 'Succulent shrubland' falls generally into the 2nd altitudinal vegetation zone. It comprise low rolling hills either on limestone or basement rocks, however it usually does not occur on the top of limestone plateaus, which in most places also lies in the 2nd AVZ. In other words, Miller's 'Suculent shrubland' is only a subset of the 2nd AVZ.

(4) 'Semi-evergreen woodland' forms relatively narrow transitional belt separating Suculent shrubland and "higher" vegetation types either 'Open and woody-based herb communities' or 'Submontane shrubland'. Consequently, it falls mainly in the 2nd AVZ and partly in 3rd AVZ.

(5) 'Open and woody-based herb communities' relatively closely resemble landcover class 'Submontane grassland' on the top of limestone plateaus. As such it forms second major counterpart (besides 'Suculent shrubland') to the 2nd altitudinal vegetation zone.

(6) 'Submontane shrubland' falls mainly into the 3rd altitudinal vegetation zone. As it appears only in central part of the island it makes just a subset of the 3rd AVZ, whose occurrence is much wider.

(7) 'Montane mosaic of evergreen woodland, grassland, dwarf shrubland and cushion vegetation' comport with the union of the 4th and 5th altitudinal vegetation zones.

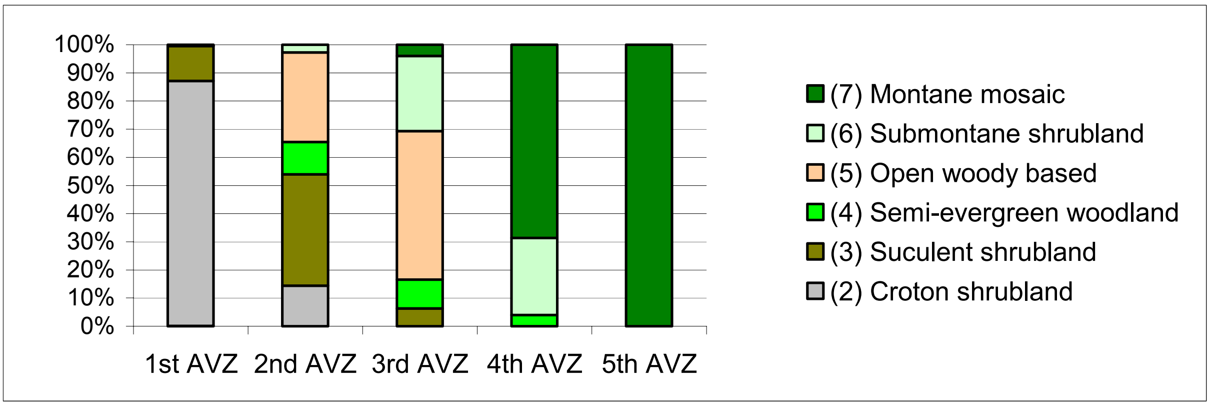


Fig. 87: Proportion of vegetation types of MILLER and MORRIS (Y axis) within particular altitudinal vegetation zones (X axis).

4.7. Phenological observations

4.7.1. Time Series Analysis

As mentioned in chapter 3.5., the Time Series Analysis (TSA) is based on Analysis of Principal Components (PCA), which was primarily developed for image data compression. Since various imagery of the same site (e.g. different spectral bands of multispectral image) are mostly highly correlated, the PCA has been often used in order to produce a new set of images - components that are uncorrelated with each other and where the first two or three components explain from 95 to 99 percent of the variance in the original set of bands. In cases like this, the components explaining less than a certain percent of the variance can be dropped (EASTMAN 1999).

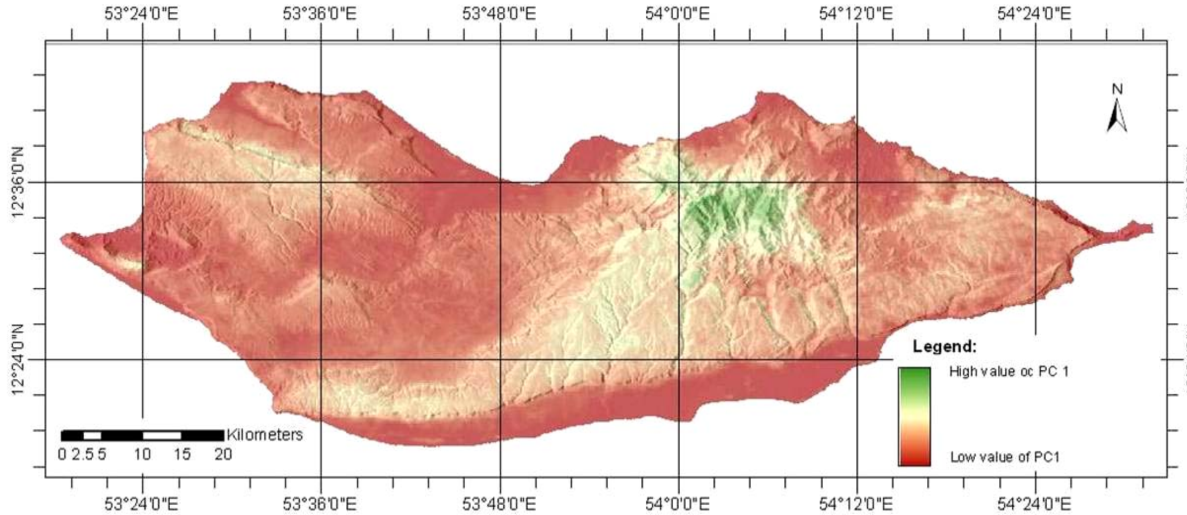


Fig. 88: The first Principal Component (PC 1) resulting from TSA.

This is very useful in the analysis of time series data – it evolved, that the first two principal components resulting from the TSA of Socotra NDVI images explain more than 98 % of variance of entire data set. Therefore the consequent discussion is focused on these two PC, while further components were taken out of consideration. The first principal component (PC 1, Fig. 88) explains 97 % of variance of NDVI time serie and explains the general trend common for all particular NDVI images that is apparent from the figure 92, where the graph shows the correlation between the component and each of the original NDVI images.

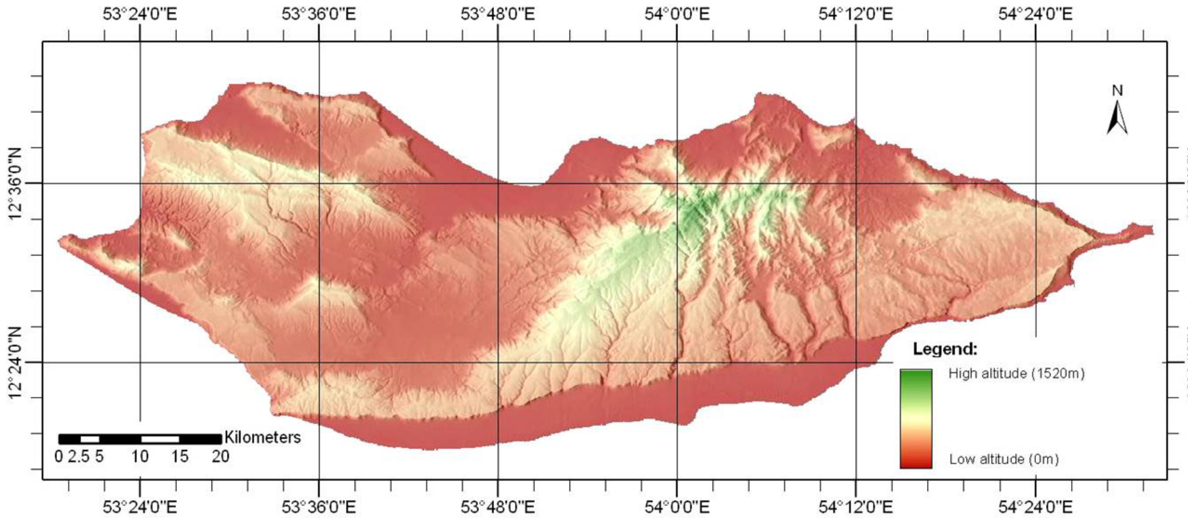


Fig. 89: Digital Elevation Model (DEM) representing altitude.

Comparing the 1st PC with the image of altitude (coming from the DEM, see Fig. 89), we can observe a strong similarity between the two. The regression analysis confirmed strong dependence of the NDVI values on altitude. Resulting scatter diagram (Fig. 90), where each pixel (250x250m) of Socotra is plotted, shows clearly the relation between altitude (X axis) and values of the first principal component (Y axis). The scattergram furthermore contains the regression statistics as the regression equation and correlation coefficient (r = 0.903). Analogical regression analysis was carried out also for particular NDVI images, but the

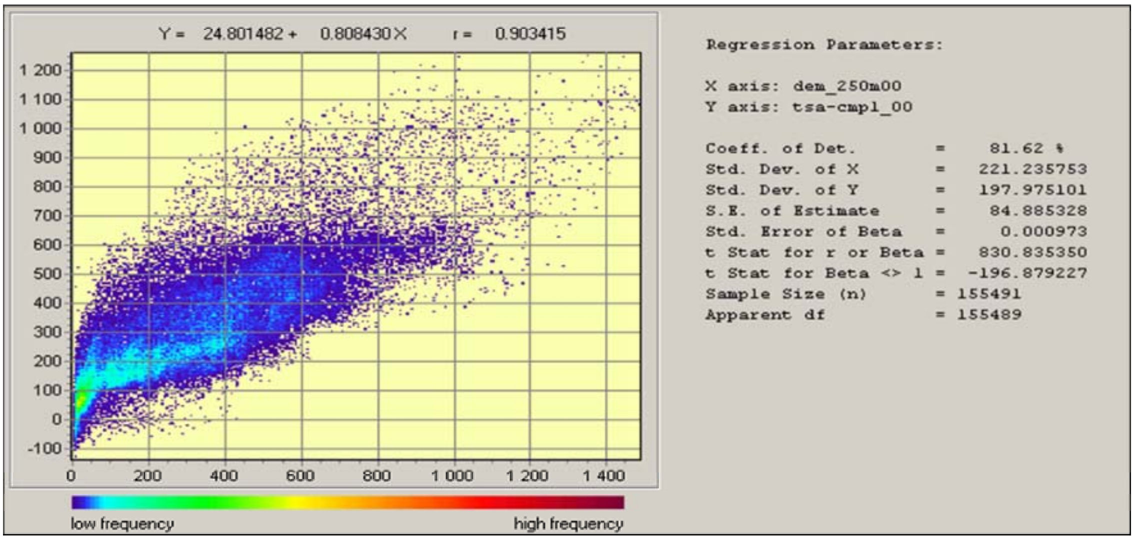


Fig. 90: Scatter-diagram showing the relation between the altitude and the value of PC 1.

correlation coefficient has never reached such high value (it varied in the range from 0.649 to 0.756). One can conclude, that the 1st PC best express the overall (increasing) trend of NDVI values caused by altitude.

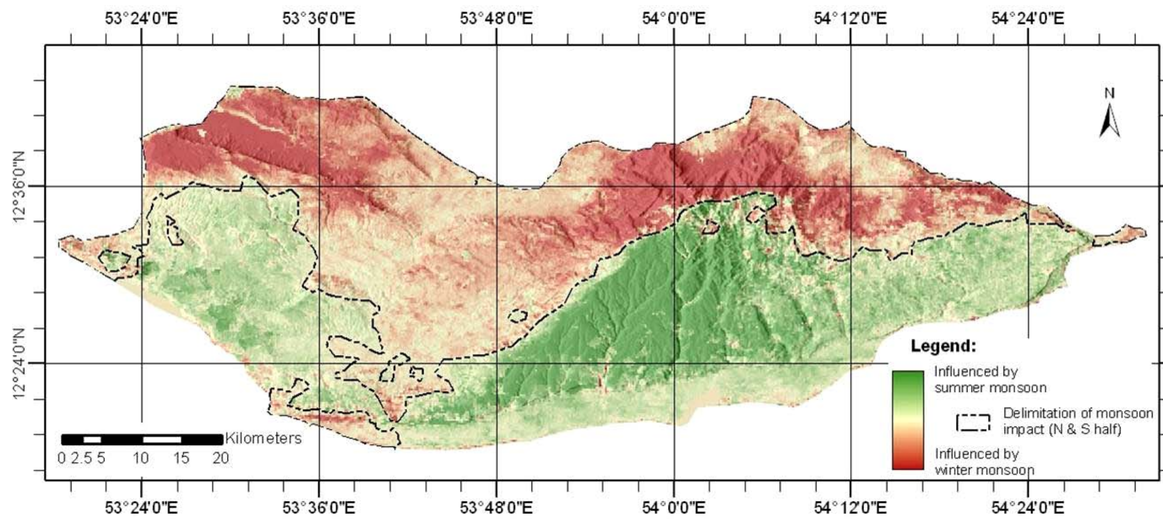


Fig. 91: The second Principal Comp. (PC 2) resulting from TSA and splitting Socotra on N and S 'half'.

The second principal component (Fig. 91) explains only 1.4 % of variability of original NDVI data set, however, this small amount represents dramatic environmental effects. It is the question of a 'shift' of NDVI values in time and space. It is apparent from following analyses that the shift is caused by monsoon phenomenon. As in the case of the 1st PC the bar chart in the figure 92 shows how particular NDVI images participate in the 2nd PC. The dates, which coincide with the summer monsoon (3.VII.2003; 19.VII.2003; 7.X.2003), exhibit the highest positive values (about 0.15), while the date associated with winter monsoon (24.I.2004) shows the highest negative value (-0.18). The lowest values (either positive or negative) lie within dates coinciding with the transitional periods. Strictly speaking, the image 7.X.2003 falls mainly within the autumnal transition period, nevertheless, the vegetation activity, as recorded by NDVI, is a response to September rains brought by the summer monsoon. This is in accordance with the findings of DAVENPORT and NICHOLSON (1993), who studied the rainfalls and the vegetation response in East Africa: 'The phenology of the vegetation, as depicted by NDVI, closely resembles the seasonal cycle of rainfall in the region, but green-up appears to lag rainfall by one to two months'. This lag was also noted by JUSTICE et al. (1986).

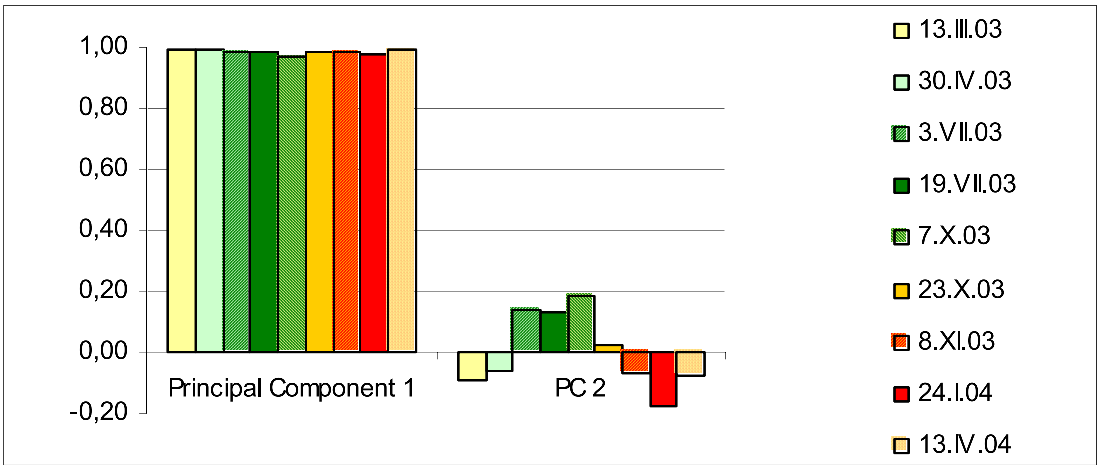


Fig. 92: Loading graph showing the correlation between PC and each of the original images.

Looking at the figure 91 one can observe, that the 2nd PC split the island on north half - influenced in particular by winter (NE) monsoon and the south half – influenced primarily by summer (SW) monsoon, where the value of the 2nd PC (intensity of colour in the figure 91) represents the intensity of the monsoon impact. The values range between –258 (maximum influence of the winter monsoon) and 107 (maximum influence of the summer monsoon). Applying a zero threshold value we can delimitate the border between the two (the dashed line in figure 91).

The winter monsoon affects the Hamadero and Homhil area in the east, the northern slopes of Haggeher mountains and big part of the Ma'alah plateau in the west, while the summer monsoon affects remainder plateaus and bigger part of Haggeher mountains. Especially in the case of summer monsoon the elevation plays an important part – in particular during August and September high plateaus (e.g. Keyrakh, Khod'oihel [Shibehon], Diksam) and Haggeher Mts. capture more horizontal precipitation than lower plateaus and plains. Besides, the monsoon effect on coastal and inland plains is rather low or minimal (more in the part 'profiles over time').

As evident from the figure 93, the elevations are not equally distributed within both sides. The northern half is generally much lower (mean altitude 263m above sea level) than the southern half (mean altitude 366m), where most of the limestone plateaus and bigger part of the Haggeher Mts. are located. This fact is interesting especially in conjunction with data coming from a time profile (Fig. 106). The peak of the curve representing a vegetation activity of northern part of the island is during the winter monsoon higher than the 'summer' peak of the curve representing the southern side. It may suggest a hypothesis, that the precipitations of the winter monsoon are either generally more intense than those of the summer monsoon, and/or that precipitations of the winter monsoon fall also in lower elevations. Although these assumptions are very likely, they are hard to prove due to the lack of disposable weather-stations.

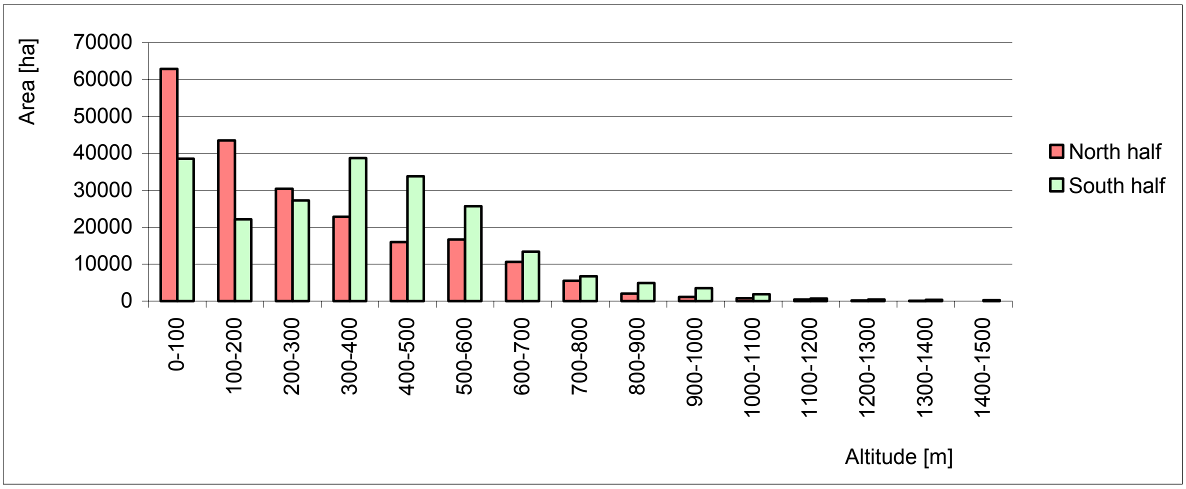


Fig. 93: Distribution of altitudes within both (N and S) sides of the island.

Comparing the layer of monsoon impact (PC2) with the layer of land-cover, some interesting pieces of evidence reveal. Figure 94 shows that some land-cover classes are largely affected by the summer monsoon (e.g. those affecting on limestone plateaus) while the others particularly by the winter monsoon (e.g those occurring on the northern coast). In particular a pattern of occurrence of 'Dracaena woodland and forest' seems likely to be a result of influence of horizontal precipitation of the summer monsoon (more in the chapter 4.2., part Dracaena woodland). Most of the classes are nevertheless occurring on both sides of the island, without any profound relation of the monsoon effect to their spatial distribution (e.g. 'Sparse dwarf shrubland', 'Low Croton-Jatropha shrubland' and 'High shrubland with succulents'). However, in those cases, the phenology of particular class can vary greatly according to the location on the island (more in the chapter 4.7.3.).

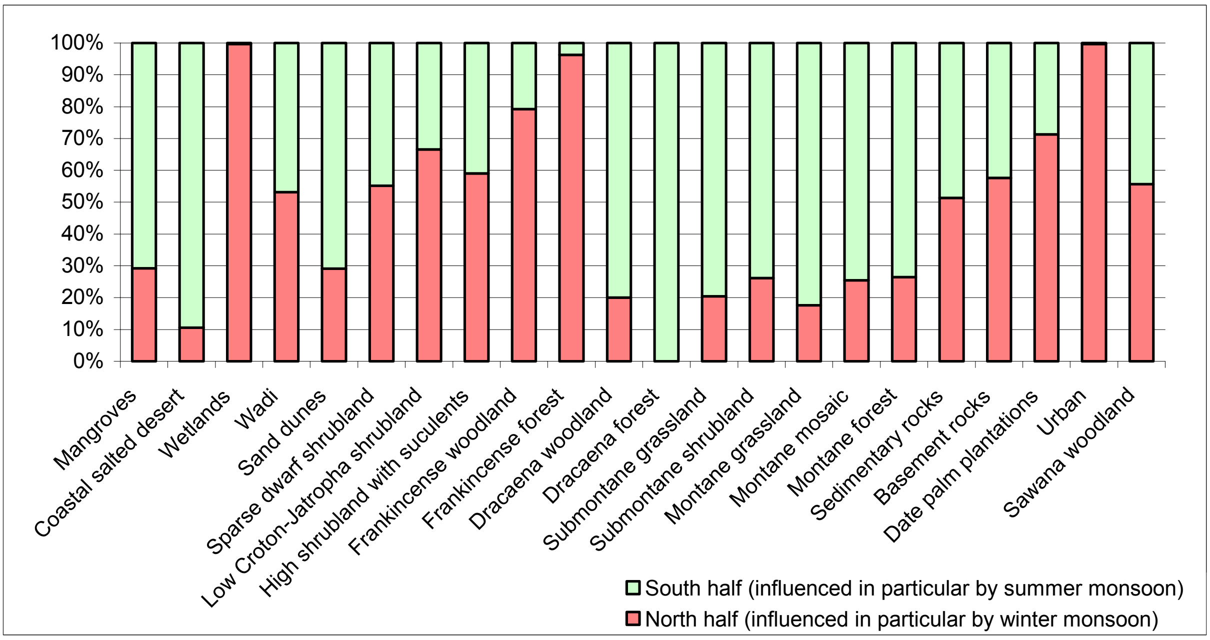


Fig. 94: Cross-tabulation of the land-cover map with map of the monsoon impact (PC 2).

4.7.2. Profiles over space

From ten spatial profiles, which were made across Socotra (see appendix No. 9), only five will be demonstrated and described in some details. It is the question of the profiles No. 1, 2, 3, 6 and 7. By means of the profiles, specific patterns of seasonal vegetation dynamics in various parts of the island are described. At first, the profiles were carried out using the digital elevation model and five of the original (cloud-free) NDVI images representing all typical climate seasons respectively: spring long dry transition period, summer monsoon, autumn short wet transition period, winter monsoon and again spring dry transition period. The typical seasonal rundown (below) expressed by reduced time series is generally common for entire island. Local variations caused by differences in terrain configuration will be described hereafter together with particular profiles.

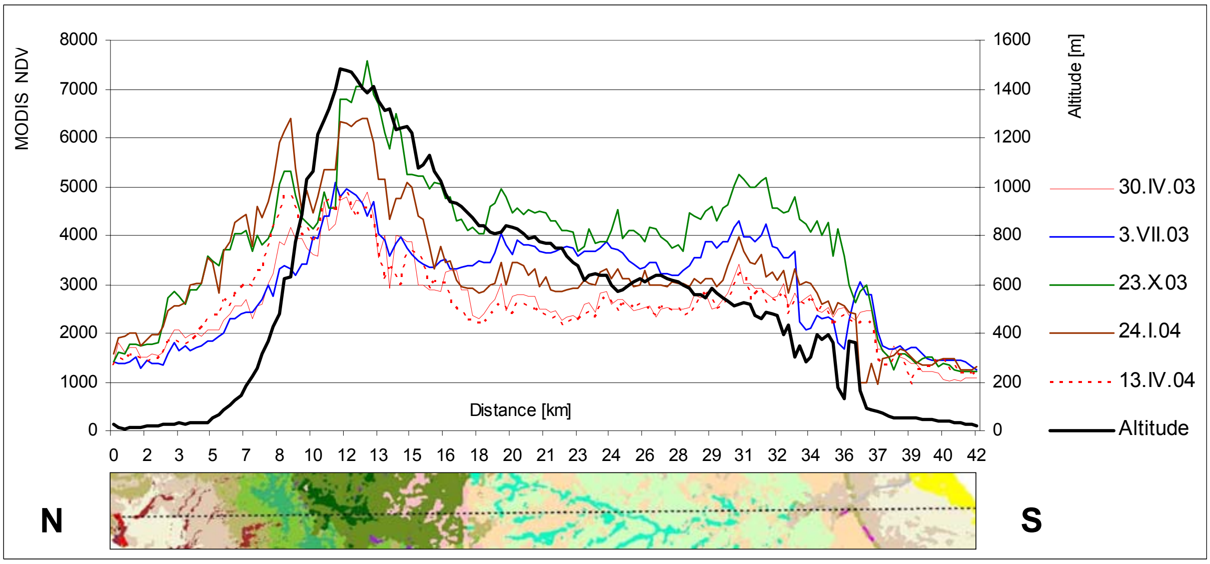


Fig. 95: Profile No.7 using image of altitude and particular NDVI images.

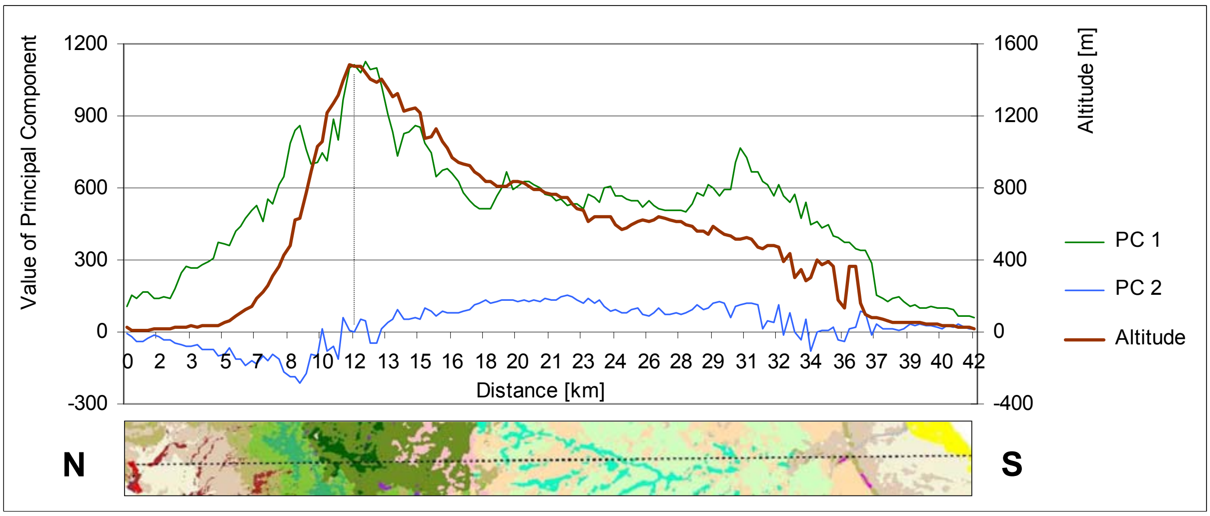


Fig. 96: Profile No.7 using image of altitude and both Principal Components of the TSA.

Description of the general rundown begins by the NDVI image from 30.IV.2003, which corresponds to the end of the transition period between the winter and the summer monsoon. This period is dry, generally with low vegetation activity all over the island (solid red line in figures 95, 97, 99, 101 and 103). The next NDVI image from 3.VII.2003 falls in the first half of the summer monsoon period. Significant increase of vegetation activity on the south half of the island (exposed to summer monsoon) is apparent as well as a vegetation decline on the opposite (northern) side, which in the mean time suffers from desiccation and during the summer monsoon period reaches its minimum (solid blue line in figures 95, 97, 99, 101 and 103). The next image from 23.X.2003 is associated with the transition period between the summer and the winter monsoon. As in September probably major precipitations brought by the summer monsoon fall, and in October usually the first precipitations on the northern side occur, the vegetation activity is in this period generally high all over the island (solid green line in figures 95, 97, 99, 101 and 103). Next NDVI image used in this profile is from 24.I.2004. Immense 'green-up' on the north half of the island is a result of the winter monsoon (solid brown line in figures 95, 97, 99, 101 and 103). The NDVI time serie is closed by the image from 13.IV.2004. The state of the vegetation is similar as on the beginning of the time serie (dashed red line in figures 95, 97, 99, 101 and 103).

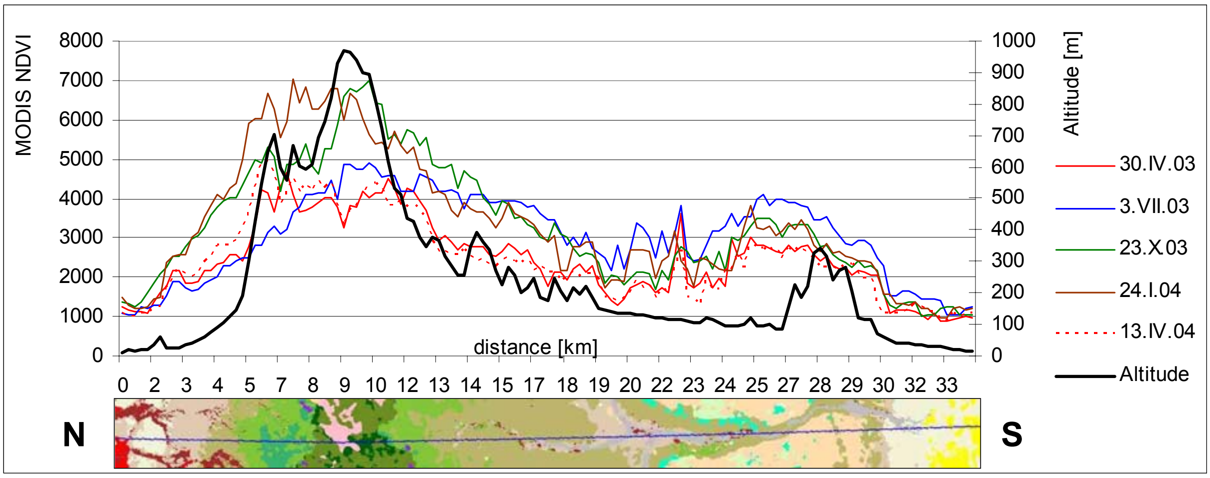


Fig. 97: Profile No.6 using image of altitude and particular NDVI images.

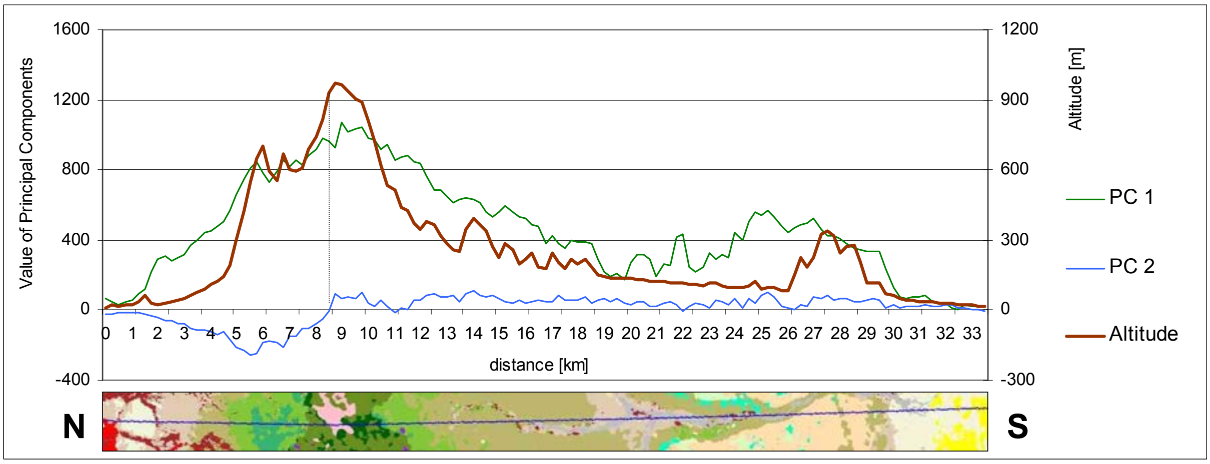


Fig. 98: Profile No.6 using image of altitude and both Principal Components of the TSA.

A causality of vegetation activity and its dynamics may be understood also by means of both principal components resulting from the time series analyses. When used in appropriate spatial profiles, it is apparent, that the 1st PC generally correlates with altitude (green solid line in figures 96, 98, 100, 102 and 104). It expresses the general trend of vegetation activity, which increases with increasing altitude. As for the 2nd PC, one can note that the slopes facing north have usually negative values (they are influenced by winter monsoon), while the slopes facing south have positive values (they are influenced by summer monsoon). This effect is stronger in higher elevations (blue solid line in figures 96, 98, 100, 102 and 104). The zero value, which makes the border between the influence of winter and summer monsoon usually coincide with the highest peak of the profile (see the vertical dotted lines in figures 96, 98, 100, 102 and 104)

Profiles No. 7 and 6 (Fig. 95, 96, 97, 98) show the vegetation phenology of the central part of the island including both southern and northern coastal plains, limestone plateau and central granitic Haggher Mountains. Both profiles closely follow the general cycle described above. Some local variations may be explained either by terrain configuration (e.g. low NDVI values in July around the 35th km of the profile No. 7 [Figs. 95, 96]) or different vegetation cover (e.g. the peaks around the 20th and 22nd kilometre of the profile No. 6 [Figs. 97, 98], where the profile crosses the date palm plantations in wadi). The latter case is more common. Local variations of vegetation activity caused by different vegetation cover are apparent from particular NDVI images (Fig. 97, 99) as well as from the 1st PC (Fig. 98, 100). In the profile No. 7 it for example refers to the 8th, 12-13th and 31st kilometer of the transect, where the profile crosses Frankincense forest, Montane forest and Dracaena woodland respectively. Actual land-cover of each profile is shown in the strip of the land-cover map under the line chart. Figure 105 shows a legend of the map (the same as in the appendix No. 2).

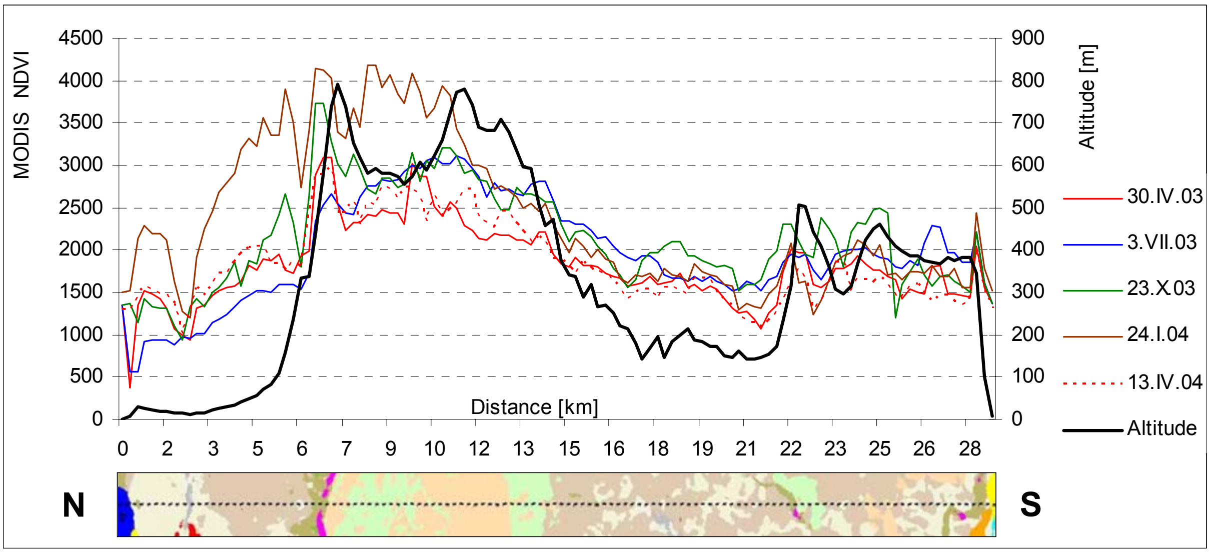


Fig. 99: Profile No.2 using image of altitude and particular NDVI images.

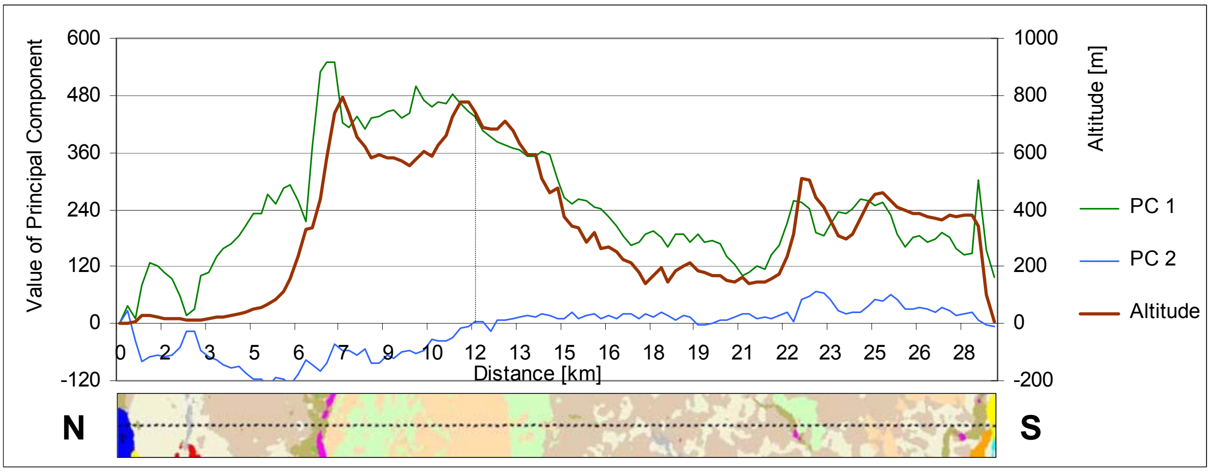


Fig. 100: Profile No.2 using image of altitude and both Principal Components of the TSA.

Phenology of the eastern part of the island is shown in profiles No. 1, 2 and 3 (Fig. 99, 100, 101, 102, 103 and 104). In profiles No. 1 and 2 there are two limestone plateaus (on both sides of the profile) with inland plain in between. Even if the profile No. 1 is oriented in NW-SE direction, the difference between 'northern' and 'southern' part of the profile, caused by monsoon effect, still exists. Southern plateau is under the marked influence of the summer monsoon, while best part of the northern plateau is influenced by the winter monsoon. Leeward (inland oriented) slopes of both plateaus as well as the inland plain are concerning the monsoon impact indifferent (see the figure 101 and blue solid line in figure 102). The situation is similar also in the profile No. 2 (figures 99 and 100), however, the southern plateau is here markedly lower and consequently the effect of summer monsoon is not so distinct. On the other hand, the impact of winter monsoon on northern plateau is outstanding. Also the great karst sink ('polje') on the top of Ma'alah limestone plateau – between the 7th and 11th km of the profile is under the influence of the winter monsoon. Interesting is also the bed of the wadi on 2,5th km of the transect, which causes significant decrease of vegetation activity all the year round.

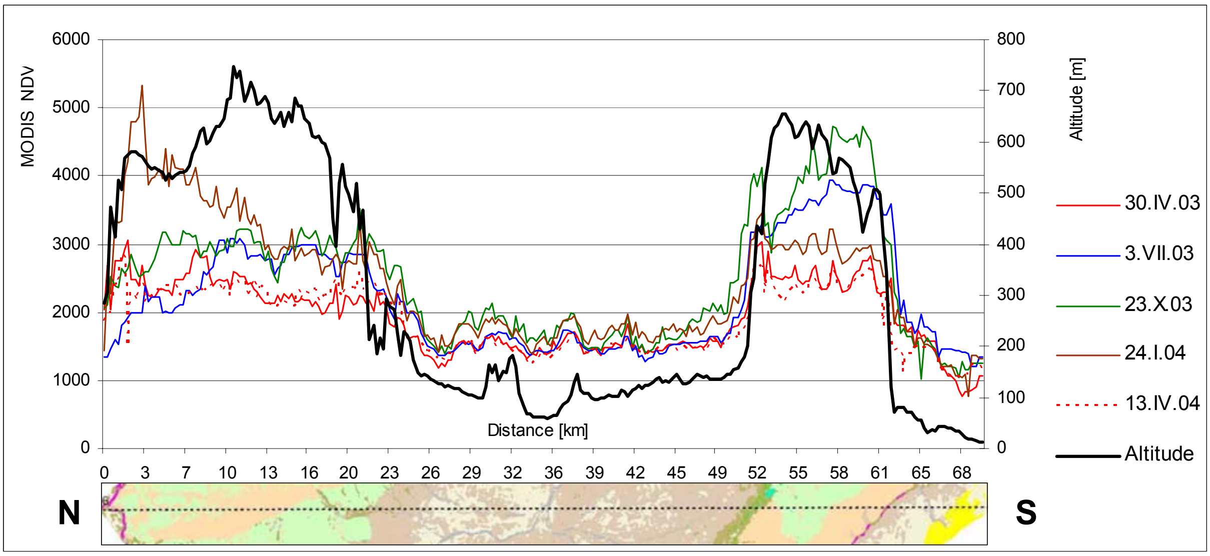


Fig. 101: Profile No.1 using image of altitude and particular NDVI images.

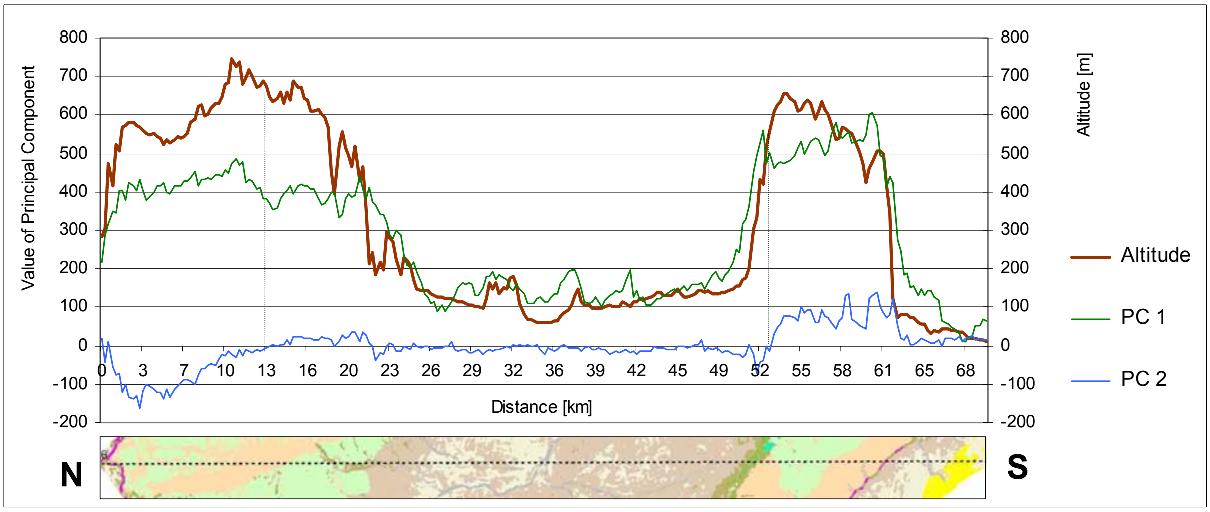


Fig. 102: Profile No.1 using image of altitude and both Principal Components of the TSA.

Profile No. 3 (Fig. 103 and 104) is slightly different. From the north it begins by coastal plain with sparse dwarf shrubland, central part is formed by inland plain with Croton-Jatropha shrubland and only southern part is closed by narrow limestone spine (Keyrakh and Quatariyah) with submontane grassland and dwarf shrubland. This limestone ridge catch precipitation of the summer monsoon, but as evident from the figure 103, the vegetation activity remains unusually high also during the winter monsoon (see the brown line). It may be caused by specific topography of the site with no natural barrier from N and NE direction, which probably enables to catch the precipitation of the winter monsoon as well. It is in accordance with MILLER et MORRIS (2004), who, in spite of its lower altitude, rank the Qatariyah limestone plateau among so called 'wet centres'. The wet centers in terms of MILLER and MORRIS (2004) exhibit perhaps the most marked patterns of plant distribution. Those areas, usually mountainous, typically catch monsoon precipitation and can all be considered as relatively wet 'islands' surrounded by inhospitable drier areas. They act as refugees of several plant species from times of greater rainfalls in the geological past.

Also according to the multitemporal image analyses (see chapter 4.5.) the Keyrakh and Qatariyah plateaus fall in the 3rd altitudinal vegetation zone.

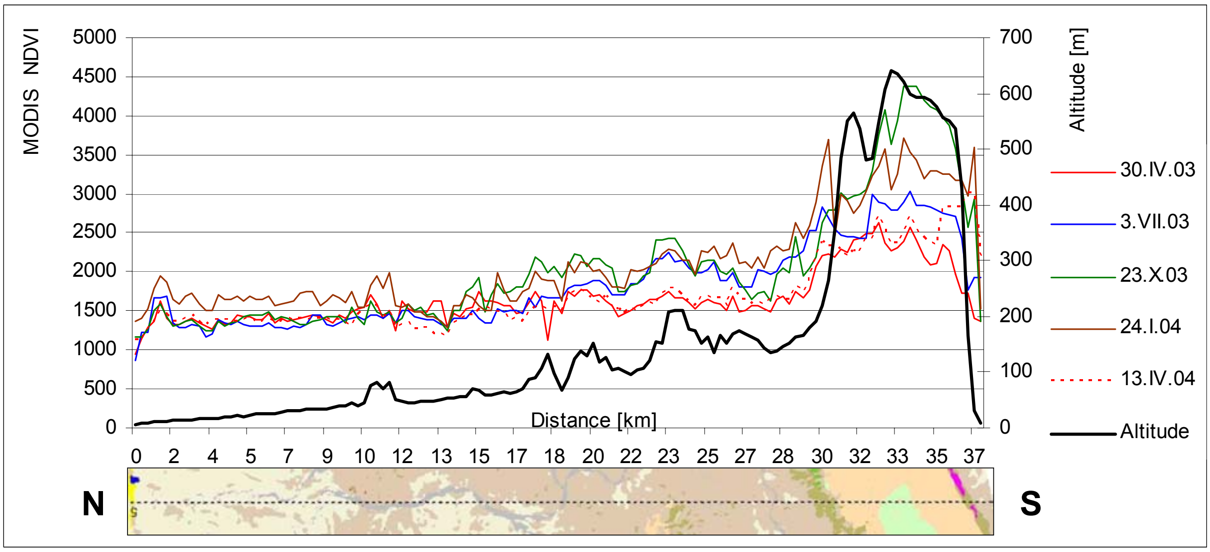


Fig. 103: Profile No.3 using image of altitude and particular NDVI images.

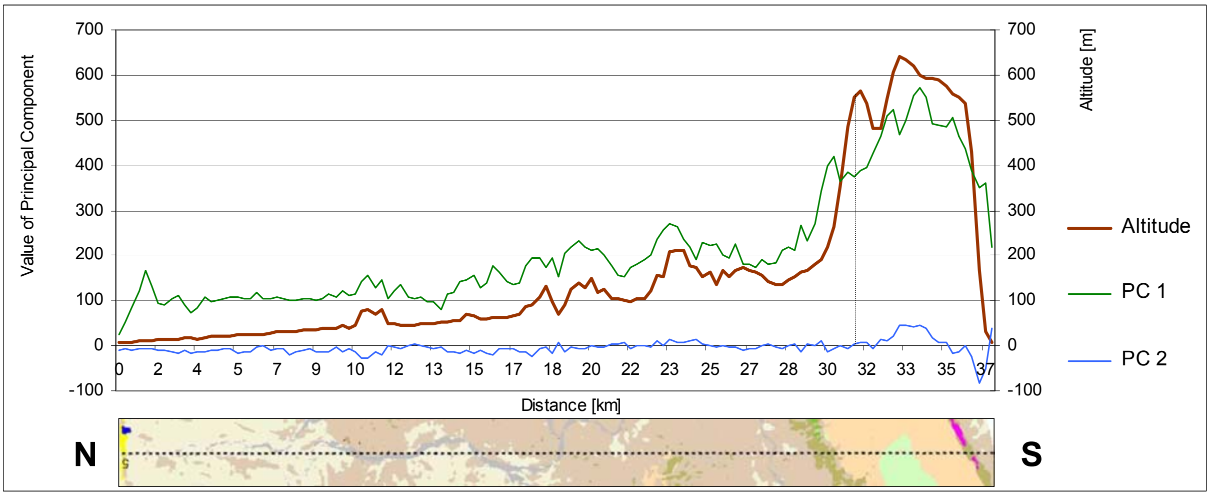


Fig. 104: Profile No.3 using image of altitude and both Principal Components of the TSA.

One effect is common for most of the profiles - comparing the 1^{st} PC (green solid line) with terrain altitude (brown solid line in figures 96, 98, 100, 102 and 104): In the highest places the value of the 1^{st} PC is usually not as high as the regression analysis and regression equation would suggest (see figure 90). It may be caused either by the saturation effect of NDVI in regions of high biomass, which was described by several authors (e.g. DAVENPORT et NICHOLSON 1993; HUETTE et al. 2002) or, in some cases, by actual vegetation cover (submontane and montane grassland). The saturation effect means that above some threshold value of biomass production, no further increases in NDVI are observed.

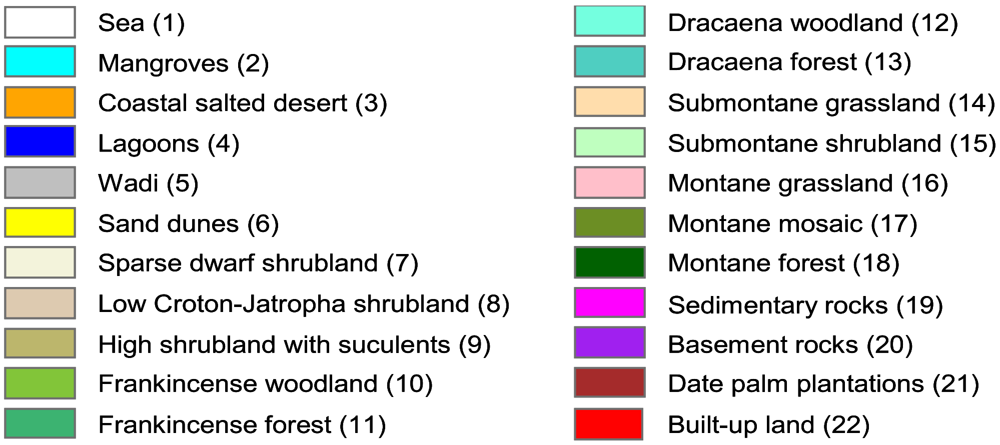


Fig. 105: Legend of the land-cover map used in spatial profiles (Fig. 97 – 104).

4.7.3. Profiles over time

While the TSA and the profile over space help to better understand overall variations of NDVI in time and space and its causalities, the profile over time in addition helps to reveal the vegetation dynamics of concrete sites and vegetation formations.

Figure 106 shows once more the time shift of vegetation activity between the 'north' and 'south' half of the island. During the long hot spring transition period (from February to April) the state of the vegetation is similar on both sides (it is mostly dry). Nevertheless, at the beginning of the summer monsoon (in May and firs half of June) some precipitations usually fall on the southern side (see Fig. 4) that cause significant local green-up of the vegetation in late June and first half of July. The north half of the island in the meantime remains dry. In July and August the summer monsoon culminates and wind reaches the highest velocity in the year, being very gusty. Regular precipitations in this period are not common, however, from current observations follows that while big part of Socotra suffer from desiccation, high limestone plateaus located on the 'south half' of the island (namely Keyrakh, Khod'oihel [Shibehon], Diksam) and Haggeher Mts. capture horizontal precipitation from drizzle and clouds. (The evidence that the impact of summer monsoon increases in higher elevations is evident also from the Fig. 84). One can note in the lower part of the figure 106 and in appendix No. 11 that August is for the southern side the cloudiest month. In fact in this period the cloud cover on the southern side is so pertinent, that appropriate NDVI values had to be often interpolated (dashed lines in the figure 106). The conditions start to equalize during the transition period between the summer and the winter monsoon. On the southern side of the island the highest precipitation falls the most probably at the very end of the summer monsoon (in September). This precipitation is likely to influence also the highest locations of the northern side. Moreover, from historical measurements (Mouri Airport 1943-1945) and from current personal and reported observations (e.g. MORRIS 2004) it evolves that in October (or at the end of September) first rainfalls already occur also even on northern coastal plains.

Consequently, the vegetation activity in this period is increasing on both sides of the island. The heavy rainfalls brought by the winter monsoon in November and December cause outstanding vegetation bloom on the whole 'north half' of the island in December and firs half of January. However, in contrast to summer monsoon, the winds of the winter monsoon does not cause marked desiccation of the opposite side of the island (probably because they are much lighter) and in higher elevations probably even bring some precipitation. Even the Firmihin station, situated actually at the leeward side cca 440m above sea level, recorded some sporadic rainfalls in December (see figure 4). The cycle is closed by the hot transition period between the winter and the summer monsoon, when the both sides of the island are drying up.

As a matter of fact, all the authors describing the climate of Socotra (e.g. POPOV 1957; DAVIS et al. 1994; MIES et BEYHL 1996; WRANIK 2000; EVANS 2001; MORRIS 2002 and MILLER et MORRIS 2004 – see chapter 2.4.) may have been partly right. The key issue is just the extreme variability of the climate caused by monsoon effect and specific topography of the island. Consequently, two sites distant just few kilometres may have completely different distribution of rainfalls and shifted vegetation seasons.

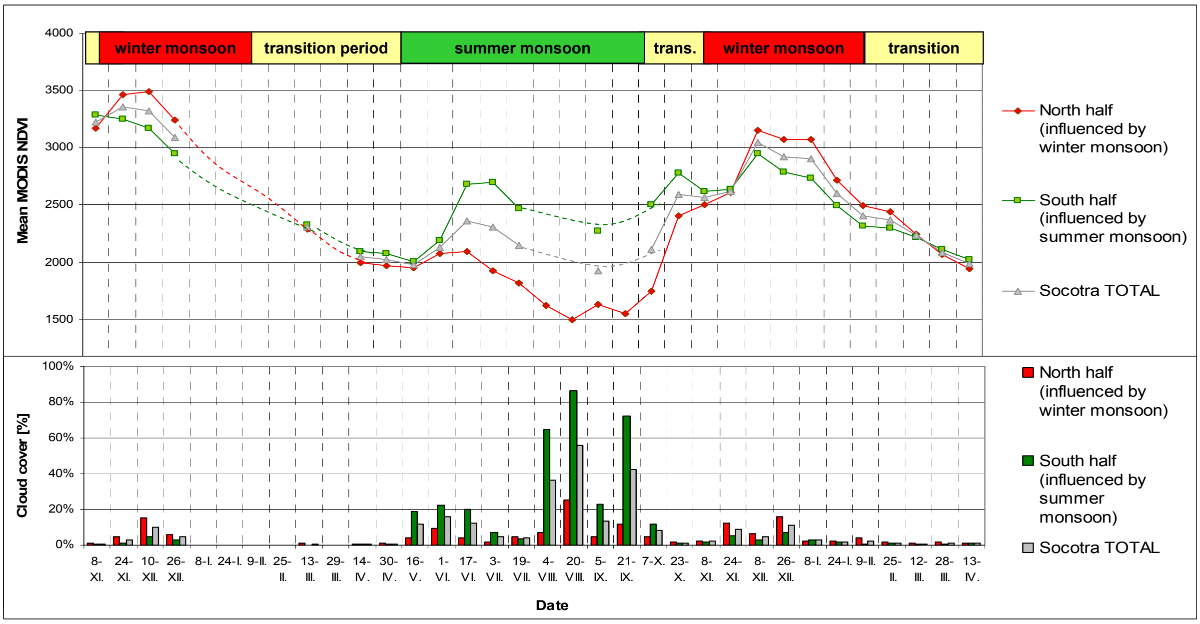


Fig. 106: Temporal NDVI profile of Socotra and the N and S 'halves' delimited by 2nd PC.

On the other hand, some former statements have to be revaluated. For example MIES and BEYHL (1996) incorrectly associate the secondary rainy season in April and May with the winter monsoon, although in reality it refers to the beginning of the summer monsoon (rather May and the first half of June) and it causes the secondary peak of vegetation activity on the southern side of the island. Similarly, some assumptions of GWYNNE (1968) were found incorrect. For example, he reported that: 'the whole island is frequently obscured by complete cloud cover during the monsoons, particularly during the period of north-east (winter) monsoon.' On contrary, according to current findings, the whole summer monsoon period and in particular August and September is the cloudiest period of the year (see lower part of Fig. 106 and raw NDVI serie in appendix No. 11), characterised by pertinent cloud cover over southern side of the island.

Of course, the most serious account is the misleading statement quoted more or less by all previous authors, that the winds of south-west monsoon are very dry causing desiccation to plants and animals alike and seldom bring rain. For the 'south half' of Socotra and in particular for high limestone plateaus and Haggeher Mts. just the opposite is true (see also the curve of air humidity in the figure 4).

The new findings can also contribute to the scientific debate about climate change hypotheses that is favoured e.g. by Dr. Miranda Morris (MORRIS 2002; MILLER et MORRIS 2004). Based on oral history and tradition reports, Morris assumed that: "not only has the extent of the drizzle/mist coverage diminished over the years, but also its duration and continuity decreased (what used to be predictable four to five months of monsoon cloud and drizzle followed by the rains of winter in the area, has become instead patchy and discontinuous)."

No direct palaeographic data are available from Socotra (MILLER et MORRIS 2004) such that a historical comparison is impossible, but as evident from the figure 106 and appendix No. 11, at present time extensive regular and pertinent cloud cover during the summer monsoon still exists. (For the interpretation of MODIS data it is important to keep in mind that this is the question of NDVI 'composites'. It means that if at least in one day during the 16-days compositing period there is a cloud-free record, than this record is used in final composite image. This in consequence means that the areas under the clouds in final images [see appendix No. 11] were cloudy for whole particular 16 days).

Following figures denote phenological differences between particular vegetation formations and even within one vegetation (or land-cover) formation, depending on its location within the island. Thus these charts help to reveal the extreme variability of the rainfall pattern of Socotra.

It is advisable to begin with the description of seasonal NDVI variations of 'Sand dunes'. Firstly thanks to its nearly null vegetation cover it is a very effective tool to test the stability of the MODIS sensor and consequently of the MODIS vegetation index. As one can observe (see fig. 107), the variations of NDVI values are really minimal. If there are some, it can be effect of scarce attendance of *Acacia edgeworthii* on sand dunes on the northern coast and *Tamarix nilotica* on the southern coast. Secondly, the value about 1000 can be considered as a base NDVI value representing a zero level of green biomass and vegetation activity.

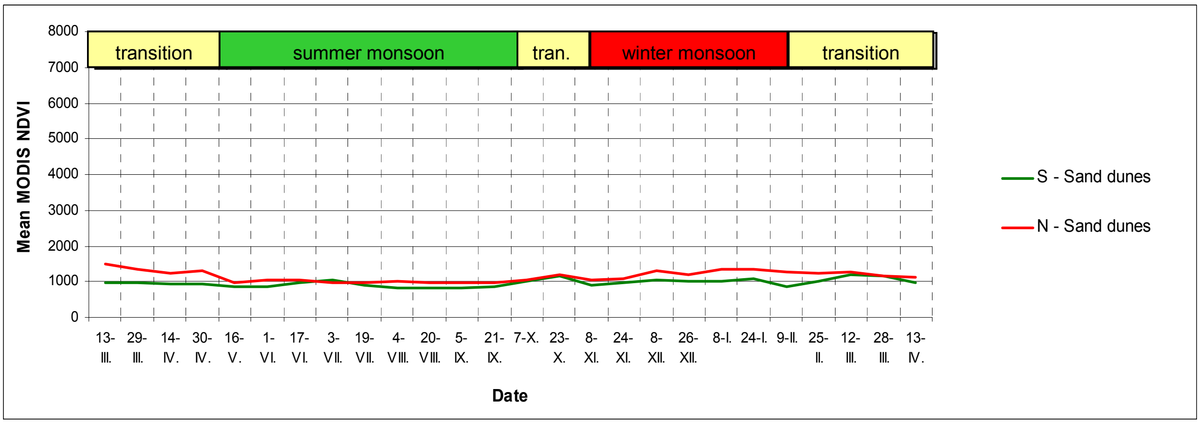


Fig. 107: Temporal NDVI profile of Sand dunes.

The second vegetation formation examined by the NDVI time profile is a 'Sparse dwarf shrubland'. One can note (see fig.108), that due to its really sparse vegetation cover the NDVI curve gets near the curve of sand dunes (however it is little bit higher). In consequence, the absolute differences between the north and the south part of the island are small, though relatively important. In any case, it appears that the impact of monsoons on low coastal plains is rather small. It seems that vegetation response of sparsely vegetated northern coastal plains on winter monsoon is somewhat higher than a response of similar vegetation on southern coastal plain on the summer monsoon (this effect is even more apparent in seasonal dynamics of 'Low Croton-Jatropha shrubland' - below).

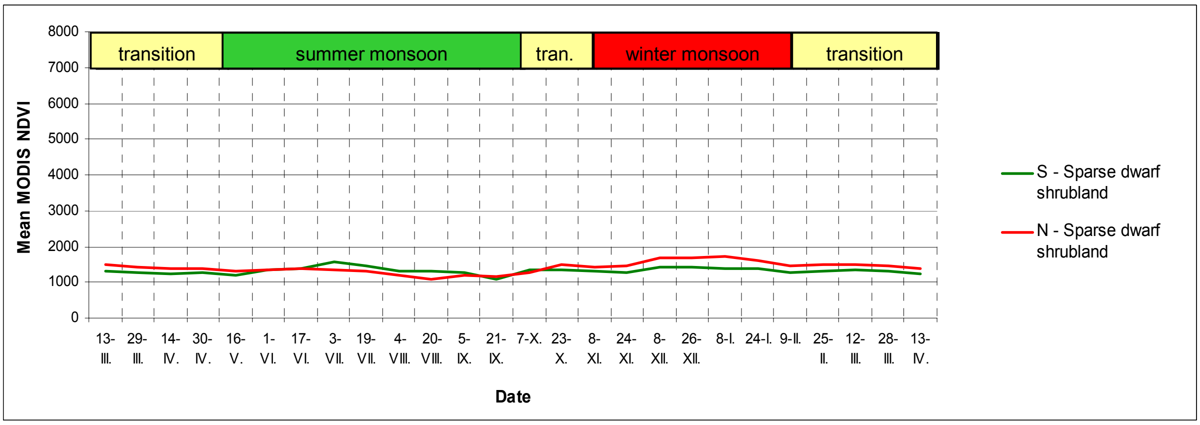


Fig. 108: Temporal NDVI profile of Sparse dwarf shrublands.

'Low Croton-Jatropha shrubland' occurs in coastal and inland lowlands and neighbouring low rolling hills. The figure 109 shows a big difference between the NDVI curves of the shrubland on the southern coast and the rest of the island. While on the southern coast (Nogad and Qa'arah plain) the Croton-Jatropha shrubland probably due to its lower density approximate the curve of Sparse dwarf shrubland, on the 'north half' the curve exhibit a significant peak, which obviously corresponds to winter monsoon period. It also favours a hypothesis, that the summer monsoon (unlike the winter one) does not affect the vegetation of the lowest elevations. The peak caused by the winter monsoon is even more distinct in shrublands of the 2nd Altitudinal Vegetation Zone (AVZ).

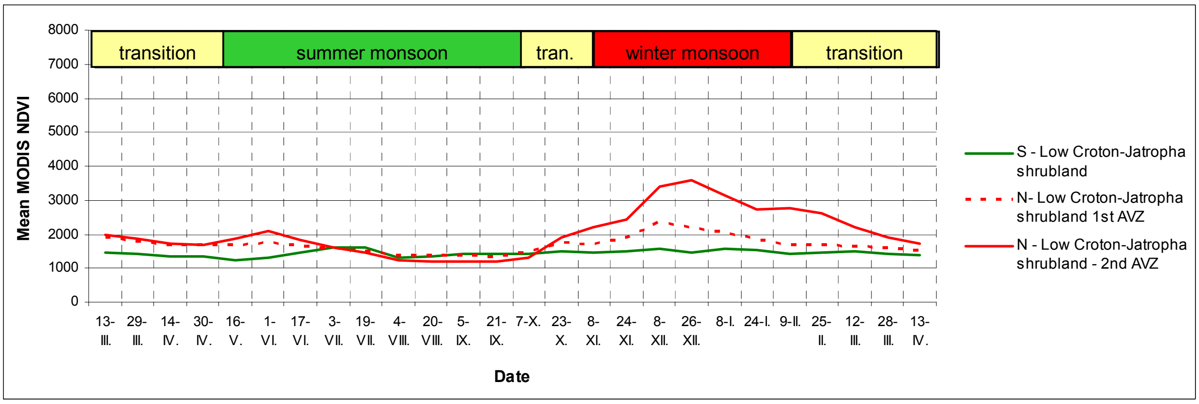


Fig. 109: Temporal NDVI profile of Low Croton-Jatropha shrublands.

In the case of 'High shrublands with succulents', the curves exhibit steeper slopes and bigger amplitudes compared to the 'Low Croton-Jatropha shrubland' (see fig. 110). It denotes faster green-up and more expressive vegetation bloom. Also the differences in phenology between the two sides of the island (N & S) are more apparent. While the green-up on the 'south half' starts in the middle of June (summer monsoon period), the 'north half' suffer from desiccation until beginning of October. Though, consecutive vegetation bloom starting in transition period and escalating during the period of winter monsoon is very expressive. In addition, the curve depicting vegetation activity of succulent shrublands on the northern side of the island has clearly unimodal character, while its 'southern' equivalent has rather bimodal nature. It closely resembles the two monsoonal rainfall patterns: the 'north half' has one rainy season in November and December, while the 'south half' receives marginal precipitation in May and June and main precipitation in September (see Fig. 4).

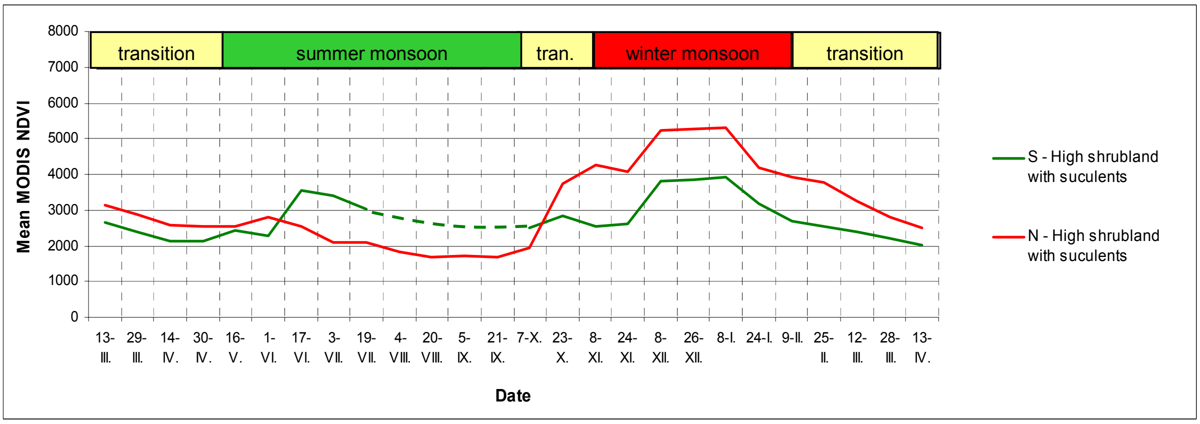


Fig. 110: Temporal NDVI profile of High shrublands with succulents.

The phenology of '<u>Frankincense woodlands</u> (open canopy closure) <u>and forests</u>' (close canopy closure) is depicted by NDVI time profile in the figure 111. Because of its dispersal the NDVI curve under the influence of winter monsoon is more typical for those vegetation formations (red lines in the figure 111). Similarly, as in the case of succulent shrubland, the October green-up of deciduous species is very fast and distinct.

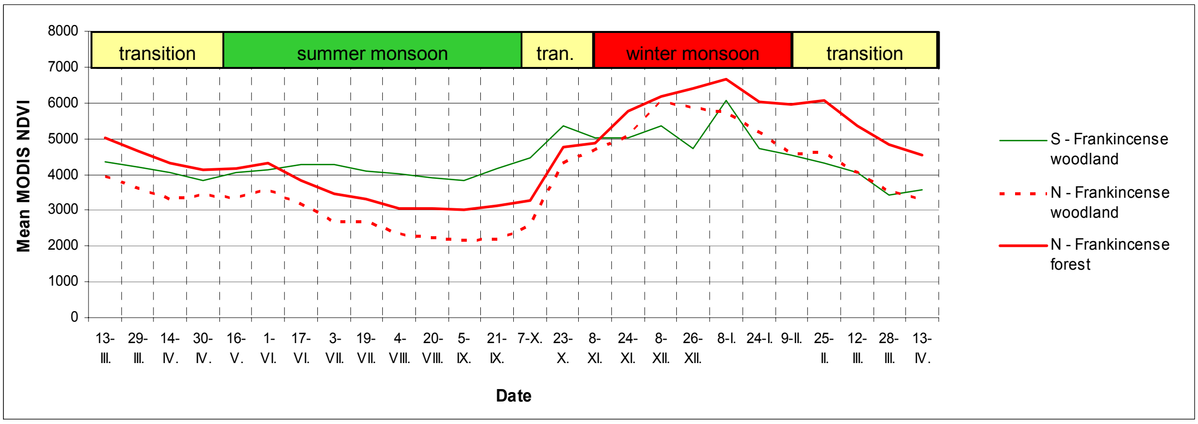


Fig. 111: Temporal NDVI profile of Frankincense woodlands and forests.

In contrast to Frankincense woodlands and forests, the '<u>Dracaena woodlands and forests</u>' are typically under the influence of summer monsoon (green lines in the figure 112). The curves of mean NDVI values are typical by its low amplitudes and high minimum values caused by presence of evergreen dragon blood trees. The phenology of woodlands and the forest is parallel, just mean NDVI values of the forest are higher thanks to higher abundance of evergreen dragon blood trees (*Dracaena cinnabari*). Slight green-up caused probably by deciduous species and (or) the herb layer appears in the middle of June and the period lasts till the end of January. Rare sites influenced by winter monsoon exhibit different dynamics also thanks to those deciduous species (red line in the figure 112).

The seasonal dynamics of semi-deciduous '<u>Submontane shrubland</u>' is apparent from the figure 113. Since this vegetation formation develops on very similar sites as Dracaena woodlands and also the species composition is very similar (except for the absence of *Dracaena cinnabari*), the curves have similar general course. Only the amplitudes are higher and overall NDVI value is lower due to the absence of evergreen *Dracaena cinnabari*. The differences between the 'north half' and the 'south half' are obvious. It is the question and it remains a task for future investigation, how much different layers (e.g. shrub layer, herb layer) and particular species participate in shaping of the total NDVI curve.

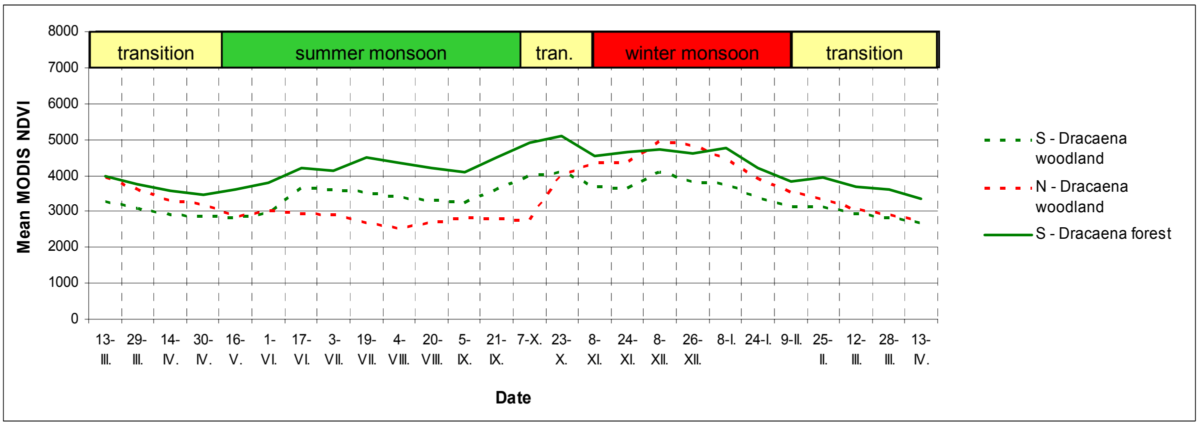


Fig. 112: Temporal NDVI profile of Dracaena woodlands and forests.

The green line in the figure 113 also clearly demonstrates the impact of horizontal precipitation on vegetation of high limestone plateaus in August and better part of September. Although in this period it usually does not rain (nor on the 'south half' of the island), horizontal precipitations are sufficient for growth of deciduous species (no apparent decline of vegetation in the middle of summer monsoon period, as depicted by the green line).

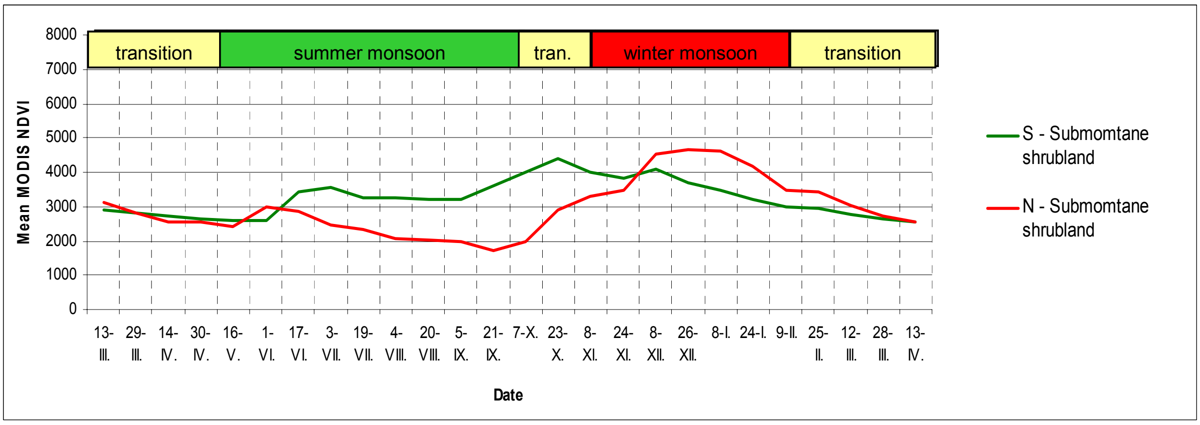


Fig. 113: Temporal NDVI profile of Submontane shrubland.

In final figure (114) the phenology of montane vegetation formations is displayed. It is the question of 'Montane grasslands', 'Montane forests' and a 'Mosaic of montane woodlands and shrublands'. One can note that the curves of mean NDVI values are similar. They reach the minimum at the beginning of summer monsoon period. Consequent slight growth of NDVI values ends in the middle of winter monsoon period and then slight decrease follows. Small differences between the curves of montane grassland and montane mosaic can be caused by resolution of MODIS sensor (250m), which is in this case insufficient. The curve of montane grassland exhibits somewhat bigger amplitudes and steeper slopes, which can denote more profound and direct response to rainfalls. The curve of montane forest is globally higher thanks to higher degree of coverage of evergreen trees. Although according to principal component analysis (see chapter 4.7.1.) most of the mountainous area is under the influence of the summer monsoon, the curves in the figure 114 clearly show that the precipitation of winter monsoon plays an important part in phenology of the highest sites of the island as well.

The curves appear to summarize the effect of both monsoons, so that two generally distinct ‘monsoonal peaks’ of vegetation activity are merged in one relatively long vegetation period.

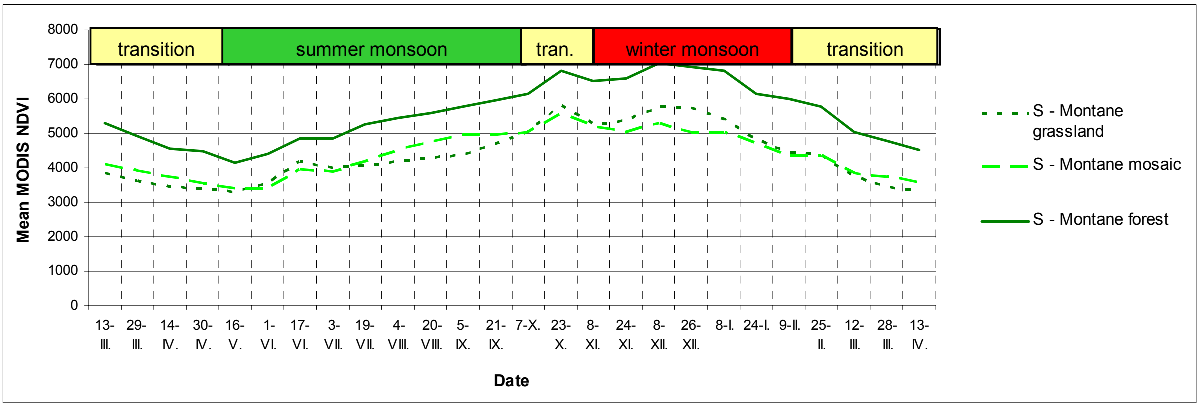


Fig. 114: Temporal NDVI profile of montane vegetation formations.

5. CONCLUSIONS

The study shows the real strength of spatial data and geoinformation methods and verifies their potentials for complex geo-ecological studies. More or less apparent as well as relatively hidden relations between different ecotope components and environmental factors were uncovered and confirmed. Comparison of various spatial data layers (land-cover, geology, altitude, vegetation indices, etc.) using even quite common GIS and image processing operations can provide new valuable findings. Geoinformation methods can therefore be very helpful as a tool in conceptualising problems or hypotheses, particularly in the wide field of landscape ecology. What is advisable to underline, extensive areas necessary for investigation of certain features are not obstacles any more.

5.1. Land-cover mapping

All the past and present exploration activities on Socotra have brought a wealth of information documenting different aspects of the islands environment. The floristic surveys already allow a detailed description of the flora and vegetation of Socotra to be made. However, existing relevant map products do not match with this high level of knowledge. This, in turn, creates severe problems for a well-prepared protection strategy. The new land-cover map of the Socotra Island should bring important detailed grounds for effective and relevant decision-making and management of local natural resources.

Experience and the first results acquired in the process of dealing with the land-cover map show that incorporation of RS data and techniques in the mapping process brings a significant improvement in terms of data accuracy, cost effectiveness, spatial differentiation and timeliness. A detailed land-cover map of the island could not be created in comparable quality, costs and time limit by the terrain survey only. Moreover, the procedure combining supervised maximum-likelihood classification and rule-based post-classification sorting (simple knowledge base classification) provides results of sufficient spatial and thematic accuracy (estimated overall accuracy about 80%, mapping 22 terrestrial land-cover classes) while maximizing user's accuracy of the final map product.

Consecutive simple GIS analysis enables estimates of highly valuable information as absolute global area and relative degree of coverage of particular land-cover classes (biotopes) over the island, their spatial distribution and ecotope characteristics. Consequently, it allows for example estimates of the current and potential occurrence of rare species - e.g. unique biotopes of endemic Dragon blood tree (*Dracaena cinnabari;* i.e. land-cover classes 'Dracaena forest' and 'Dracaena woodland'), which are essential for their protection and management. Derived information may be very interesting also for donor community and as such undoubtedly extremely important for effective fund-rising.

The conclusions are accordant for example with findings of HELMER et al. (2002), who stated that for reasonable mapping of tropical island vegetation the spatial scale and class resolution become critical: "The spatial and class resolutions of recent ecoregions and land-cover maps are too coarse for biodiversity conservation on tropical islands". Similarly OLDFIELD et SHEPPARD (1997) concluded that "lack of species and ecosystem inventory data currently unfortunately hinders development of biodiversity conservation strategies, which are needed at a time of intense development pressures."

As reported by MYERS et al. (2000), who was engaged in biodiversity 'hot spots' assessment, in fact "almost all tropical islands fall into one or another hotspot", because high species endemism combines with proportionally extensive habitat loss. Also Socotra Island is known for its high degree of endemism, though habitat loss has currently there rather hidden character given by permanent, long-term, though escalating overgrazing. Recent fast development of the island (e.g. road construction and urban development) together with expressive population growth can, however, change the character of human pressure on Socotran environment very quickly. Produced land-cover map can therefore offer so valuable data for future conservation strategies.

5.2. Mapping Altitudinal Vegetation Zones

Experimental use of multitemporal MODIS NDVI data for outline mapping of Altitudinal Vegetation Zones (AVZ) provided surprisingly good results. A simple logic that general NDVI values and their seasonal variations closely correlate with differences in altitudinal and exposure climate was used (e.g. 1st AVZ is characterized by generally low NDVI values with rather low seasonal variations, 2nd and 3rd AVZ by lower and intermediate NDVI values with very high variations, etc.). Achieved approximate overall accuracy of resulting map (over 80%) is higher than expected. Of course, the success of the method used is given by specific local conditions as extreme altitudinal climatic gradient between costal plains at one end and Haggeher Mts. at the other, as well as by relatively natural character of vegetation cover that is not disrupted by any arable land etc. (e.g. harvest would cause severe corruption of natural NDVI variations).

5.3. Studying seasonal vegetation dynamics by means of RS data

The time series of MODIS 16-days NDVI composites of 250m resolution proved to be very strong tool in the study of seasonal vegetation dynamics. The time series analyses uncover very effectively seasonal vegetation patterns and their causalities. It was proved, that overall NDVI value (and so vegetation activity) of particular site on Socotra is caused mainly by altitude and appropriate current vegetation type, while the time variations of the value are affected especially by monsoon effect. Therefore, the location of the particular site (whether it is on the 'north' or 'south half' of the island and at which altitude) is from the viewpoint of vegetation dynamics very important. This is in accordance with DAVENPORT et NICHOLSON (1993), who studied the relation between the rainfall and NDVI for diverse vegetation types in East Africa. They concluded, that the phenology can vary greatly within the vegetation formation in response to different patterns of rainfall.

The analysis also showed that some former findings related to Socotran climate (in particular rainfall) have to be revaluated. With some simplification, one can say that one year MODIS data helped to resolve several decades of 'disputes' regarding amount, timing and causality of rainfalls and their distribution over the island (see chapter 2.4.). It also makes a serious argument in a scientific debate concerning the impact of climate changes on Socotran vegetation (e.g. MILLER et MORRIS 2004).

With respect to recent more than 4 years climatic observations on Firmihin locality (see chapter 2.4.) and with respect to its proved strong connection to monsoon phenomena, the findings about the seasonal dynamics of Socotran vegetation (and consequently about the annual rainfall pattern) may be considered as more or less generally true. On the other hand, numerous phenological studies denote remarkable inter-annual variations caused by variations in rainfalls (DREGNE et TUCKER 1988; DAVENPORT et NICHOLSON 1993; ANYAMBA et al. 1998; PELKEY et al. 2000). It would be very advisable to continue in monitoring of NDVI values and their both spatial and temporal (both seasonal and inter-annual) variations.

Correspondingly, MALO et NICHOLSON (1990) stated: "It is noteworthy that the NDVI values are sufficiently sensitive to rainfall variations that they can distinguish among anomalously dry years. This suggests that NDVI would be a useful tool for reconstructing rainfall conditions in relatively dry locations where conventional rainfall measurements are sparse or completely unavailable". Thus, the NDVI time series could also be a very effective means for recognition of extraordinary climatic events (e.g. too long dry periods, abnormally wet and dry years, etc.) and their impact on Socotran vegetation. As quoted by MIES et BEYHL (1996 ex BELTRANDO et CAMBERLIN 1993) some variations of monsoonal course probably may occur: "It may be presumed (though this is not proven at the moment) that both extent and timing of the summer monsoon are modified by the ENSO (El Nino-Southern Oscillation) phenomenon, as is the case elsewhere around the Horn of Africa."

Simply said: Since the long-term climatic observations from different parts of the island are still completely lacking and the strong relationship between the NDVI and some environmental variables (especially rainfall) have been proved (HIELKEMA et al. 1986; DREGNE et TUCKER 1988; MALO et NICHOLSON 1990; DAVENPORT et NICHOLSON 1993; SCHUTS et HALPERT 1993), further monitoring of NDVI time series could considerably contribute to the detailed recognition of the climate of the island or particular sites (e.g. constructing of the long-term temporal NDVI profiles for Target Areas proposed by Miller and Morris [2004], etc.).

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7. APPENDICES