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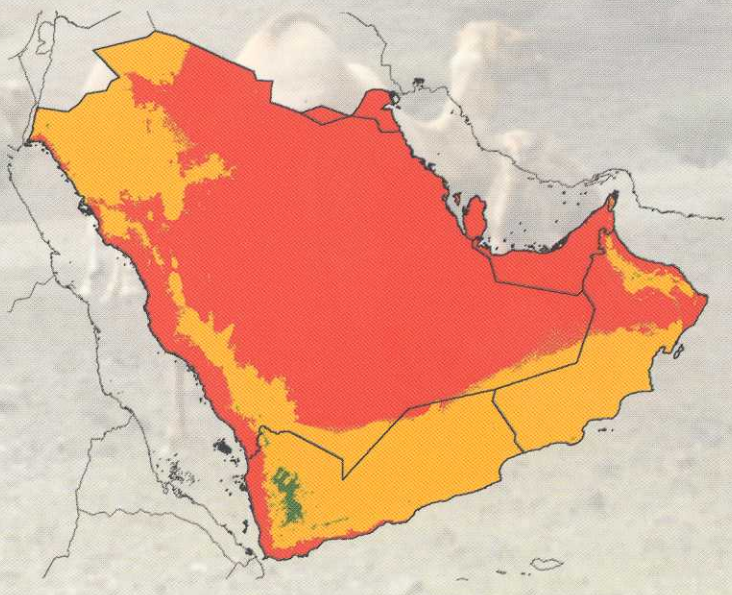
An Agroecological Exploration of the Arabian Peninsula

Eddy De Pauw



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Front cover photograph
Landscape in Ahfara, Fujairah, United Arab Emirates. The relative lushness of the vegetation is the result of above-normal rainfall. Pronounced rainfall variability, both in space and time, is a key characteristic of climate in the Arabian Peninsula, and responsible for tremendous variations in rangeland productivity.

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Foreword

The Arabian Peninsula constitutes one of the largest contiguous arid zones in the world. Within this context of aridity the region is surprisingly diverse in climatic conditions, soil types, landscapes, and land use patterns. Agroecological niches occur with edaphic conditions that can deviate substantially from those of surrounding areas and often have a higher biomass or agricultural productivity. In the context of global climate change this agroecological diversity is also an important source of abioticstress resistance in plants against drought, high temperatures, and salinity.

However, the region is also ecologically fragile. Firstly, it is vulnerable to natural processes, such as primary salinization, and wind and water erosion. In addition, overgrazing, fuel-wood extraction, drought, and depletion of fossil water resources are increasingly threatening the sustainability of the natural resource base, and may lead to potentially irreversible desertification.

A rational approach to combating desertification requires in the first place differentiating true degradation, as a result of over-exploitation, from processes and conditions that are the natural outcome of the biophysical limits imposed by the harsh climates that prevail in the Arabian Peninsula. Such an approach necessitates the development of agroecological frameworks, which allow assessing the spatial and temporal variations in the natural resource base and associated land use systems.

To combat desertification effectively, a good agroecological characterization is of vital importance. Numerous thematic surveys in the form of soil survey reports, climatic maps, and groundwater surveys already exist in the Arabian Peninsula. However, the challenge is to develop integrated land and water resource information systems, based on GIS-technology. This integration will allow linkage of multidisciplinary, geographically referenced databases at different resolutions, and to develop decision-support systems for more sustainable land use management and resource use regulations.

By bringing together information sources from the international public domain and the Arabian Peninsula itself, and processing them with state-of-the-art GIS technology, this report aims to initiate this process of data integration at the regional level. As such it will be of value for agricultural research planning, biodiversity management, land use planning, and public awareness at the national and regional level. We hope it will fill a major gap in our understanding of the agroecological diversity, vulnerability, and agricultural productivity of one of the most important arid regions in the world.

Prof. Dr Adel El-Beltagy
Director General, ICARDA

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Abstract

This report provides an overview of the agroecological characteristics of the Arabian Peninsula.

The Arabian Peninsula is a vast plateau bounded by mountainous terrain. It can be subdivided into 15 geomorphological regions. Its main characteristic is aridity, due to low and erratic rainfall, and high temperatures. As a result, productivity of rangelands and agriculture is variable and poor. The interaction of temperature and precipitation gradients leads to a great diversity of climatic conditions, which is evidenced by 22 distinct agroclimatic zones, of which eight comprise 95% of the region.

The soils of the Arabian Peninsula reflect the general aridity of the climate. Most are poorly developed, shallow, or are enriched in lime, gypsum, or salts. Transported materials, such as sand dunes and sheets, cover large areas. That said, there is no shortage of good agricultural soils. The obvious limitation to put them into production is water availability. Where irrigation water is available, standard fertility management practices are required, and, if provided, allow maintenance and enhancement of soil quality.

Cropped areas are very limited in the Peninsula and most are irrigated, although substantial rainfed areas exist in Yemen and in Saudi Arabia. Between 1980 and 1996, area under irrigation more than doubled, aided by modern irrigation technology, such as center-pivot and drip irrigation. This use of fossil groundwater, however, is not sustainable.

The Arabian Peninsula is perceived as having limited heterogeneity, poor agricultural potential, and low population densities, and, therefore, it has generated limited interest with regard to global biodiversity. This view is oversimplified. The region has great agroecological diversity and much potential as a source of genetic diversity and of abiotic stress resistance. To achieve this goal there is a clear need to integrate existing thematic datasets into agroecological frameworks for development. Specific methodologies, models, and decision-support systems must be developed to achieve and make use of this integration.

Priority should be given to the regional assessment of crop water requirements with a view to enhancing water use efficiency, and agroecological zoning for biodiversity conservation, rangeland rehabilitation, abiotic stress identification, and development planning. Underpinning these research goals should be a strengthening of climate monitoring networks.

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1. Introduction

The Arabian Peninsula, also called Arabia, is a vast landmass, covering about 2,590,000 km^2. It is bounded by the Red Sea on the west and southwest, the Arabian Sea on the south, and the Gulf of Oman and the Persian Gulf on the northeast. It is composed of seven countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, the United Arab Emirates, and Yemen).

Arabia is one of the driest subcontinents in the world. With an average precipitation of less than 100 mm per year it can be considered a desert region. It is also one of the hottest, with daytime temperatures often exceeding 50°C in summer. Yet, despite its general aridity, its ecosystems are surprisingly diverse. The rich biodiversity of the Arabian Peninsula is important to agriculture. The plants that are able to survive in this harsh environment might be carriers of traits useful in developing new drought and heat tolerant crop varieties.

However, the biodiversity of the Arabian Peninsula is under threat. An inherent fragility of the environment, combined with over-exploitation of the vegetation resources, has severely reduced the plant cover and narrowed the species pool. Huge parts of the Peninsula are now completely bare, not because of agroecological constraints, but because of overgrazing and fuelwood extraction. Given the long time required for biomass production in arid environments, recovery under conditions that do not provide total plant protection might be close to impossible. This is the true meaning of ‘desertification’ in a desert environment.

The Arabian Peninsula has enormous reserves of groundwater. In many parts of the Peninsula this precious resource has been exhausted in order to maintain agricultural production systems, such as irrigated field crops, which are essentially not adapted to the over-riding climatic constraint of hyper-aridity. Such systems are unsustainable because they consume huge amounts of water, where the supply is virtually non-renewable on a human time scale.

Combating desertification in the Arabian Peninsula requires good

information on the different environments. To some extent this information is already available. Many environmental studies have been undertaken, which have produced inventories of climatic, soil, terrain, vegetation, and water resources. Depending on the investments made by the governments of the region, the level of detail, updating, and integration varies considerably between countries. In addition, the access of the general public to this information is not always easy. As a result, it is difficult to obtain a synthesis of the agroecology at the level of the whole Peninsula.

Much information on the environments of the Arabian Peninsula exists also in the international community, in the form of books, journal articles, and international databases. Putting national and international data sources together in a concise booklet and integrating them through a Geographical Information System (GIS) is the main subject of this publication.

Given the size and diversity of this subcontinent, this publication is restricted to the level of 'exploration,' hence the title. Nevertheless, it is hoped that the 'bird's-eye view' it provides will be of value for agricultural research planning, biodiversity management, land use planning, and public awareness at the national and regional level. In short, the publication is meant to fill an important data gap and permit a better understanding of the resource diversity and environmental problems of the Arabian Peninsula.

This booklet is organized in several sections. The first gives a brief overview of the human geography of the Peninsula. The second describes the characteristics of the natural environment in terms of relief, climate, soils, land use, and cover. It also addresses the problem of land degradation assessment. A third section looks into the current status of agroecological characterization in the Arabian Peninsula, identifying knowledge gaps, thematic research priorities, and follow-up studies at the national and regional level.

This booklet is richly illustrated with maps. These maps were derived, through GIS techniques and methods of agroecological characterization, from the various data sources to which the author had access. Section eight briefly describes the methods used in generating the maps and lists the data sources. The maps in this publication are also available on a separate CD as GIS files (ARCView shape files and grids), and can be imported into compatible GIS software.

2. Human Geography

The Arabian Peninsula comprises the countries of Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, the United Arab Emirates (UAE), and Yemen.

Notwithstanding the low aptitude of the subcontinent to support high population densities (see section on 'Climate'), these countries have witnessed a tremendous population increase over the last 50 years (Table 1).

Table 1. Population in the Arabian Peninsula

Country	Population		Population change, %		Density, persons/km^2	
	1950	2000	1975-80	1995-2000	Overall	Rural
Bahrain	116,000	617,000	4.9	2.0	778	5,789
Kuwait	152,000	1,972,000	6.2	3.1	82	1,017
Oman	456,000	2,542,000	5.0	3.3	9	3,759
Qatar	25,000	599,000	5.8	1.8	53	667
Saudi Arabia	3,201,000	21,607,000	5.6	3.4	8	90
UAE	70,000	2,441,000	14.0	2.0	27	968
Yemen	4,316,000	18,112,000	3.2	3.7	27	690

Source: World Resources Institute (2001) URL: http://earthtrends.wri.org/country_profiles

In all Gulf countries, population increased between 1950 and 2000, by a factor of 5 to 30. The more spectacular growth rates (e.g., Kuwait, Qatar, UAE) are mostly due to a large net immigration of guest workers. However, the population data for Yemen, a country of net emigration, shows that increase in the native population is also a major contributing factor to population growth in the Peninsula.

The distribution of the population centers is shown in Figure 1. With the exception of the agricultural hinterland of Riyadh, Saudi Arabia, most of the population lives at the edges of the Peninsula, near coastal areas or in the mountains bordering the sea. This is to be expected. Given the aridity of the interior, people have historically concentrated in areas with higher rainfall (e.g., Yemen, Asir), or along trade routes. As the rainfall map shows, the density of population centers is associated with the higher rainfall areas. Very few people, with the exception of nomadic tribes, live in the desert interior.

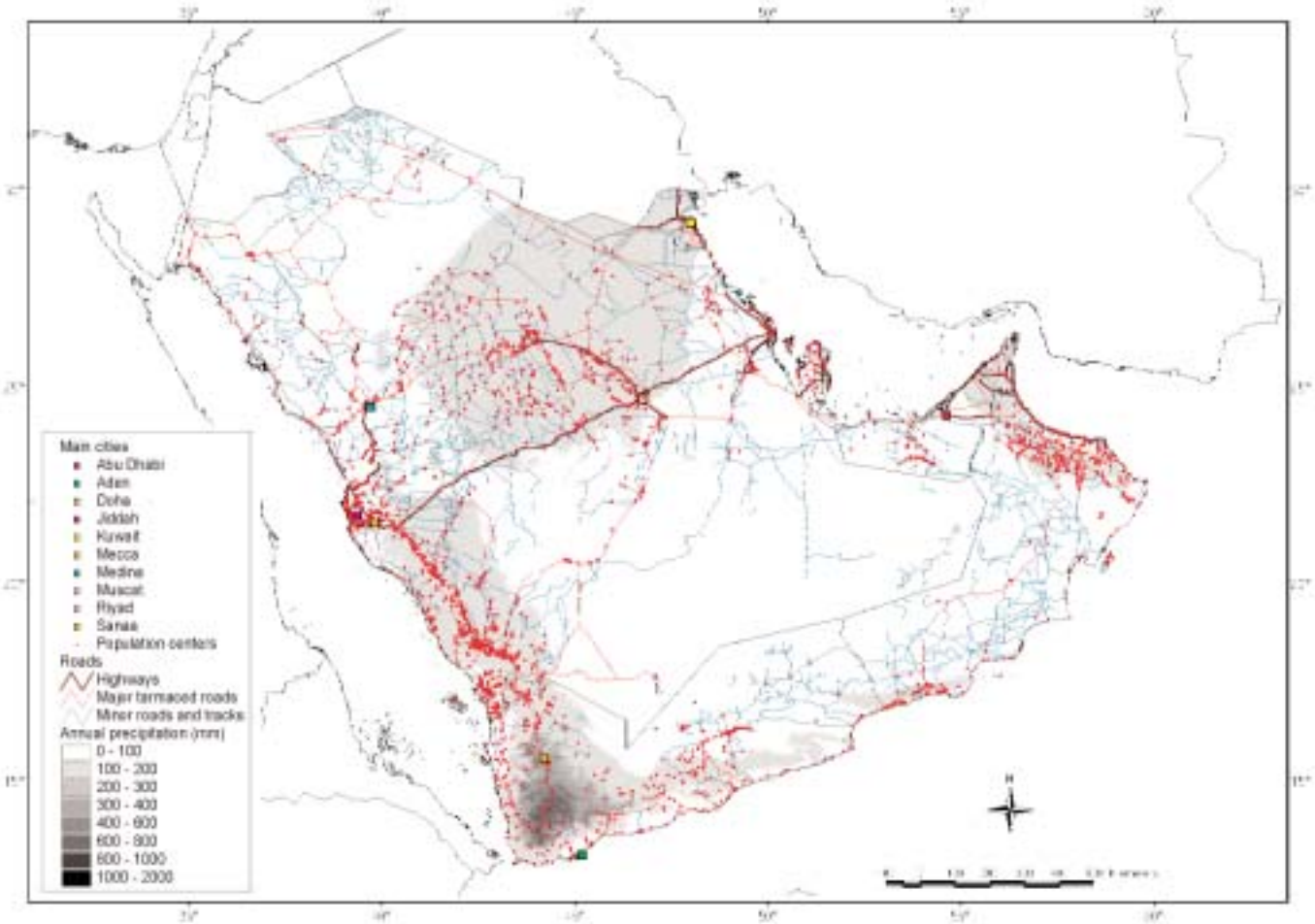

Fig. 1: Arabian Peninsula: General

The population density is shown in Figure 2. The subcontinent is characterized by generally low population density and high urbanization, with pockets of high rural population density. A high proportion of the country population still makes a living in agriculture in Yemen, and to a lesser extent in Saudi Arabia. Low cropland area (Table 1) and urbanization of the countryside (e.g., Kuwait, Bahrain, Oman, Qatar, UAE) might artificially raise the rural population density above levels that bear any relationship with the intensity of rural land use.

3. Relief and Geomorphology

The Arabian Peninsula is a vast plateau, gently sloping northeastward from the Red Sea to the eastern lowlands bordering the Persian Gulf. It is bounded on the west, south and east by mountainous terrain. According to the digital elevation model (DEM) GTOPO30 (Gesch and Larson, 1996), the altitude varies between –37 m in the lowest point, in the Matfi salt flat south of Qatar, and 3660 m at the Peninsula's highest peak, Jebel An Nabi Shu'ayb. The elevation map, derived from this DEM, is shown in Figure 3.

Elevation does not really show a landscape. In addition to its elevation, a landscape is defined by its degree of dissection, or the range between high and low points. Plains are defined by a very small elevation difference between neighboring points, rolling topography by a higher difference, and mountains by a very large difference. The map of Figure 4, derived from the GTOPO30 DEM, captures the 'ruggedness' of the landscapes of the Arabian Peninsula. It should be noted that this map evidences errors in the DEM used. The checkerboard pattern in the central Rub-al-Khali desert in Saudi Arabia is due to inadequate coverage by detailed topographical maps with elevation benchmarks and does not constitute a natural pattern.

The blue lines on Figure 4 delineate 15 major geomorphological regions (modified after Guba and Glennie, 1998, and Barth, 1976). The superimposed areas in red are salt flats. The geomorphological regions are briefly described in Table 2.

Among the most common and important landscape elements of the Arabian Peninsula are its drainage channels. These seasonal watercourses, or wadis, drain wide catchment areas and high mountains through networks of well-developed tributaries, ravines and runnels. An example of the drainage network

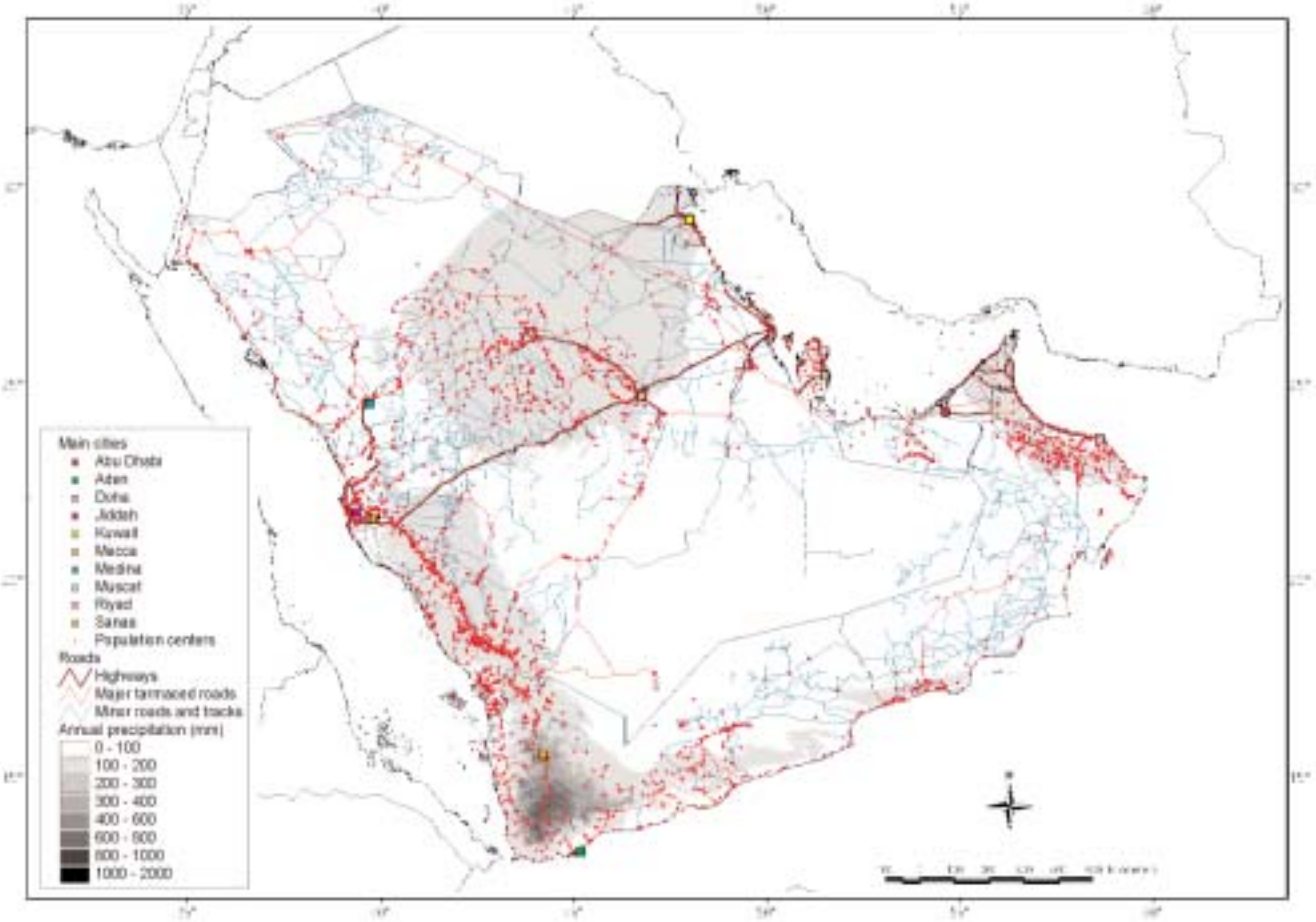

Fig. 2: Population density

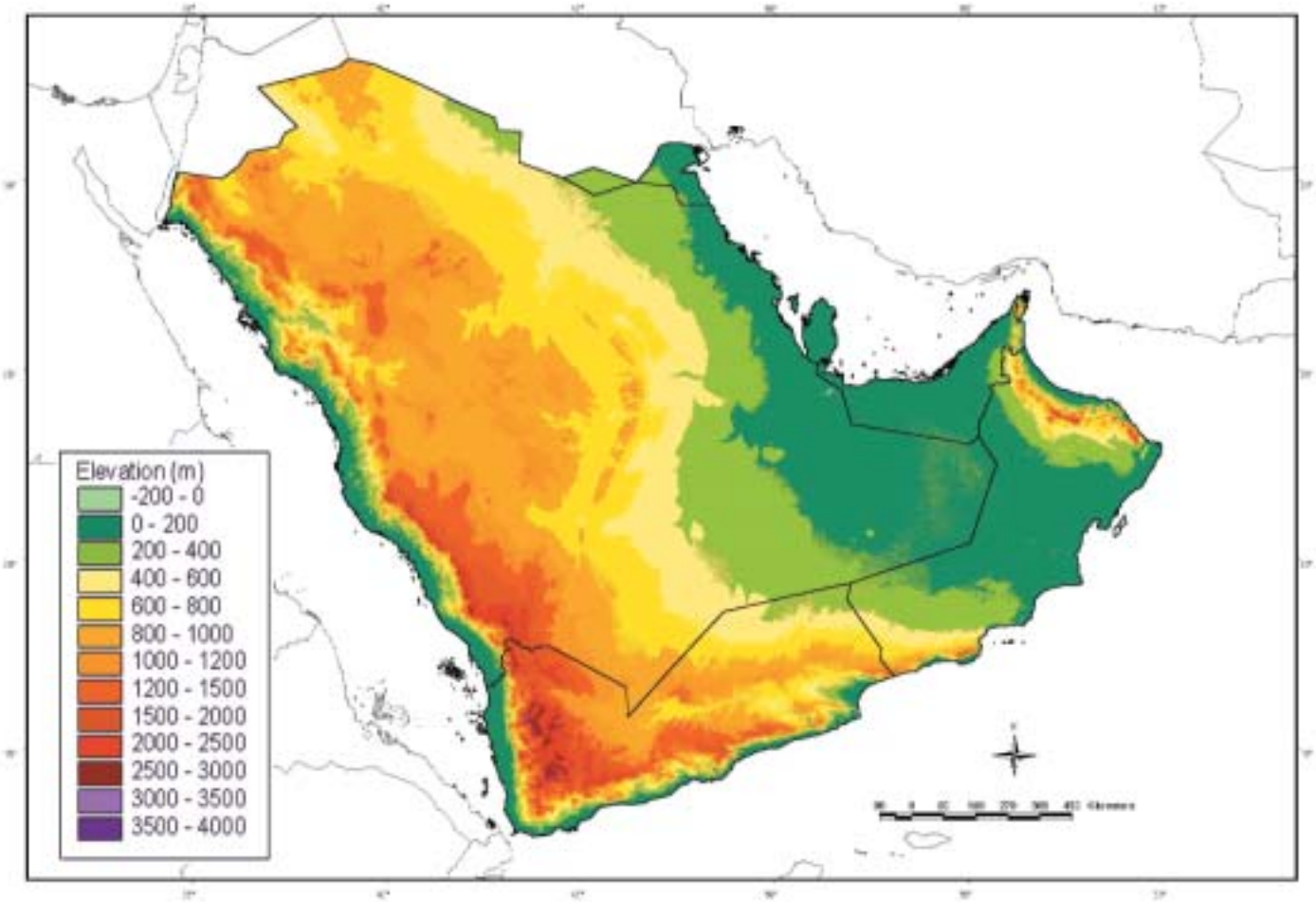

Fig. 3: Altitude

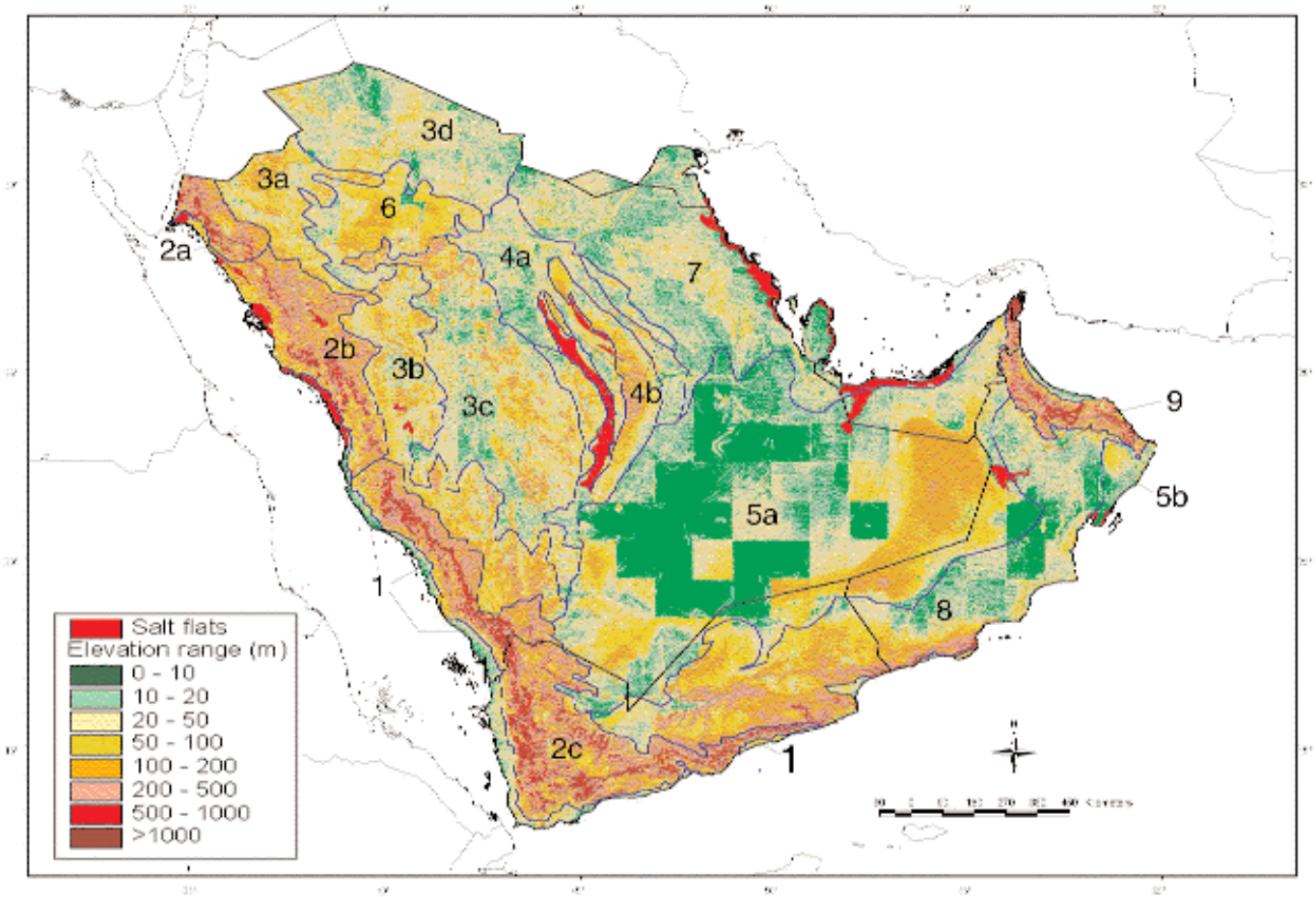

Fig. 4: Elevation range and geomorphological regions

Table 2. Geomorphological regions of the Arabian Peninsula (adapted from Guba and Glennie, 998)

symbol	Name	Altitude range (m)	Description
1	Coastal plain	0-200	Includes two sub-regions, the Tihama bordering the Red Sea, and the Batinah bordering the Gulf of Oman. Both plains are mostly pediments, gently sloping upward from sea level to the foothills of the mountains.
2	Western Escarpment Mountains		
2a	Midian Mountains	300-2000	Scarp mountains, very strongly dissected, with high peaks rising up to 3000 m.
2b	Hijaz Mountains	300-2000	Scarp mountains, rising less high, with interspersed high plateau areas. Very complex lithology, including granitic, metamorphic, volcanic, and sedimentary rocks
2c	Asir Mountains and Yemen Highlands	300-2500	Scarp mountains, very strongly dissected in the Asir, with high peaks rising up to 3000 m. Towards the Yemen highlands the high plateau areas become more widespread. Granitic and metamorphic rocks dominate the Asir, sedimentary rocks are predominant in the northern Yemen Highlands, and extrusive volcanic rocks in central and southern Yemen.
3	Arabian Shield		
3a	Sandstone plateau	700-1000	High plateau of fairly uniform elevation covered with sandy soils.
3b	Harrats (western Najd)	1000-1500	Area transitional towards the Najd plains at high elevation. Structural slope from SW to NE. Complex terrain with salt flats, pediments, and hills.
3c	Central plateau	800-1200	Mostly plains and plateaux with inselbergs and hill areas, built on the structural slope of the Arabian shield. Covered mostly by granitic and metamorphic basement complex rocks. Includes large areas with basaltic rocks.
3d	Summan plateau	250-500	Low-lying plateau with fairly uniform topography composed of flat-lying limestone with typical karst topography of sinkholes and caves.
4	Central Arabian Cuesta		
4a	Dahna sands and adjacent areas	500-800	Narrow belt of dunes and shifting sands extending over 1,300 km and connecting the Rub Al-Khali with the Great Nafud.
4b	Tuwayq mountain systems	500-1000	Cuesta region with 800-km-long escarpments composed of sedimentary rocks curving around the crystalline shield of the Central Plateau. Elevation may locally rise to 1500 m.
5	Southern Arabian Deserts		
5a	Rub al-Khali and adjacent areas	100-1000	The ‘Empty Quarter’ is the largest uninterrupted sand desert in the world. Contains both transverse and longitudinal dunes. Individual dunes reach heights exceeding 200 m.
5b	Wahiba Sands	0-300	Small sand sea formed by winds of the southwest monsoon, with longitudinal dunes mainly.
6	Great Nafud	700-1000	Second largest sand desert of the Arabian Peninsula
7	Eastern Gulf Region	0-500	Coastal plain rising gently to inland plateau areas. Covered mainly by unconsolidated beach sands, gravels, salt flats, and aeolian sands.

Table 2. Continued

symbol	Name	Altitude range (m)	Description
8	Southern limestone plateaux	300-1200	Includes the Hadramaut plateau and the raised plateau of Dhofar, which can locally reach an altitude of 2000 m, and dips to the north. The Dhofar plateau is bounded southward by an escarpment.
9	Hajar Mountains	500-2500	Steeply dissected narrow mountain range with heights up to 3000 m, formed by sedimentary rocks.

density, covering the northwestern part of the Peninsula, is shown in Figure 5. It is worth noting the absence of drainage channels in the eastern part, which is occupied by sand dunes.

The wadis are common to all geomorphological units, with the exception of sand dune areas, and support plant communities that are dependent on the water regime. Along wadis the vegetation cover is usually denser, except under conditions of overgrazing, fuelwood extraction, or aquifer over pumping. However, the vegetation pattern is highly site-specific, determined by the frequency of flooding, the stream velocity, type of sediments and coarse materials deposited, and variability of rainfall in the catchment areas ((Kürschner, 1998).

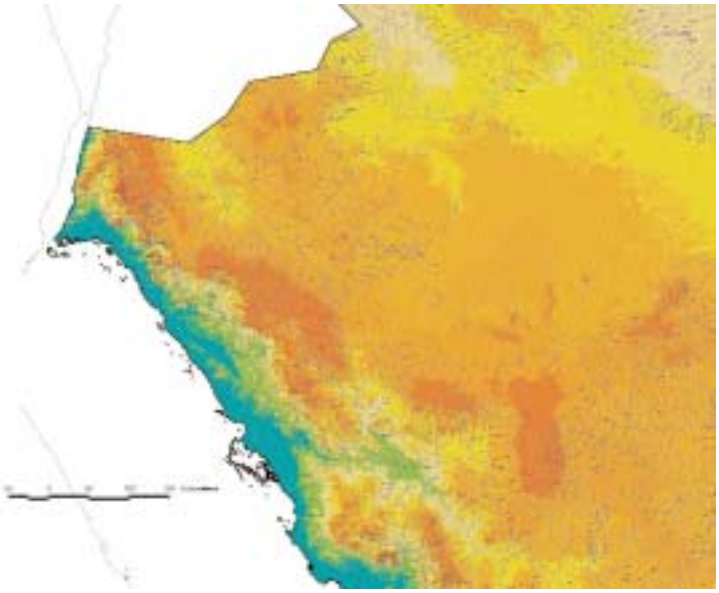

Fig. 5: Wadi network in the northwest of the Arabian Peninsula(Note: Wadis shown as blue lines. Elevation range is the same as in Fig.3)

4. Climate

4.1. General

The Arabian Peninsula is an ecoregion in which biomass productivity is primarily limited by the availability of water. Although there are exceptions, notably the Yemen Highlands and their extension into the Asir Mountains, the region is essentially arid or even hyper-arid. In addition to generally low rainfall amounts, rainfall distribution is usually unfavorable, coming in sudden and erratic showers, and variability is high between years.

The weather in the Peninsula is controlled by four air masses. The main reasons for the region's aridity are its remoteness in relation to the major rain-bearing weather systems, such as the North Atlantic depressions and the Indian monsoon, and its exposure to air predominantly continental in origin.

With the exception of winter in the northern part of the Peninsula and high-altitude locations, temperatures are high to very high, causing high evaporation, but also high biomass productivity, if water is available.

The low and erratic rainfall causes large fluctuations in the productivity of rangelands. It also enhances the importance of soils and landscape position in capturing the little rainfall available. Their ability to generate, concentrate, or receive runoff is the main reason for the 'patchiness' of vegetation cover in the Peninsula.

Within the overall limitations imposed by aridity, there is an unexpected diversity in climatic conditions. This diversity is usually related to differences in temperature and moisture regimes as a result of different exposure to rain-bearing systems, but also altitudinal gradients. The mountains at the edge of the Peninsula generally act as 'moisture traps.' At certain times of the year the influence of the mountains can be strong enough to generate their own weather through erratic and intensive thunderstorm activity. This is certainly the case in the Yemen and Asir highlands and the Hajar mountains in Oman. Topography also influences climate by 'guiding' wind flows and rain along favored paths. The Zagros mountains in western Iran, through this mechanism, play an important role in generating precipitation over the extreme east of the Peninsula (Fisher and Membery, 1998). In the same way, the western mountains influence rainfall production along the Red Sea.

4.2. Precipitation

4.2.1. Types and amounts

Precipitation is mostly in the form of rainfall, although occasional snowfall has been recorded in the Yemeni and Asir highlands.

Fisher and Membery (1998) report the regular occurrence of fog in the western highlands, the Dhofar region, and the central desert of Oman. The contribution of this 'occult precipitation' from fog, mist, low clouds, or dew, to the regional waterbalance might be doubtful. However, these sources of hidden precipitation can help significantly in creating, at a micro-scale, improved conditions for more productive and diverse plant life, particularly grasslands and woodlands.

The distribution of the mean annual precipitation is shown in Figure 6. Generally speaking, precipitation levels are associated with elevation. The highest rainfall occurs in the Yemeni highlands and Asir mountains, and to a lesser extent in the mountains of northern Oman. The lowest precipitation is recorded in the low-lying areas of the Rub al Khali, the Najd in the north of the Peninsula, and the northern Red Sea coast.

4.2.2. Seasonal patterns

During winter the region is under the influence of polar continental air masses that originate in Central Asia. The influx of these air masses is accompanied by dry weather with generally clear skies and fairly low temperatures. Occasionally the Peninsula is affected by polar maritime air coming from the North Atlantic. These air movements are the remainder of the mid-latitude depressions that have already traversed North Africa and the Mediterranean. They are the main source of winter rainfall.

During summer the Peninsula is influenced by tropical continental air masses, which bring hot and very dry air from Egypt and Sudan. These air masses allow the region to become a stable high-pressure zone and source of tropical continental air. Cloudless skies, low humidity, very high temperatures (often >45°C), intensive surface heating, and dust characterize the weather system during summer (Fisher and Membery, 1998). The Indian monsoon system exercises some activity in summer, particularly in parts of Yemen, southwestern Saudi Arabia, and coastal Oman. However, its influence is limited by the strong tropical continental air mass, which prevails over the Peninsula at the time.

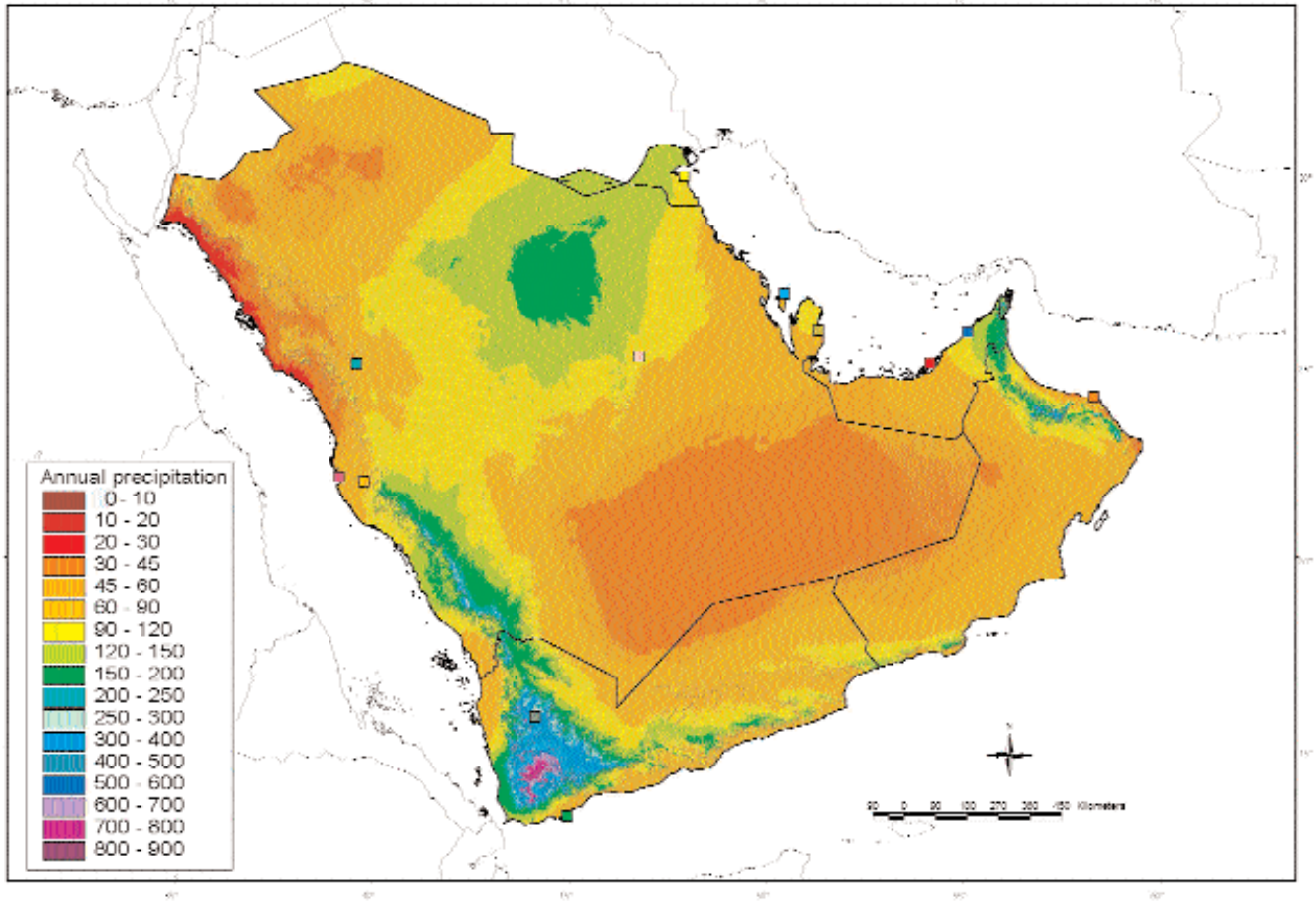

Fig. 6: Mean annual precipitation (mm^2)

The seasonal distribution is shown in Figures 7a-7d as the percentage of the annual rainfall that falls in each of the four seasons. This distribution is explained by the prevalence of one or another weather system at different times of the year.

Figure 7a shows the influence of the winter rainfall pattern, which is common throughout Europe, North Africa, West Asia, and Central Asia. Figure 7b shows the importance of spring rainfall (also largely associated with the westerly systems) for the central landmass of the Peninsula. Figure 7c shows the area of influence of the Indian monsoon, with peaks in the Yemen highlands and the Dhofar area in southern Oman. Autumn does not contribute much rainfall, except in the northern Red Sea coast region (Figure 7d).

4.2.3. Variability

As in other arid parts of the world, high rainfall variability is the norm and the impact of drought severe. Variability affects the amount and distribution of rainfall at different time scales.

Figure 8 shows a typical example of inter-annual variations for Muscat, time period 1893-1978, an unusually long dataset for the Arabian Peninsula. A typical characteristic of rainfall in the arid zones is its negative skew. This means that the probability of having rainfall below the mean is higher, but compensated for by few high rainfall events, as represented by the peaks in Figure 8. The probability distribution of annual precipitation in Muscat, as approximated by a log-normal transform, is shown in figure 9.

This figure shows that the probability of exceeding the mean (105 mm) is only 40%, illustrating the greater likelihood of smaller rainfall amounts.

At smaller time scales, variability increases even more. Figure 10 shows, for each month of the year, the mean rainfall and the amounts that might not be exceeded in one year out of four (2nd decile), and in four years out of five (8th decile).

In the same figure it can be noted that between April and October, the 8th decile is lower than the mean. This demonstrates that in areas (or times of the year) with very low rainfall, the concept of an average rainfall pattern is a statistical artifact. It is caused by the lumping together of a few high-rainfall events with very low probability, with numerous low-rainfall events with high probability.

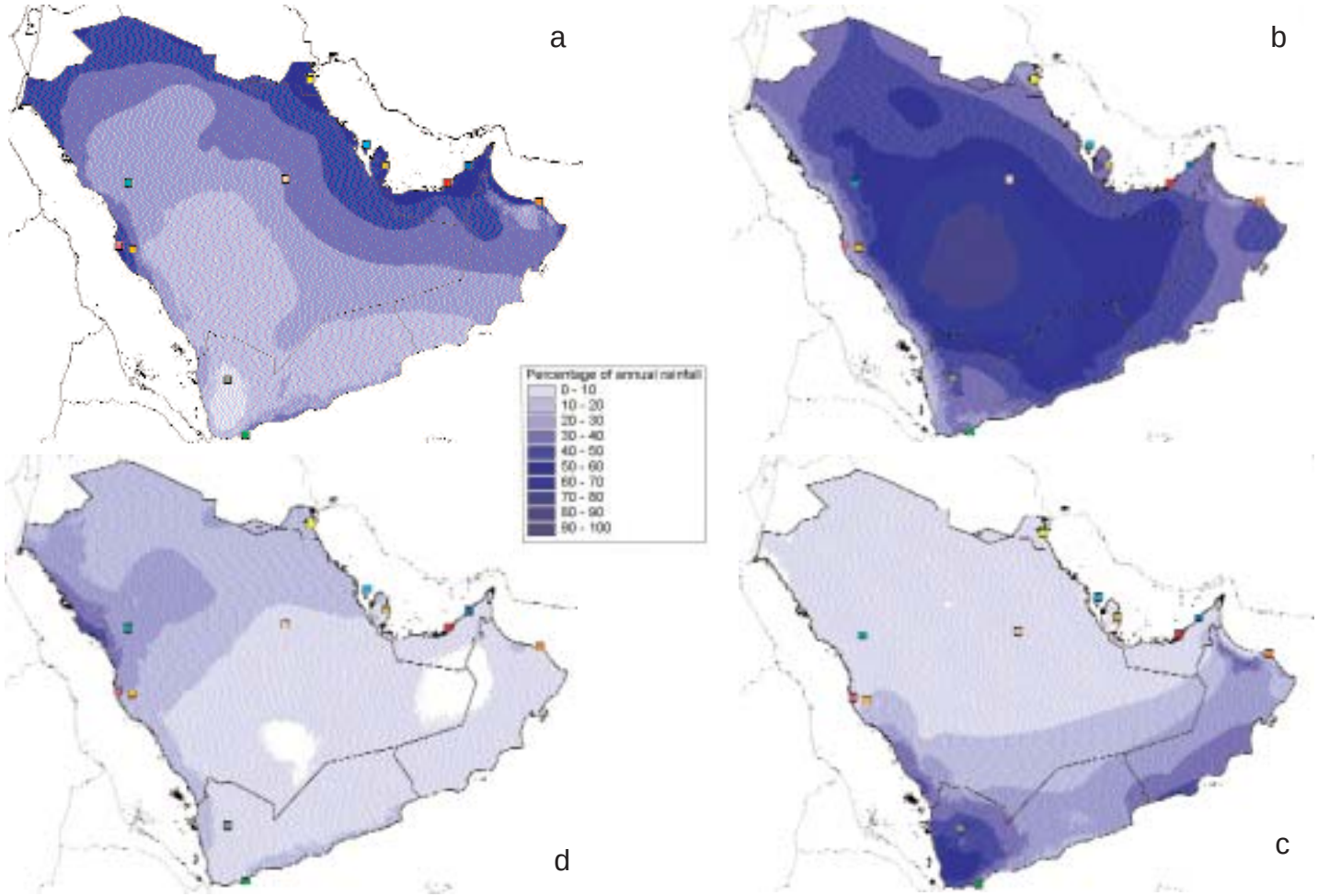

Fig. 7: Seasonal distribution of precipitation. Clockwise from top left: winter (a), spring (b), summer (c), autumn (d)

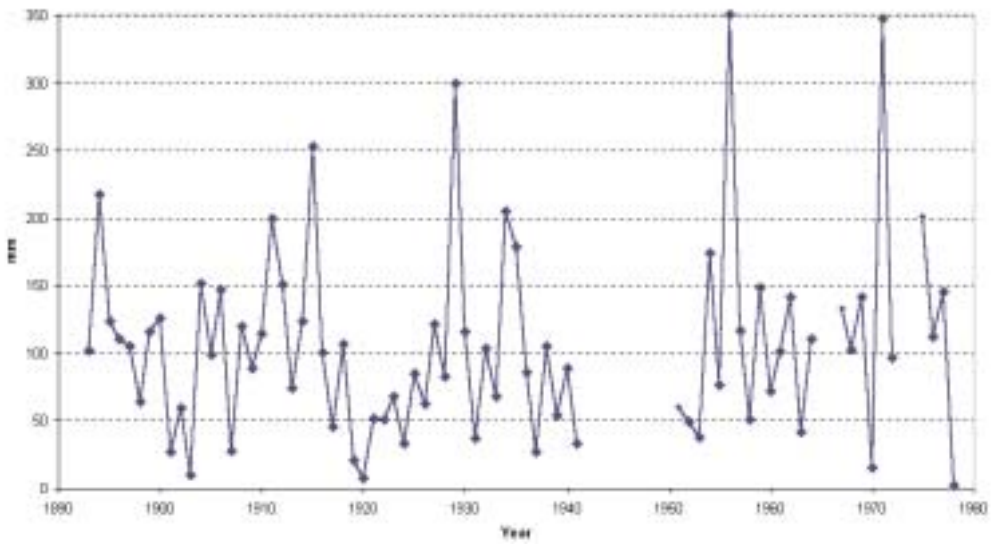

Fig. 8: Variability of annual rainfall, Muscat, Oman (period 1893-1978)

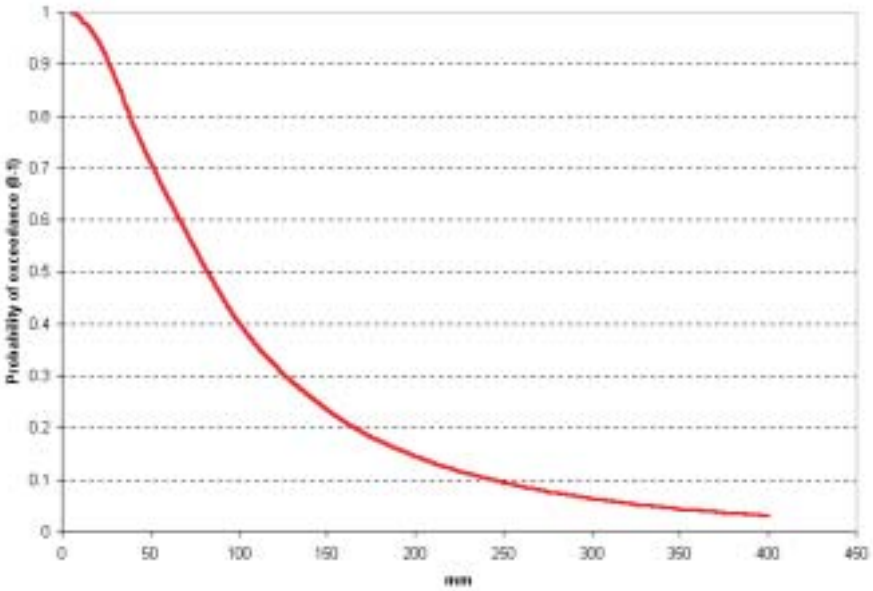

Fig. 9: Probability distribution of annual rainfall, Muscat, Oman (period 1893-1978))

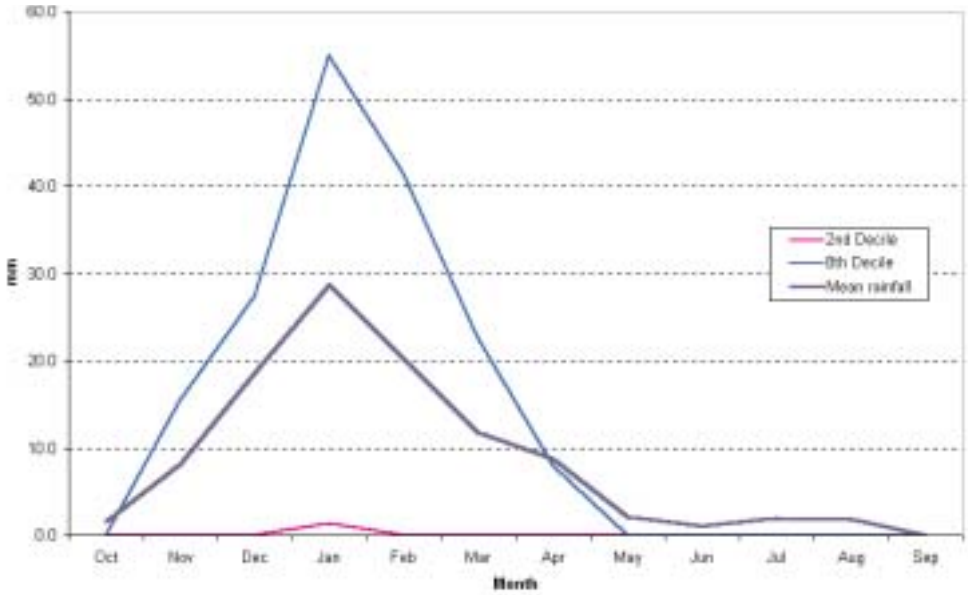

Fig. 10: Variability of monthly rainfall, Muscat, Oman (period 1893-1978)

The nature of individual rainstorms is such that they are often of limited spatial extent with considerable gradients in intensity and amount. This implies that in large areas in the middle of a 'rainy season,' the pattern in reality might be one of intense rains separated by dry conditions or light falls (Jackson, 1977). This 'spottiness' of rainfall has also been suggested by Fisher and Membery (1998).

The implication of increasing rainfall variability with decreasing time scale is of fundamental importance to our understanding of vegetation growth, biomass productivity, and climatic adaptation in the Arabian Peninsula. Since temperature is usually not limiting, growth and flowering occurs whenever and wherever water is available, irrespective of time of year and 'statistical' dry and wet periods.

4.3. Temperature

The Arabian Peninsula is warm. More than 90% of its area has a mean annual temperature of 20°C. A small area (shown in red) has a mean annual temperature exceeding 30°C. The cooler areas are shown in magenta in figure 11. They correspond with the western Yemen highlands, the Asir mountains, and the sandstone and limestone plateaux bordering Jordan.

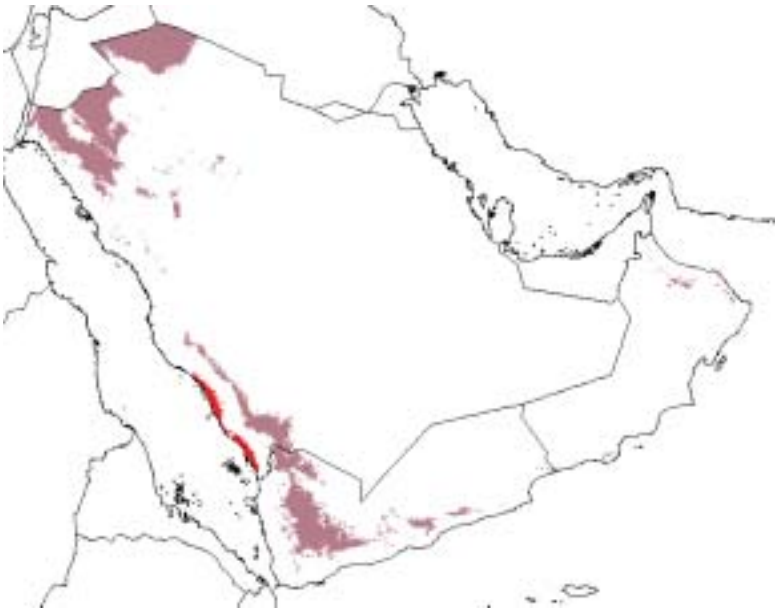

Fig. 11: Areas of the Arabian Peninsula with mean annual temperature exceeding 30°C (in red), or below 20°C (in magenta)

The major factors controlling temperature are elevation and latitude. From south to north there is a clear cooling trend, owing to increased exposure to cold continental air masses in winter. The map of mean annual temperature (Figure 12) illustrates these controls on temperature.

Temperature is strongly seasonal, with the lowest temperatures in the period December-February and the highest in the period June-September. The areas exposed to the Indian monsoon are an exception. These show a noticeable temperature drop in July-August, as illustrated by the climate diagram for Salalah (Figure 13).

Figures 14 and 15 show the temperature of the coldest and the warmest month, respectively.

Temperature seasonality tends to increase from the southeast to the northwest. The variability of temperature between years, in contrast with rainfall variability, is very low.

Temperature patterns can also be represented as the distribution of available atmospheric energy, which evaporates water or makes plants grow faster, for example. This representation of temperature as a source of energy for plant growth and biomass production can be done through the concept of *accumulated heat units* or *growing degree days*, which sum the daily

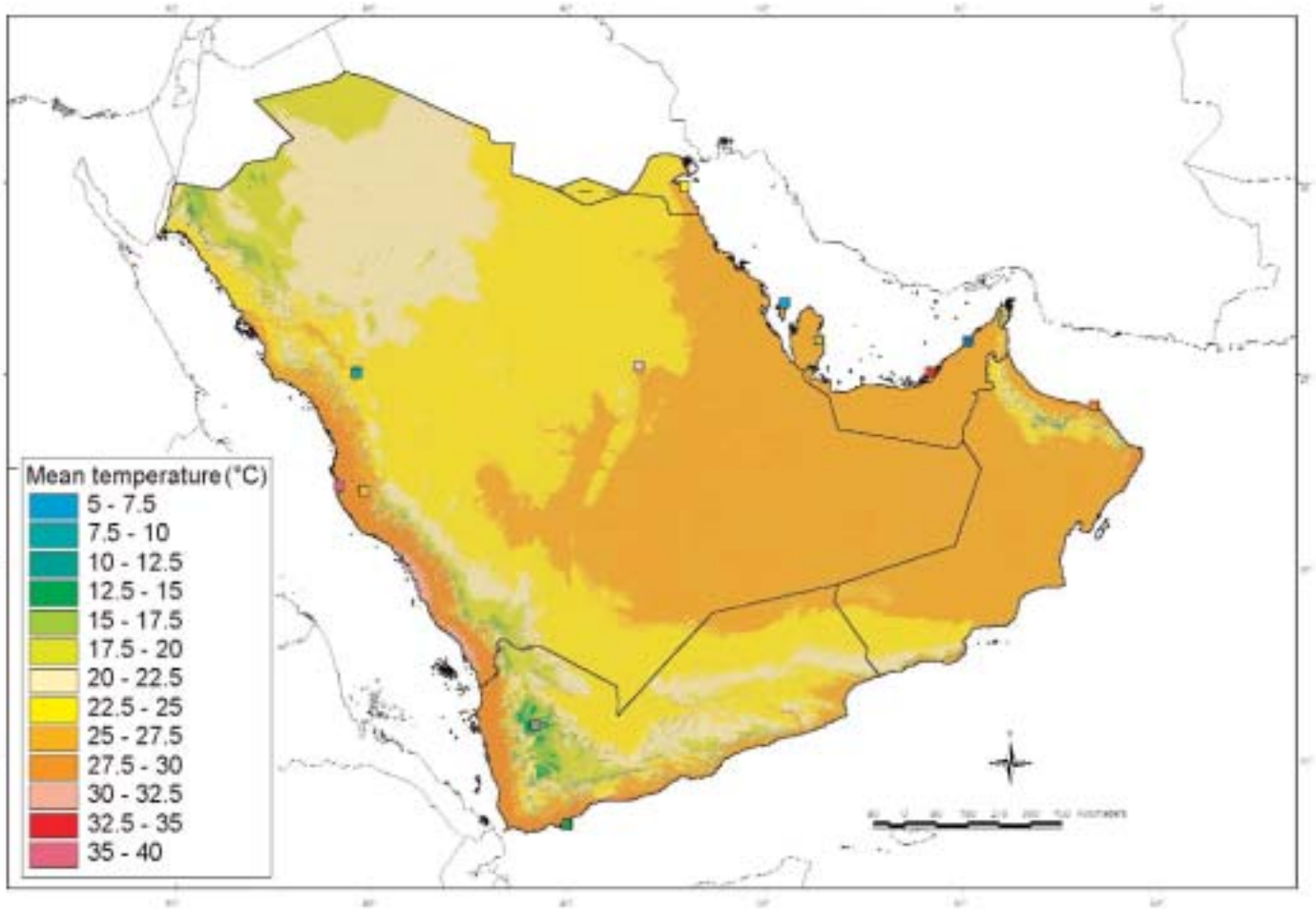

Fig. 12: Mean annual temperature

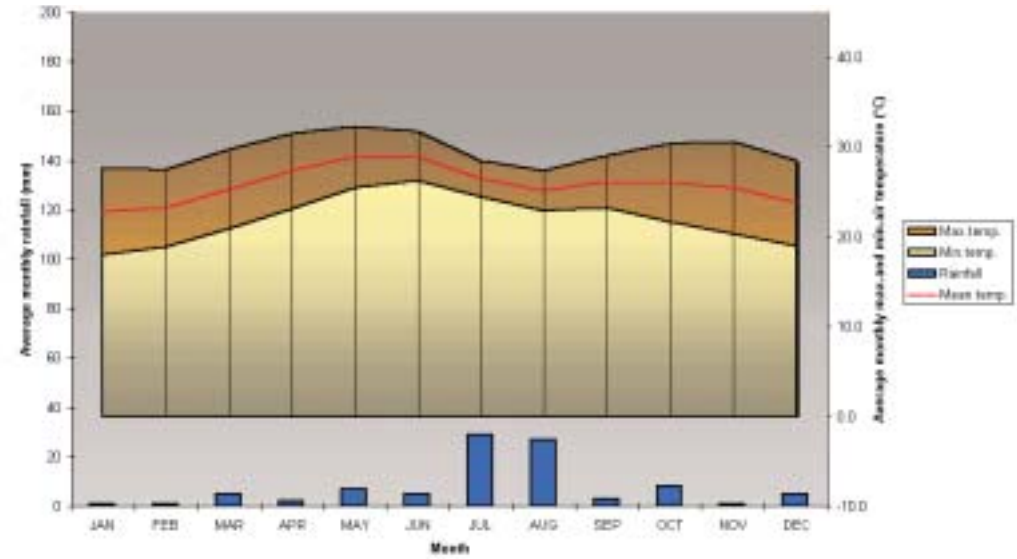

Fig. 13: Climate diagram for Salalah, Oman

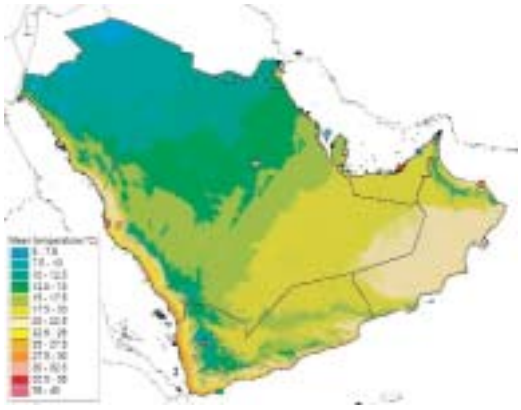

Fig. 14: Mean temperature of the coldest month

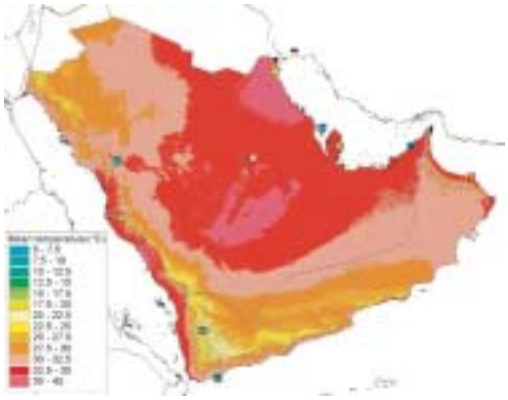

Fig. 15: Mean temperature of the warmest month

temperatures above a threshold (e.g., 0 °C) for a specified period (e.g., one year). The map of accumulated heat units in Figure 16 shows, unsurprisingly, the same pattern as the map of mean annual temperature, only the units (°C days) are different. It will be used later (see Section 4.7) to assess by proxy the potential productivity of natural vegetation.

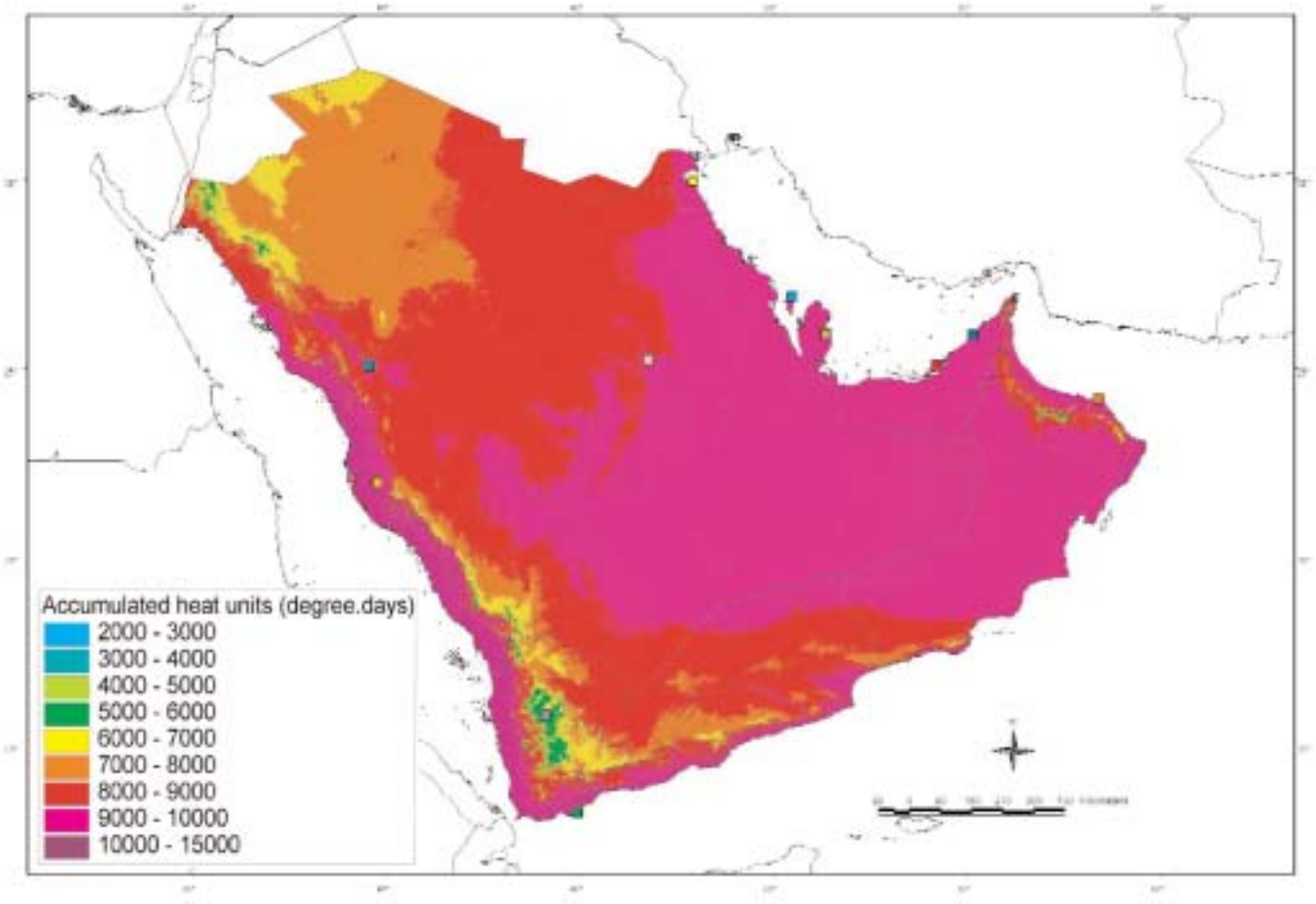

Fig. 16: Mean annual heat units

4.4. Evapotranspiration and water deficit

4.4.1. Potential evapotranspiration

The evaporative demand of the atmosphere can be represented by the potential evapotranspiration (PET), which is the evapotranspiration of a reference crop, a grass cover. The PET can be calculated by the Penman-Monteith method from elementary climatic parameters, such as temperature, air humidity, radiation, and wind speed (Allen et al., 1998). The PET concept is the basis for the assessment of crop water requirements and for scheduling irrigation.

The pattern of mean annual PET throughout the region (Figure 17) is very similar to the pattern of mean annual temperature (Figure 12) and shows the same trends, as governed by altitude and latitude. The PET is very high in the interior of the Peninsula and decreases towards the edges.

4.4.2. Aridity

The Arabian Peninsula is characterized by a severe deficit of precipitation over atmospheric water demand. The UNESCO (1979) 'aridity index' can be used to quantify this deficit and map the severity of 'dryness' based on the ratio of annual precipitation to annual potential evapotranspiration.

Figure 18 shows the distribution of the aridity index, corresponding with the thresholds for the hyper-arid (<.0.03), arid (0.03-0.25), semi-arid (0.25-0.5), and sub-humid climatic regimes (>0.5). The areas under each moisture regime are summarized in Table 3. Nearly 99% of the Peninsula is either hyper-arid (HA) or arid (A). Only part of the Yemen highlands is in the semi-arid (SA) class. A very small area is sub-humid (SH). The relationships between moisture regimes (as expressed by aridity index) and agriculture are discussed further in section 4.5.1.

Table 3. Areas under different moisture regimes

Moisture regime	Aridity index	%	km^2
Hyper-arid (HA)	< 0.03	32.02	1,020,107
Arid (A)	0.03 - 0.2	66.72	2,125,415
Semi-arid (SA)	0.2 - 0.5	1.22	38,788
Sub-humid (SH)	> 0.5	0.04	1,199

These results reflect the huge negative balance between water supply from precipitation and the evaporative demand of the atmosphere. The size of the hydrological deficit on an annual basis is shown in figure 19.

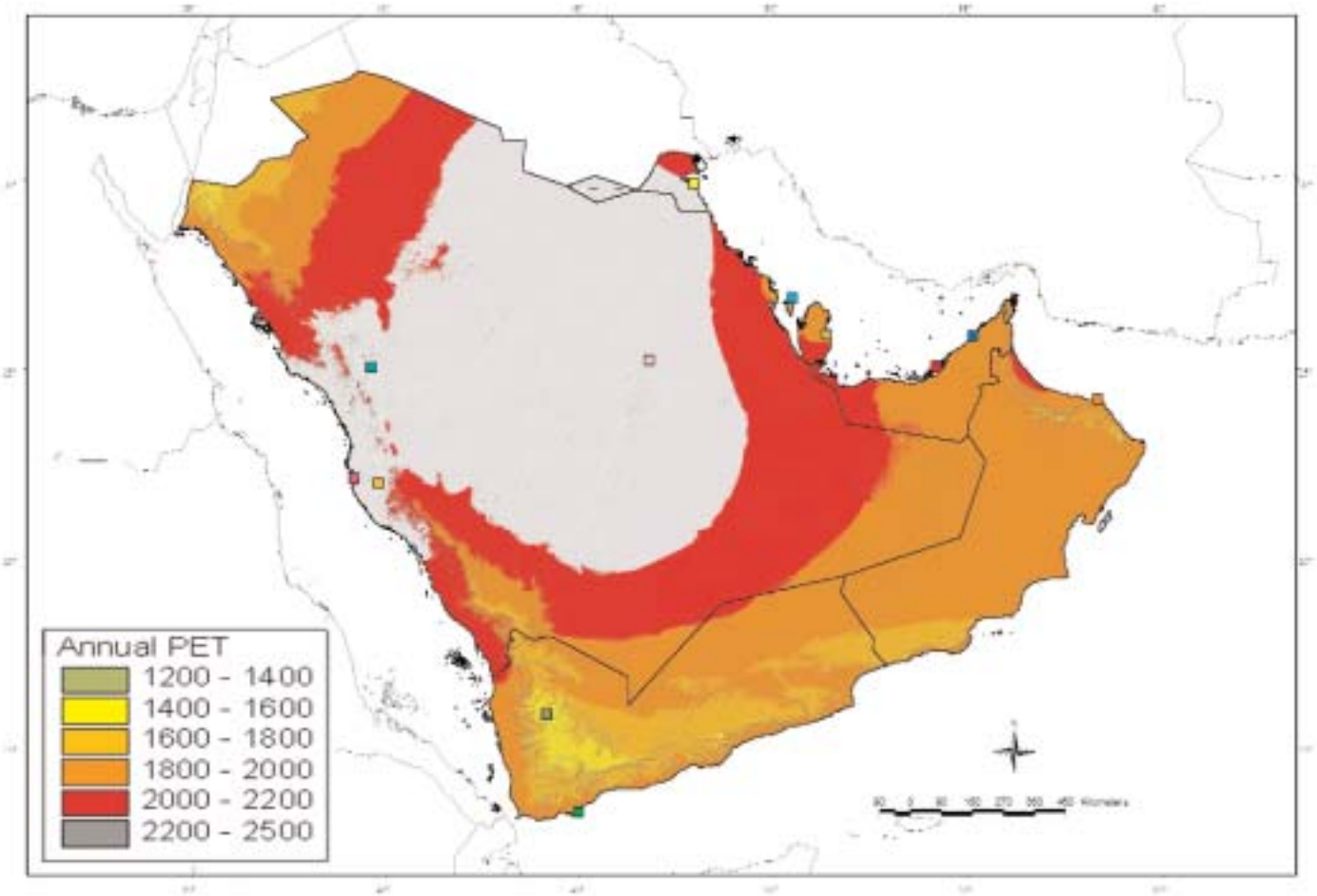

Fig. 17: Mean annual potential evapotranspiration (mm)

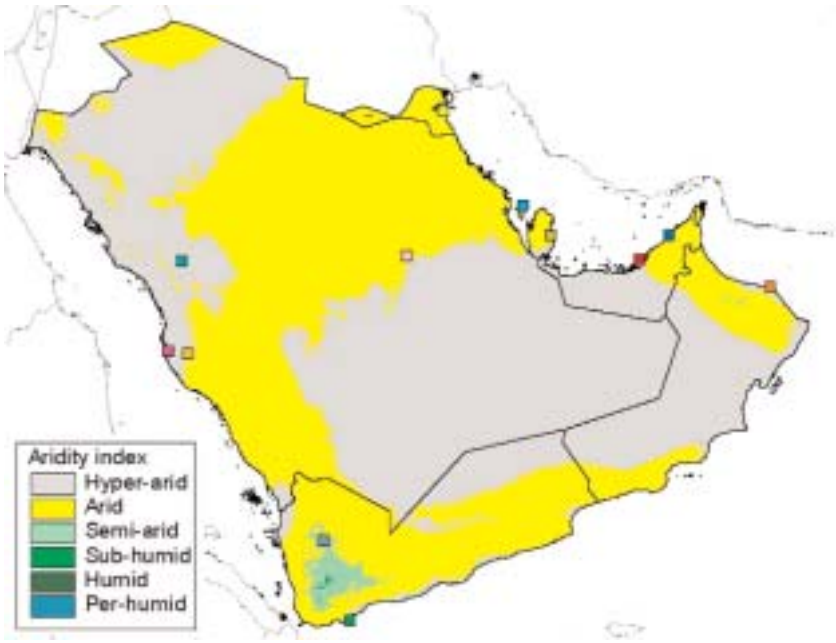

Fig. 18: Aridity index

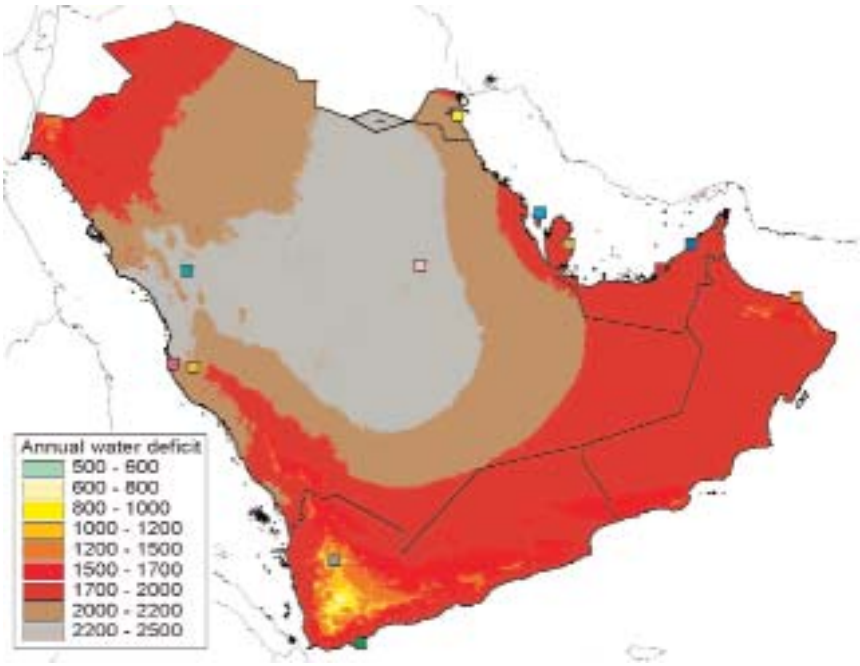

Fig. 19: Annual precipitation deficit (mm)

4.5. Agroclimatic patterns

4.5.1. Agroclimatic zones

Climatic diversity in the Arabian Peninsula can be adequately represented by a simple system of agroclimatic zones that takes into account the key determinants of climate: moisture and temperature. UNESCO (1979) has developed a simple system for differentiating agroclimatic zones based on three major criteria:

- Moisture regime
- Winter type
- Summer type

The *moisture regime* is determined by the aridity index, as defined in section 4.4.2. In the *hyper-arid* moisture regime there is almost no perennial vegetation, with the exception of some bushes in riverbeds. In good years, annual plants can grow, but agriculture and grazing are generally impossible (UNESCO, 1979). In the *arid* moisture regime, scattered vegetation does grow, which might include bushes, and small woody, succulent, thorny, or leafless shrubs. Very light pastoral use is possible. Rainfed agriculture is only feasible with some form of water harvesting and irrigation, and only where terrain conditions are favorable or where there are local water resources. As a result, agriculture, if any, is patchy. In the *semi-arid* moisture regime, vegetation is denser and might include bushes, scrubs and even trees. Good grazing areas might be found and rainfed agriculture is possible, albeit with great yield fluctuations due to rainfall variability. Agriculture in either the arid or hyper-arid classes requires irrigation (see section on land use). Even in the semi-arid mountainous uplands of Yemen, agriculture is stabilized by terrace-based supplemental irrigation.

The *winter type* is determined by the average mean temperature during the winter months. Table 4 shows the winter type classes and the areas they occupy. Figure 20 shows the spatial distribution of the winter types.

Table 4. Areas under different winter types

Winter type	Temperature class (°C)	%	km²
Cool (C)	<10	2.81	89,622
Mild (M)	10-20	74.71	2,379,883
Warm (W)	20-30	22.48	716,005

Fig. 20: Winter types (blue: cool; green: mild; yellow: warm)

In areas with *cool* winters, vegetation growth is limited by cold. If rainfall is concentrated in winter, plants adapted to these conditions will be characterized by rapid phenological development in spring and efficient soil moisture extraction. In areas with *mild* and *warm* winters, vegetative growth is possible in winter, and becomes more rapid with increasing temperature.

The *summer type* is determined by the average mean temperature during summer months. Table 5 shows the summer type classes and the areas they occupy. Figure 21 shows the spatial distribution of the summer types. The *mild* summers are confined to the highest parts of the Yemen highlands.

Table 5. Areas under different summer types

Summer type	Temperature class (°C)	%	km^2
Mild (M)	10-20	0.48	15,417
Warm (W)	20-30	36.12	1,150,600
Very warm (VW)	>30	63.40	2,019,492

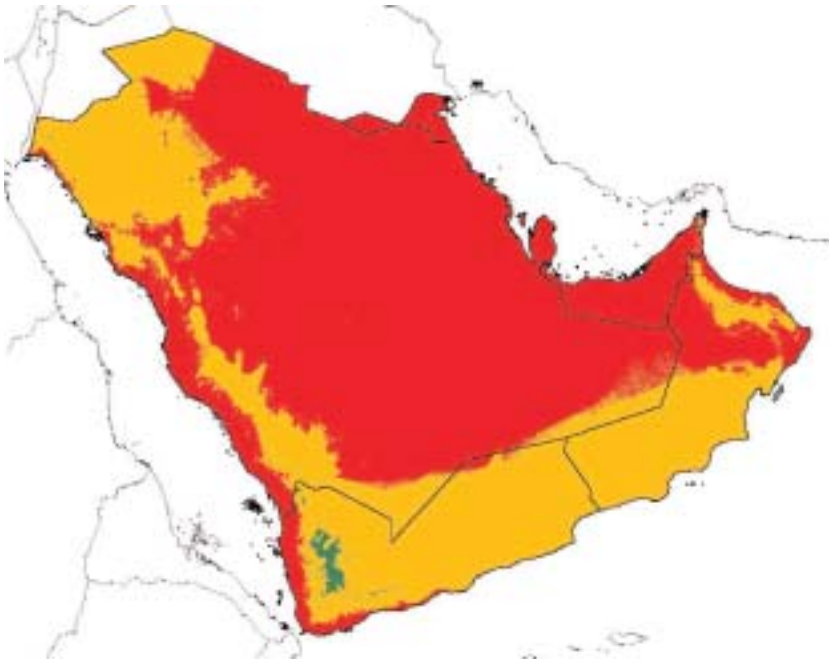

Fig. 21: Summer types (green: mild; yellow: warm; red: very warm)

The combinations between moisture regimes and winter and summer types form individual climatic patterns, or *agroclimatic zones*. For example, the pattern HA-M-VW represents a climate with a hyper-arid moisture regime, mild winter type, and very warm summer type. In total, 22 agroclimatic zones have been differentiated in the Arabian Peninsula. Of these, eight taken together comprise 95% of the region. The remaining 14 are fairly small agroclimatic 'islands' with climatic conditions that are either more humid or colder than surrounding areas.

The extent of the agroclimatic zones is shown, in order of importance, in Table 6. The spatial distribution is shown in Figure 22.

Figures 23a-23h are climate diagrams of stations representing some agroclimatic zones. Some zones cannot be represented due to their limited extent and the lack of meteorological data (see further).

4.5.2. Similarity of climatic conditions

In all the maps in this chapter, the value of selected climatic parameters is shown as classes with well-defined ranges, e.g., precipitation classes 0-10 mm, 10-20 mm, etc. These classes show similarity in a way that is independent of

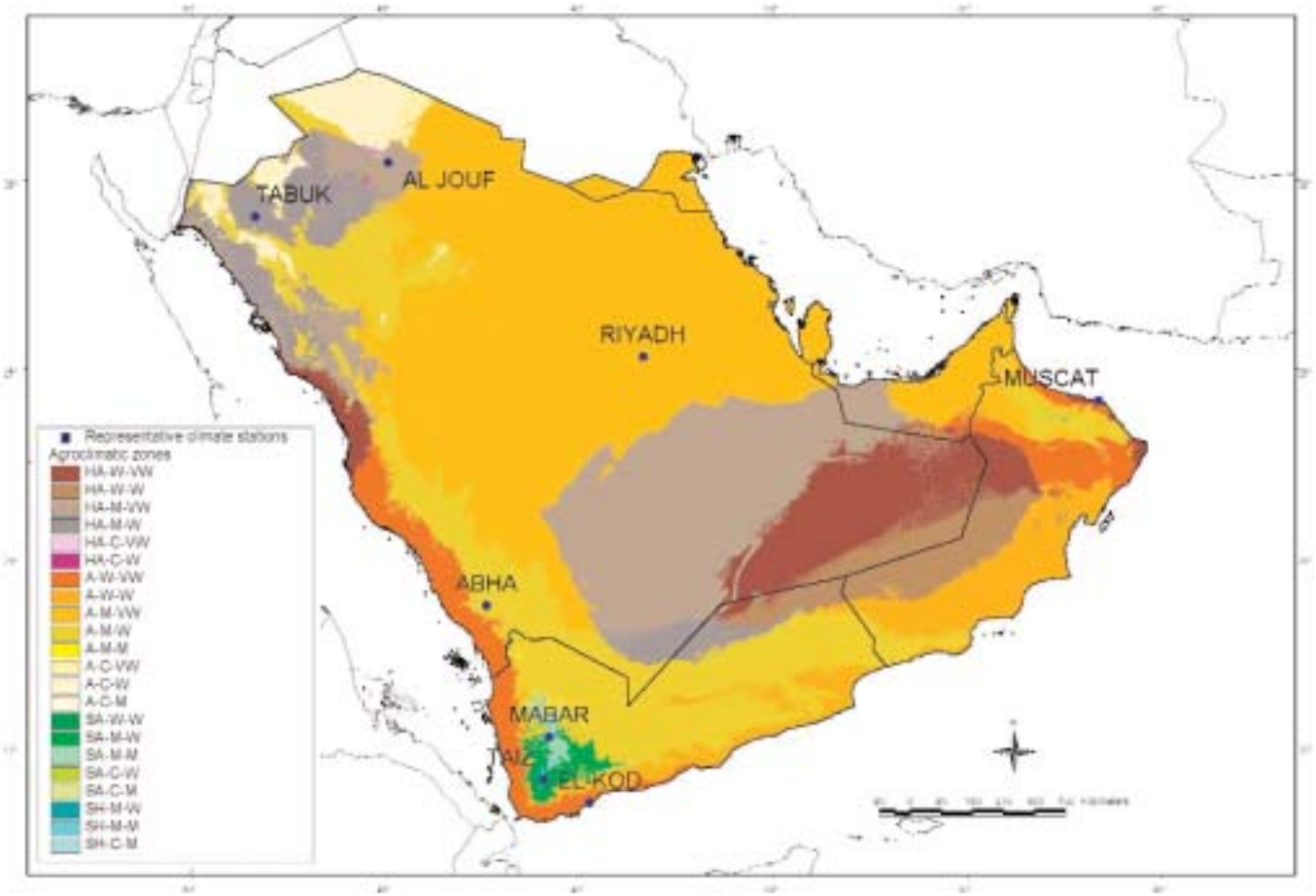

Fig. 22: Agroclimatic zones (classified according to UNESCO, 1979)

Table 6. Extent of agroclimatic zones of the Arabian Peninsula

ACZ	Representative station	%	Km^2	ACZ[1]	%	km^2
A-M-VW	Riyadh	35.3	1,123,841	SA-M-M	0.4	11,522
A-M-W	Abha	17.7	563,774	SA-W-W	0.1	3,481
HA-M-VW	Al Jouf	15.5	495,144	A-M-M	0.1	1,925
HA-W-VW	Muscat	7.2	229,484	SA-C-M	0.0	866
A-W-W		6.0	190,051	SH-M-M	0.0	828
HA-M-W	Tabuk	5.0	160,135	HA-C-VW	0.0	663
A-W-VW	El Kod	5.0	158,775	HA-C-W	0.0	469
HA-W-W		4.2	134,213	SA-C-W	0.0	426
A-C-W		2.4	75,341	SH-M-W	0.0	222
SA-M-W	Taiz	0.7	22,492	SH-C-M	0.0	148
A-C-VW		0.4	11,580	A-C-M	0.0	127

[1] All data from mabar station.

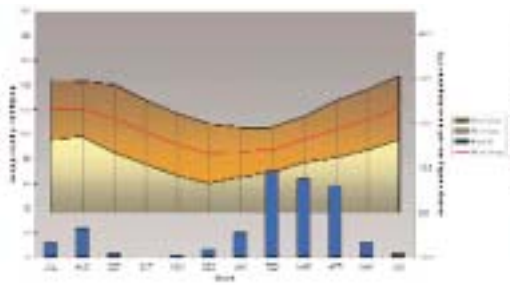

Fig. 23a: Station representative for agroclimatic zone A-M-W: Abha, Saudi Arabia

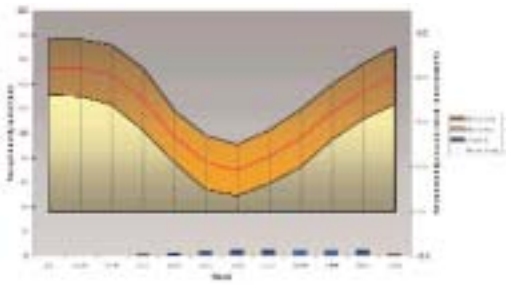

Fig. 23b: Station representative for agroclimatic zone HA-M-VW: Al Jouf, Saudi Arabia

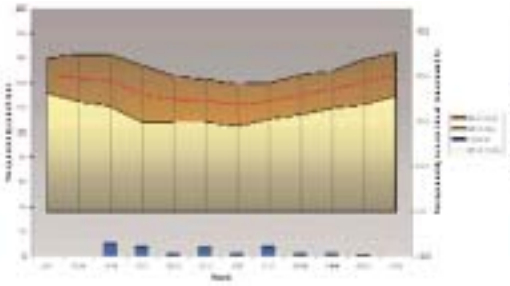

Fig. 23c: Station representative for agroclimatic zone A-W-VW: El Kod, Yemen

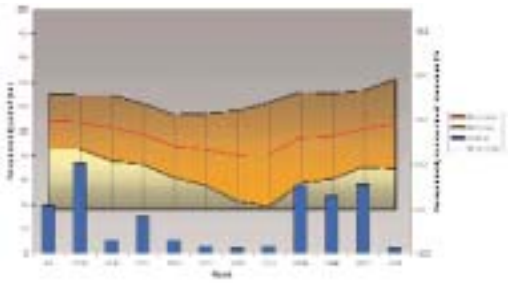

Fig. 23d: Station representative for agroclimatic zone SA-M-M: Mabar, Yemen

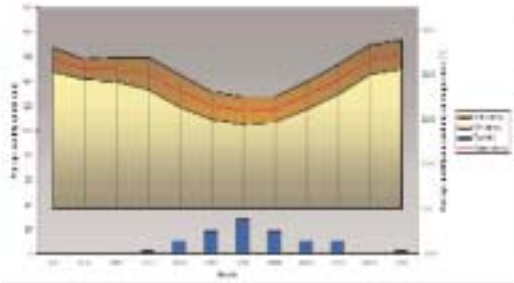

Fig. 23e: Station representative for agroclimatic zone HA-W-VW: Muscat, Oman

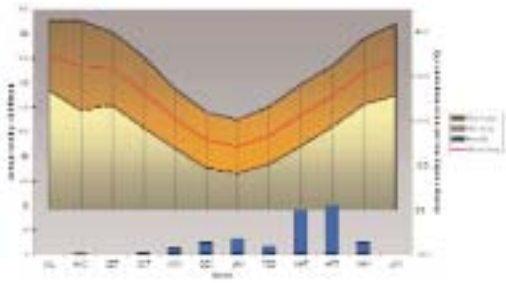

Fig. 23f: Station representative for agroclimatic zone A-M-VW: Riyadh, Saudi Arabia

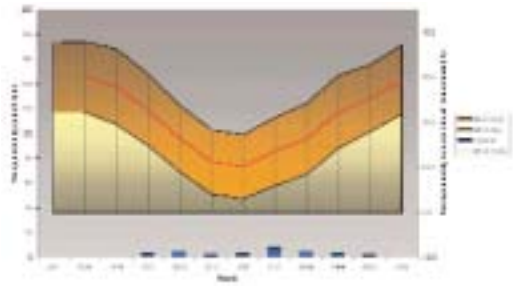

Fig. 23g: Station representative for agroclimatic zone HA-M-W: Tabuk, Saudi Arabia

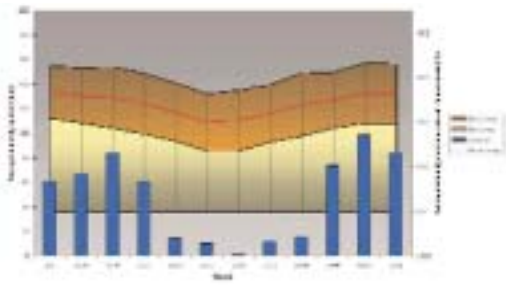

Fig. 23h: Station representative for agroclimatic zone SA-M-W: Taiz, Yemen

the values in individual locations. There is, however, a very different approach that consists of taking the value of a climatic parameter or index at one location (the ‘match‘ location) and mapping similar locations (‘target’ locations). This approach is valuable for assessing the likelihood of successful introduction of a plant species in a different area, in the assumption that the more similar the environments the more likely will be the adaptation.

The key is to be clear in the purpose and define similarity indices accordingly. If the purpose is to assess adaptation to heat stress, a temperature-based similarity index is needed. If the objective is to assess adaptation to drought, a precipitation-based index is needed. In this publication the purpose is to assess similarity both in moisture and temperature conditions, and for this reason a combined similarity index has been developed (see Section 8.3.).

Figures 24a-24h show similarity between each part of the Arabian Peninsula and a reference location. In this case the reference locations are the stations that represent the main agroclimatic zones. In all cases, similarity is shown on the same scale between zero and one, with zero indicating total

dissimilarity and one total similarity. These examples demonstrate that in some cases the adaptability domain, as expressed by a high similarity index value, is very widespread, and in other cases very limited.

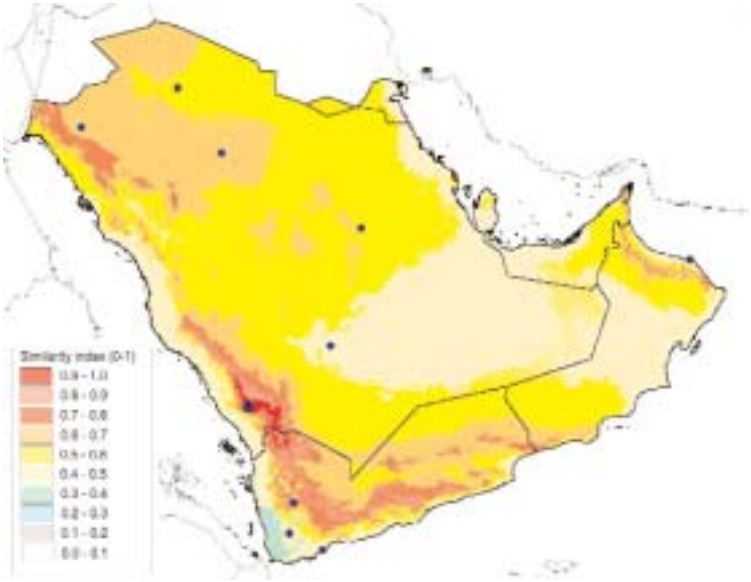

Fig. 24a: Similarity in temperature and precipitation patterns with Abha, Saudi Arabia

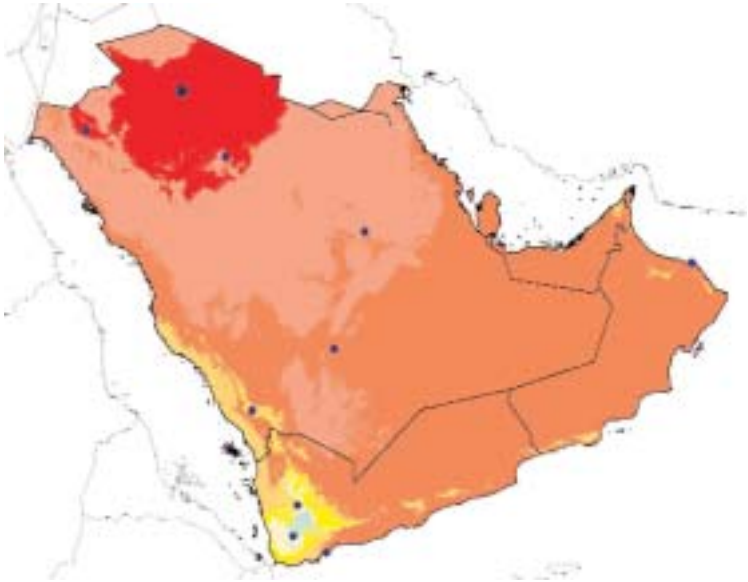

Fig. 24b: Similarity in temperature and precipitation patterns with Al Jouf, Saudi Arabia

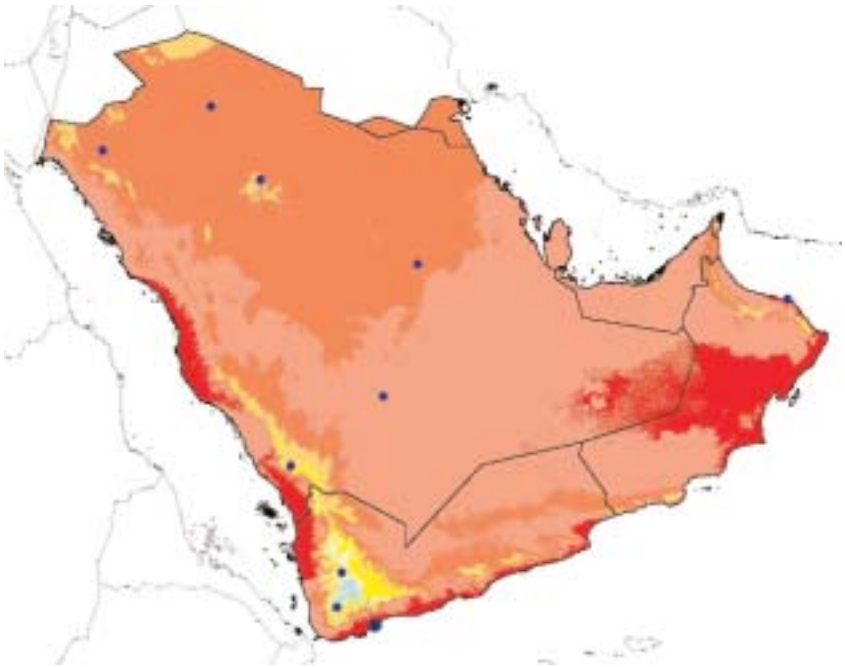

Fig. 24c: Similarity in temperature and precipitation patterns with El Kod, Yemen

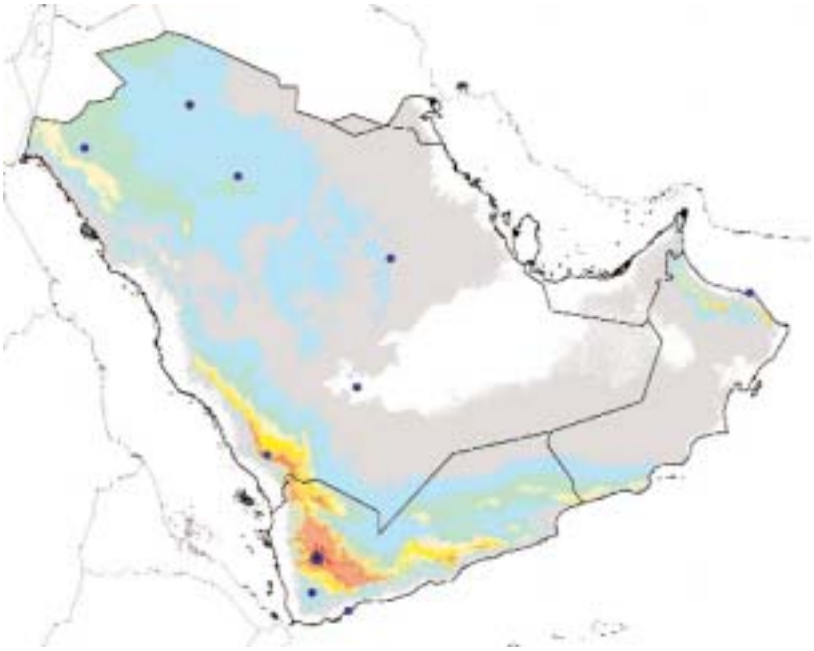

Fig. 24d: Similarity in temperature and precipitation patterns with Mabar, Yemen

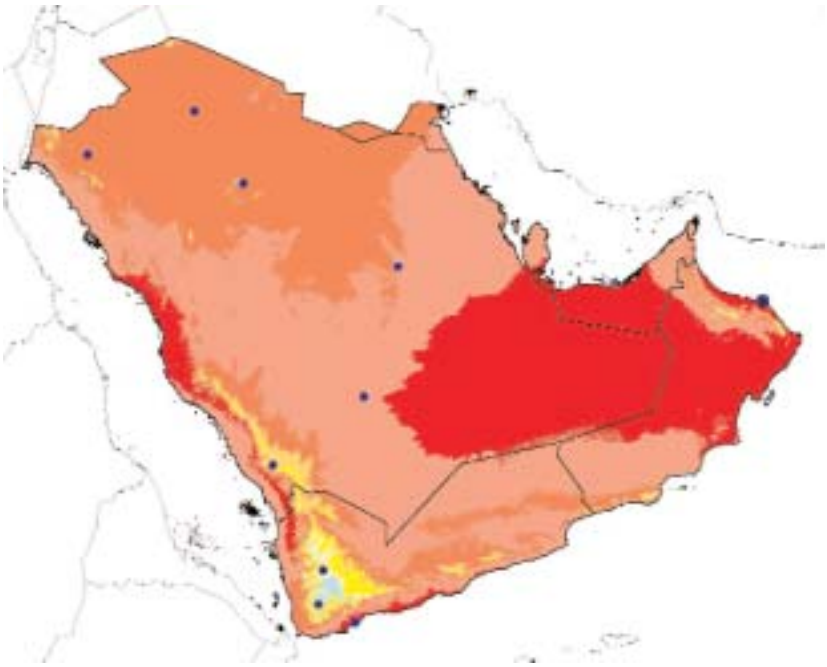

Fig. 24e: Similarity in temperature and precipitation patterns with Muscat, Oman

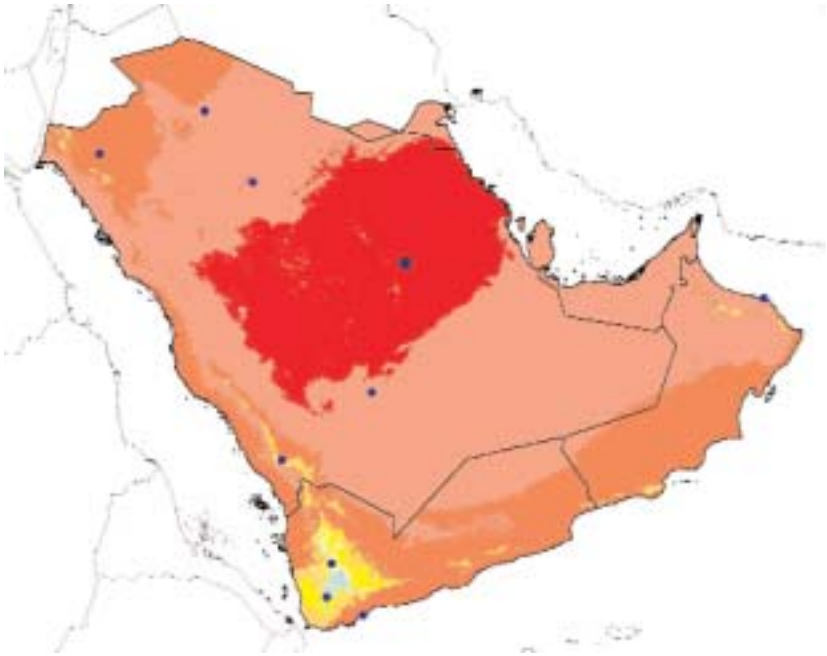

Fig. 24f: Similarity in temperature and precipitation patterns with Riyadh, Saudi Arabia

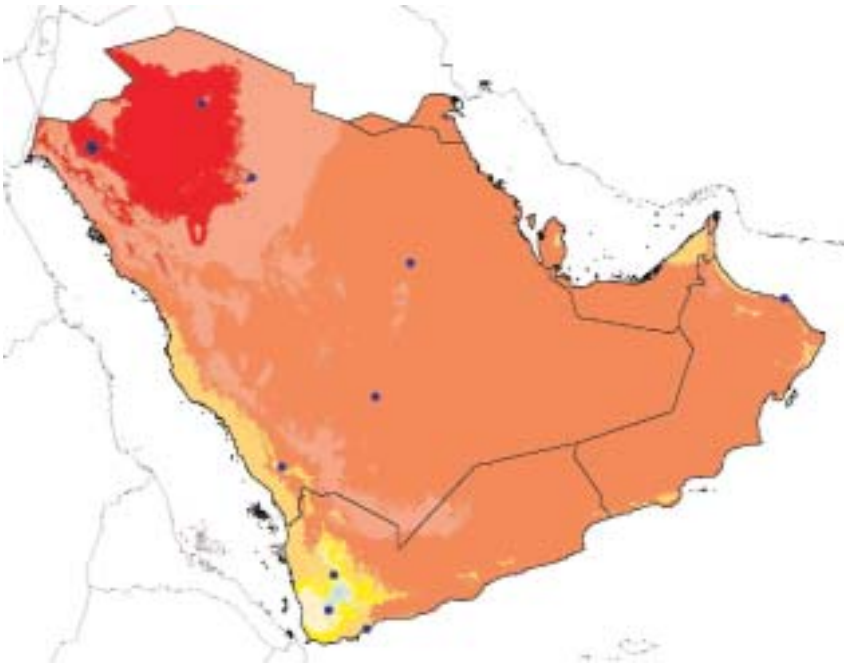

Fig. 24g: Similarity in temperature and precipitation patterns with Tabuk, Saudi Arabia

Fig. 24h: Similarity in temperature and precipitation patterns with Taiz, Yemen

4.6. Climatic growing period

Growing period, as a climatic concept, is the time of year when neither moisture nor temperature limit crop production. Developed about 30 years ago (e.g. Cochemé and Franquin, 1967), it was subsequently adapted and applied by the Food and Agriculture Organization of the United Nations (FAO, 1978-81) to assess potential plant productivity and land suitability at the global, continental, and regional scale.

The components of the climatic growing period (onset, duration, and end) are determined by a waterbalance approach, which matches monthly rainfall to monthly potential evapotranspiration. In technical terms the growing period is the 'period of the year during which the actual evapotranspiration exceeds a critical threshold' (De Pauw, 1983). This threshold is usually 50% of the potential evapotranspiration.

4.6.1. Types of growing period

Three types of growing period are described for the Arabian Peninsula. Their distribution is shown in figure 25.

The vast majority of the region is characterized by an ***all-year-round dry period.*** There is no growing period because the critical ratios of actual to potential evapotranspiration are not exceeded. In this moisture regime the quality of the growing period is no longer determined by the rainfall but by the level of potential evapotranspiration; the higher the latter, the higher the irrigation requirements. An example of an all-year-round dry period is shown in figure 26a.

In the Yemen highlands, northern Kuwait, and parts of the mountains of northern Oman, a second type of growing period occurs. The ***intermediate growing period*** lacks a humid sub-period: when rainfall exceeds potential evapotranspiration soil moisture is not recharged. Crop production in such areas is very risky and usually requires an additional source of water to stabilize yields. However, this type of growing period has a reasonable productivity for natural vegetation. An example, with two sub-periods, is shown in figure 26b.

In a very few areas of the Peninsula, located in the most rainy parts of the Yemen highlands, the ***normal growing period*** occurs. It is characterized by a *humid sub-period*, when soil moisture is recharged. This soil moisture can later be released to crops when rainfall drops below the potential evapotranspiration, thus buffering crops against drought stress. This type of growing period is of the

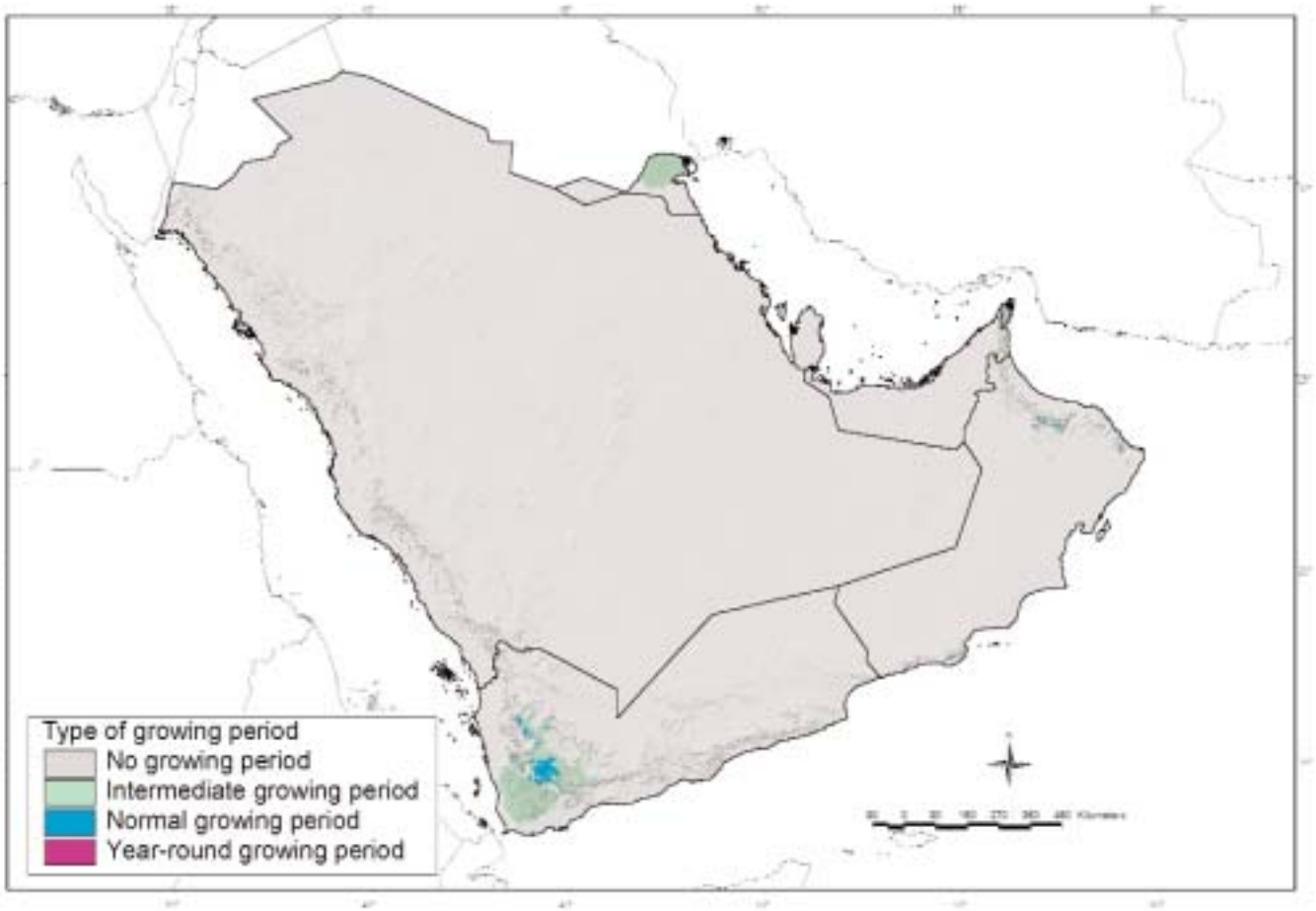

Fig. 25: Types of growing period

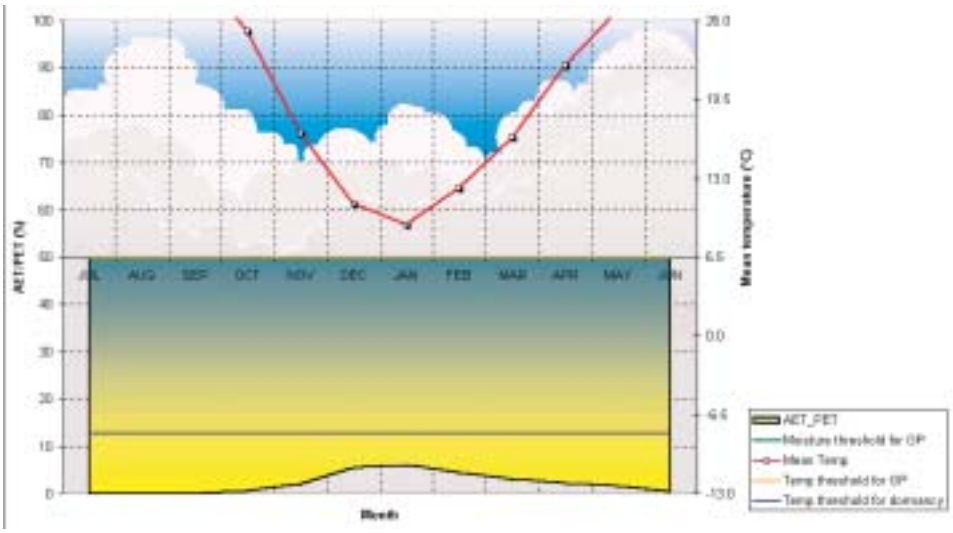

Fig. 26a: Example of a year-round dry period (Al Jouf, Saudi Arabia)

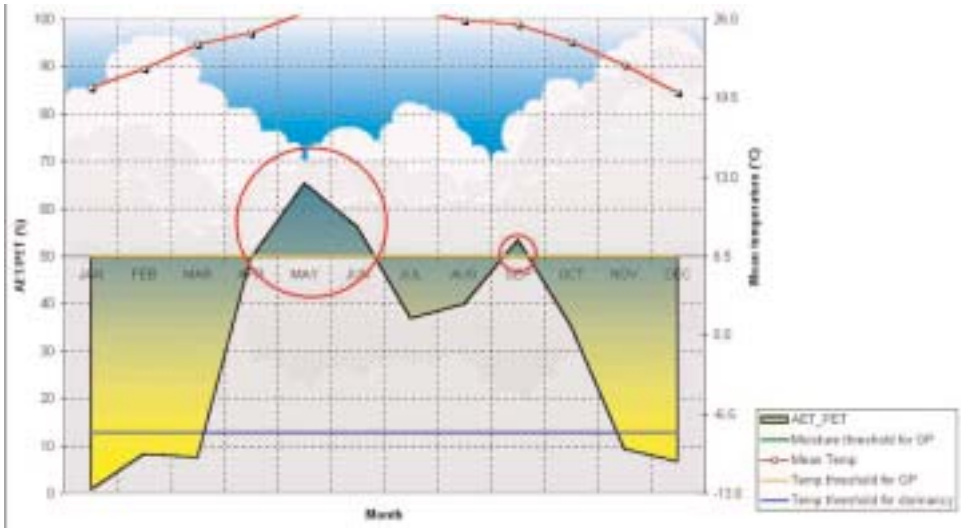

Fig. 26b: Example of an intermediate growing period (Taiz, Yemen)

highest quality, ensuring optimal biomass productivity, and, if of sufficient length, good crop yields. No representative station is available for the Arabian Peninsula; therefore, the concept is illustrated with an example from Aleppo, Syria (Figure 26c).

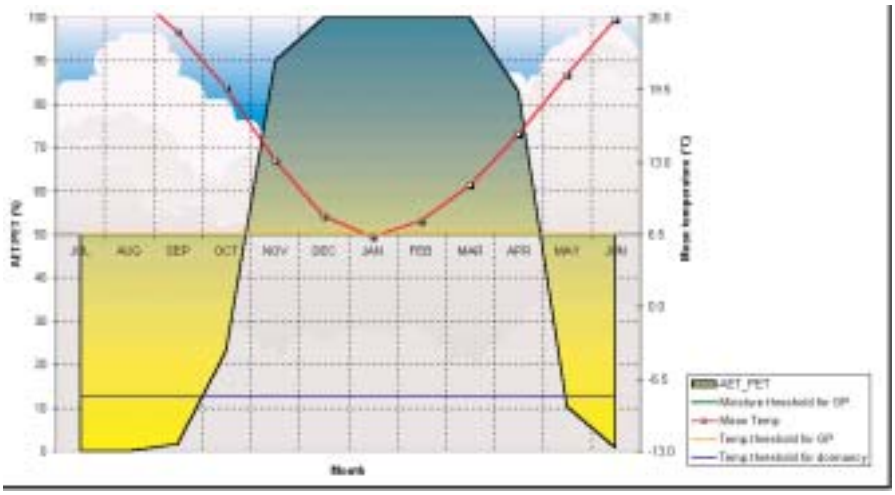

Fig. 26c: Example of a normal growing period (Aleppo, Syria)

4.6.2. Duration and onset of the growing period

In most of the Arabian Peninsula, length and timing of the growing period are highly variable as a result of pronounced rainfall variability (see section 4.2.3.). The only areas where the growing period is sufficiently reliable to appear in average data are the highlands of Yemen. This part of the Peninsula has two rainy seasons, one in March-May, the other in July-September. The durations of the resulting two growing periods are shown in figures 27a and 27b. The onset date of the main growing period is shown in Figure 27c.

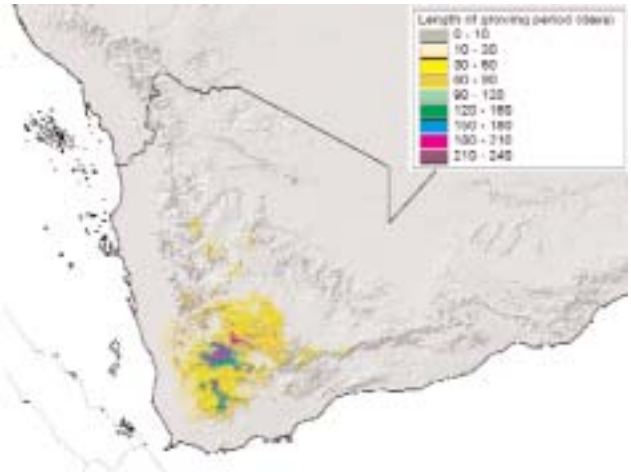

Fig. 27a: Length of the first growing period, Yemen Highlands

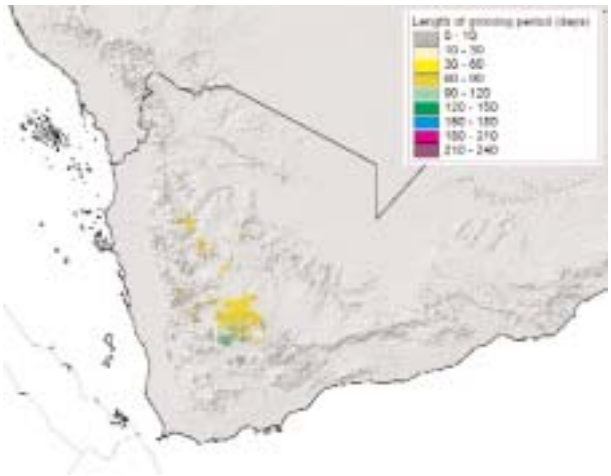

Fig. 27b: Length of the second growing period, Yemen Highlands

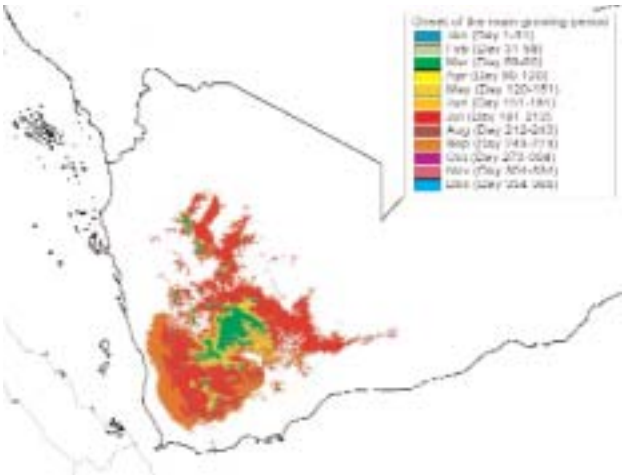

Fig. 27c: Onset of the main growing period, Yemen Highlands

4.7. Biomass productivity and climate

Climate is the primary determinant of potential biomass productivity of plants and crops. This is because assimilation – the capture by plants of carbon dioxide from the atmosphere and its conversion into carbohydrates – is determined by radiation energy and water availability. Biomass productivity should, therefore, be related to climatic factors, in particular temperature (as proxy for the radiation energy) and soil moisture. Apart from radiation and moisture regime,

the rate of assimilation and biomass production is strongly determined by crop characteristics.

According to the response of assimilation rate to temperature, FAO (1978-81) has proposed four crop groups (Table 7). Each crop group has a different response function, or adaptability range, to temperature (Figure 28).

Table 7. Adaptability ranges of different crop groups

Crop group	Crop types	Optimal mean temperature range	Examples
1	C3	15-20	Barley, bread wheat, chickpea, lentil, olive, sunflower, cabbage, oats, rye, grape, sugar beet; temperate grasses; almost all trees
2	C3 adapted for higher temperatures	25-30	Cotton, groundnut, cowpea, soybean, tobacco, sunflower, sesame, rice, fig, grape, olive
3	C4	30-35	Maize, sorghum, sugarcane, all millets, fonio rice; tropical grasses
4	C4 adapted for lower temperatures	20-30	Maize, sorghum, millets

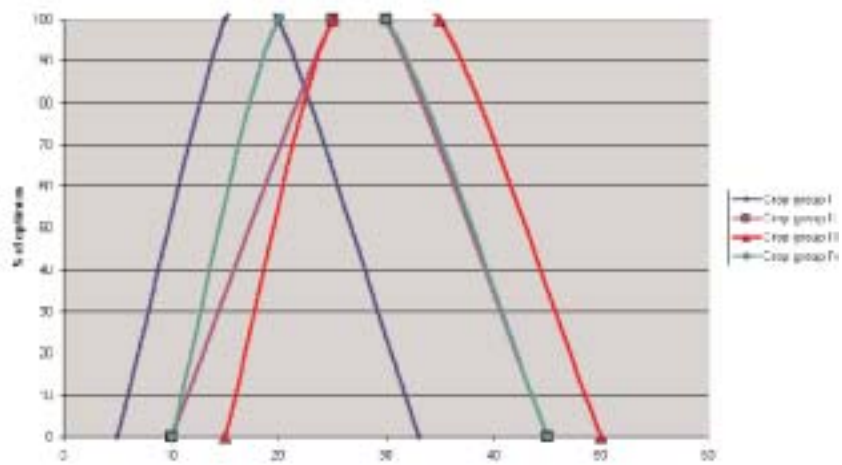

Fig. 28: Temperature adaptability ranges for different crop groups

Using this concept of crop adaptability groups, biomass productivity indices have been developed for each crop group. For the exact definition of each crop biomass productivity index (CBPI) refer to Section 8.3.

The biomass productivity index was calculated for each crop group (CBPI1, CBPI2, etc.) for each location in the Arabian Peninsula. The results show that only in part of the Yemen highlands do the indices have non-zero values. This is not surprising because the CBPI is strongly correlated with growing period, which is absent in most of the Peninsula.

Figures 29a-29d focus on the Yemen highlands and show the values of the CBPI for each crop group. Generally speaking, these figures show that the areas are better adapted to crop groups 2, 3, and 4 than to crop Group 1.

To assess the potential productivity of rangelands, a different kind of index is required that is less demanding in terms of moisture regime. The rangeland biomass productivity index (RBPI) is the product of the aridity index (see Section 4.4.2.) and the annual accumulated heat units (see Section 8.3.). Distribution of the RBPI is shown in Figure 30.

The value of these biomass productivity indices is that they can be derived from simple climatic data and allow extrapolation from site-specific productivity measurements. It has to be realized that they provide a measure of *potential* productivity, not current productivity, and, therefore, do not take into account management factors, such as overgrazing, etc.

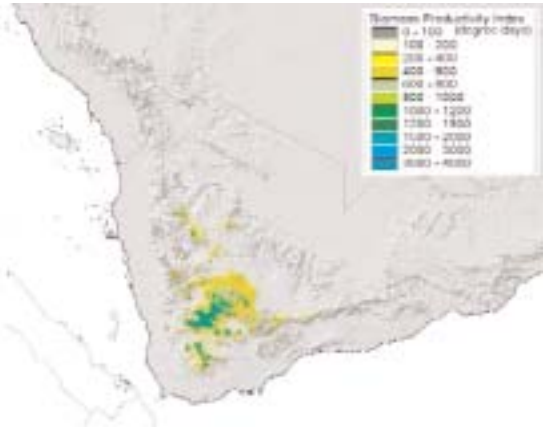

Fig. 29a: Biomass productivity index for crop group I, Yemen Highlands

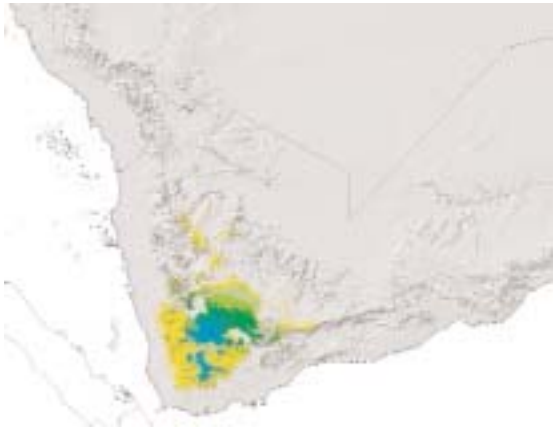

Fig. 29b: Biomass productivity index for crop group II, Yemen Highlands

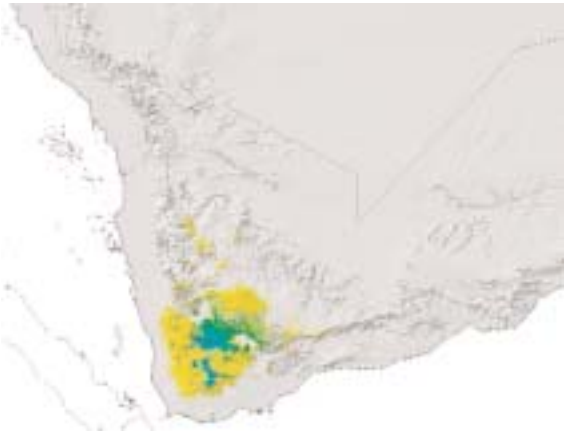

Fig. 29c: Biomass productivity index for crop group III, Yemen Highlands

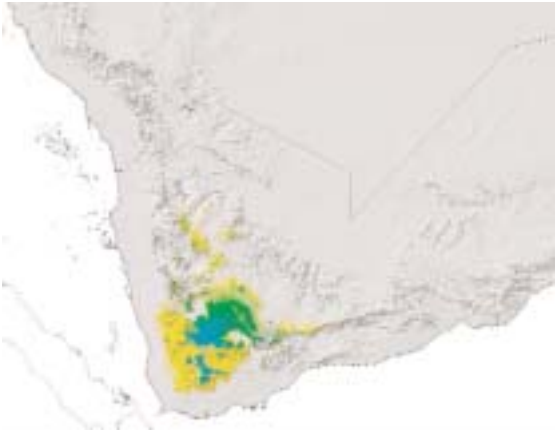

Fig. 29d: Biomass productivity index for crop group IV, Yemen Highlands

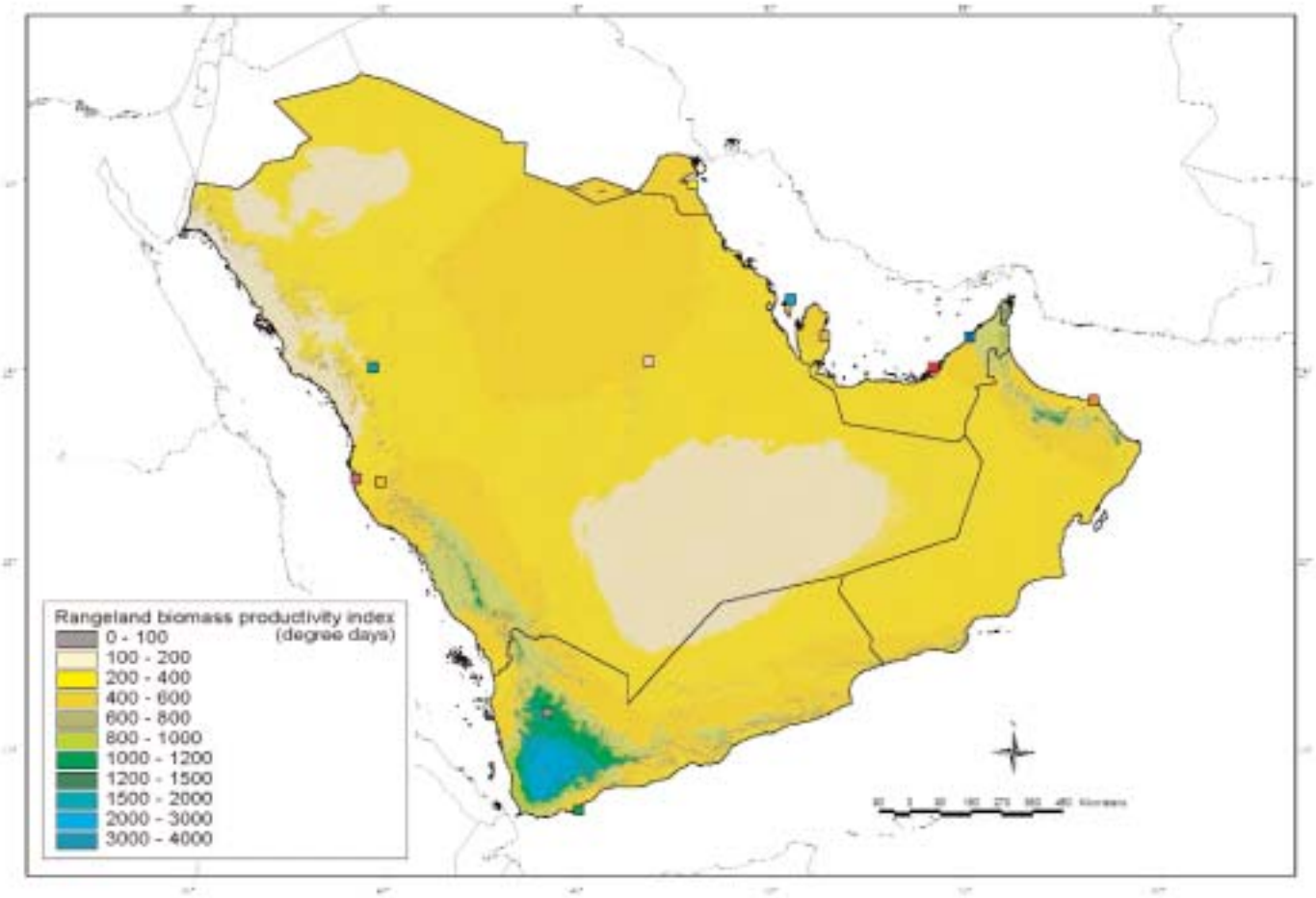

Fig. 30: Rangeland biomass productivity index

5. Soils of the Arabian Peninsula

5.1. General soil pattern

The soils of the Arabian Peninsula reflect the aridity of the climate. Most are poorly developed, shallow, or are enriched in lime, gypsum, or salts. In addition, transported materials, such as sand dunes and sheets, cover large areas. The soils are mostly formed by the physical breakdown of geological materials and their subsequent removal, sorting and deposition by wind and water.

The distribution of the soils of the Arabian Peninsula is represented in the Map of Soil Associations (Figure 31). Soil association maps show *patterns* of soil occurrence, instead of the location of individual soils. Individual soils cannot be located at the scale of a subcontinent. Soil associations are characterized by the recurrence of a limited number of specific soil types within particular landforms, but in different proportions. The main associations of the Arabian Peninsula are listed in Table 8.

As shown in the example of Figure 32, the name of the soil association is determined by the dominant soil type, the textural class, and the broad landform type.

The association is further described by its full soil composition, which lists each soil type and its proportion (in percent) within the soil association (Table 8).

The main soil types that occur in the Arabian Peninsula, classified according to the FAO Soil Map of the World (FAO, 1974), are listed in Table 9. Three textural classes are distinguished:

1: Coarse (predominantly sandy)
2: Medium (predominantly silty)
3: Fine (predominantly clayey)

These distinctions are further defined in the discussion on soil management properties (Section 5.2.).

In addition, the soil associations do consider three broad landform classes: a: flat topography; b: undulating topography; c: hilly topography

Looking only at the dominant soils within the different soil associations, the soil association map can be simplified, as shown in the map of dominant soils (Figure 33).

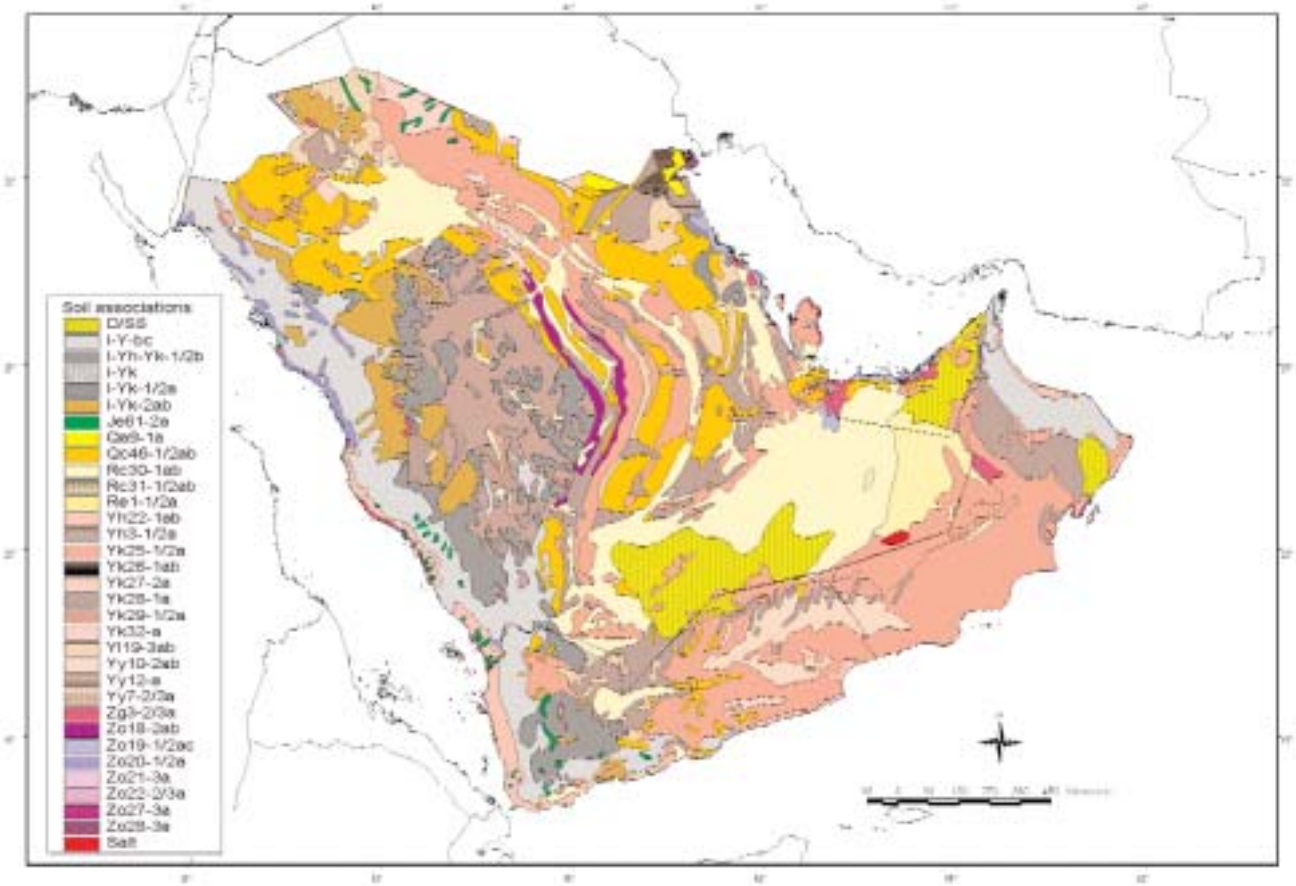

Fig. 31: Soil associations (FAO, 1995)

Table 8. Main soil associations of the Arabian Peninsula (FAO, 1995)

Soil Association	% of the Peninsula	Soil Types and Proportions					
		%1	%2	%3	%4	%5	%6
D/SS	5.80 DS	100	0	0	0	0	0
I-Y-bc	20.28 I	50 Y	50	0	0	0	0
I-Yh-Yk-1/2b	4.00 I	34 Yh	33 Yk	33	0	0	0
I-Yk	0.04 I	50 Yk	50	0	0	0	0
I-Yk-1/2a	0.26 I	50 Yk	50	0	0	0	0
I-Yk-2ab	2.41 I	50 Yk	50	0	0	0	0
Je61-2a	0.32 Je	90 Zo	10	0	0	0	0
Qa9-1a	0.48 Qa	100	0	0	0	0	0
Qc46-1/2ab	6.51 Qc	50 I	20 Y	20 R	10	0	0
Rc30-1ab	9.33 Rc	50 Qc	20 Yk	20 Z	10	0	0
Rc31-1/2ab	1.23 Rc	70 Z	30	0	0	0	0
Re1-1/2a	0.00 Re	100	0	0	0	0	0
SALT	0.05 ST	100	0	0	0	0	0
Yh22-1ab	4.96 Yh	30 Qc	20 Yk	20 Jc	10 Rc	10 Z	10
Yh3-1/2a	3.74 Yh	70 I	30	0	0	0	0
Yk25-1/2a	10.94 Yk	40 I	20 Yl	20 Jc	10 Z	10	0
Yk26-1ab	3.39 Yk	70 Qc	30	0	0	0	0
Yk27-2a	0.09 Yk	60 Z	30 I	10	0	0	0
Yk28-1a	6.40 Yk	60 Rc	30 I	10	0	0	0
Yk29-1/2a	0.25 Yk	60 Rc	30 Z	10	0	0	0
Yk32-a	8.12 Yk	60 I	20 Yl	20	0	0	0
Yl19-3ab	2.68 Yl	50 I	20 Yk	20 Rc	10		
Yy10-2ab	3.79 Yy	60 I	20 Yk	20	0	0	0
Yy10-2ab	0.37 Yy	60 I	20 Yk	20	0	0	0
Yy12-a	0.54 Yy	60 I	30 Yk	10	0	0	0
Yy7-2/3a	0.05 Yy	50 Yk	20 Zo	20 Jc	10	0	0
Zg3-2/3a	1.18 Zg	70 Zo	30	0	0	0	0
Zo18-2ab	0.51 Zo	60 I	30 Yk	10	0	0	0
Zo19-1/2ac	1.35 Zo	50 I	30 Qc	10 Rc	10	0	0
Zo20-1/2a	0.19 Zo	60 Yh	30 Rc	10	0	0	0
Zo21-3a	0.03 Zo		Composition unspecified				
Zo22-2/3a	0.21 Zo						
Zo27-3a	0.37 Zo						
Zo28-3a	0.11 Zo	50 Zt	30 Jc	10 Zg	10	0	0

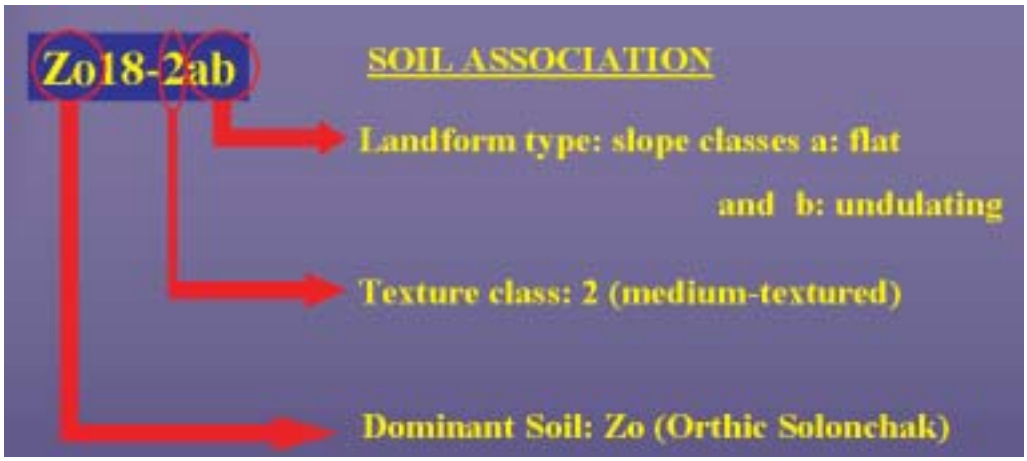

Fig. 32: Soil associations: explanation of legend

Table 9. Main soil types of the Arabian Peninsula

Symbol	Name	Summary description
I	Lithosols	Undifferentiated very shallow soils; unsuitable for agriculture
Je	Eutric Fluvisols	Alluvial soils with good fertility status; the best soils for agriculture
Qa	Albic Arenosols	Strongly leached sandy soils, do not retain soil moisture; unsuitable for agriculture
Qc	Cambic Arenosols	Slightly matured sandy soils, retain soil moisture better; suitable for agriculture under sprinkler irrigation
Rc	Calcaric Regosols	Calcareous poorly developed soils, poor physical properties for agriculture
Re	Eutric Regosols	Poorly developed soils with moderate fertility; poor physical properties for agriculture
Yh	Haplic Yermosols	Undifferentiated very poorly developed soils of (semi-) deserts; management properties vary considerably; full irrigation is needed for all agricultural uses
Yk	Calcic Yermosols	Very poorly developed soils of (semi-) deserts with calcium-enriched subsoil; unsuitable for agriculture
Yl	Luvic Yermosols	Very poorly developed soils of (semi-) deserts with clay-enriched subsoil; can be made suitable for agriculture if full irrigation is available
Yy	Gypsic Yermosols	Very poorly developed soils of (semi-) deserts with gypsum-enriched subsoil; unsuitable for agriculture due to poor physical properties and need for full irrigation
Zg	Gleyic Solonchaks	Saline soils with insufficient drainage; unsuitable for agriculture
Zo	Orthic Solonchaks	Undifferentiated saline soils; unsuitable for agriculture

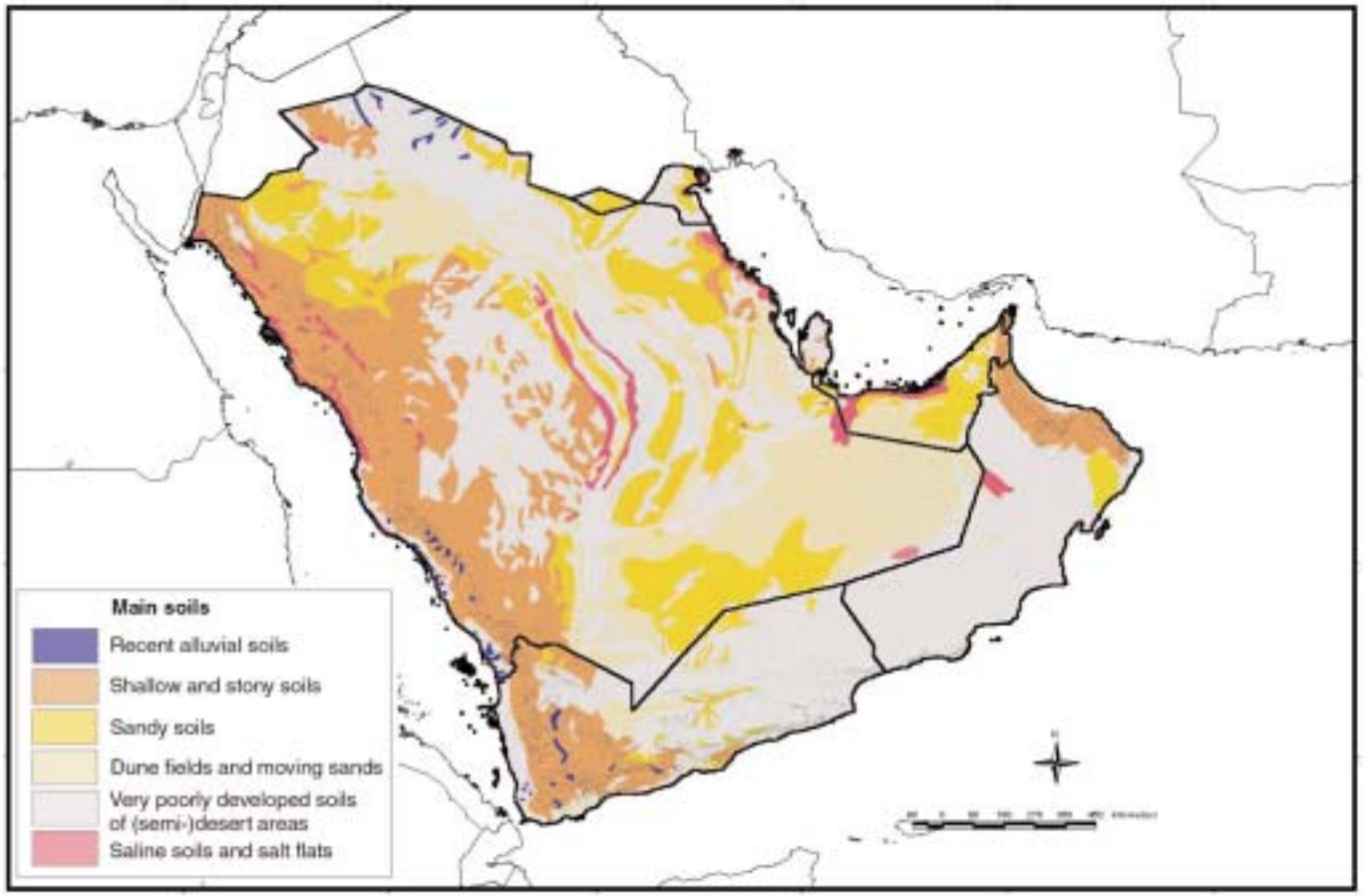

Fig. 33: Simplified soil map (dominant soils)

5.2. Soil management properties

Soil maps, particularly those at the regional or national level, are notoriously difficult to interpret as a guide to agricultural management. In most cases, only classification names are provided, but not the associated management properties, which are assumed to be understood. This is rarely the case, since most potential users of soil maps are not familiar with soil scientist jargon. For this reason, maps are needed that show the spatial distribution of soil management properties.

This is a particularly daunting task because soil management properties tend to vary considerably, even within classified soils. The best that can be done on a regional scale is to show the distribution of certain soil properties, which can be associated with reasonable likelihood to the soil classification. For example, Lithosols are by definition associated with shallow soil depth. Arenosols are sandy soils, Fluvisols are likely to have optimal depth, water holding capacity, and fertility status, Yermosols are associated with very low organic carbon levels, and Solonchaks cover the wide spectrum of saline soils. By looking at soil classification units as 'indicators' of soil management properties, it is feasible to map the distribution of some properties, but not others. It is possible to map soil texture, depth, stoniness, and some important fertility indicators, such as organic carbon content, pH, and cation exchange capacity (CEC). These are the more stable properties of soils, and are more shaped by climate, geology, and landform, than by human intervention. However, it is not possible to map physical properties, such as infiltration capacity, aggregate stability, or nutrient availability (N, P, K), because these properties are very site-specific and highly responsive to management.

The spatial distribution of some management properties is shown in the following set of maps. Refer to the legend in Figure 34 to link the properties to the dominant soil type and the other soil types of the soil association. The yellow color indicates, for example, that the particular soil management property is likely to occur in about 10-20% of the areas colored yellow.

5.2.1. Soil texture

Soil texture refers to the relative proportions of various particle size groups in a mass of soil (Soil Survey Staff, 1951). Specifically, it refers to the proportions of clay (<.002 mm), silt (.002-.05 mm), and sand (.05-2 mm). Soil scientists use a system of 12 standard textural classes (Figure 35). For a regional assessment

of textural distribution these classes are reduced to the three mentioned in section 5.1. The relationships between the standard and 'regional' textural classes are shown in Figure 35.

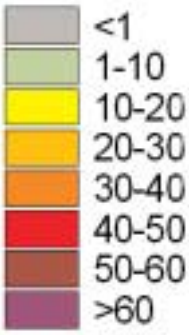

Fig. 34: Legend of soil property distribution maps – % of area

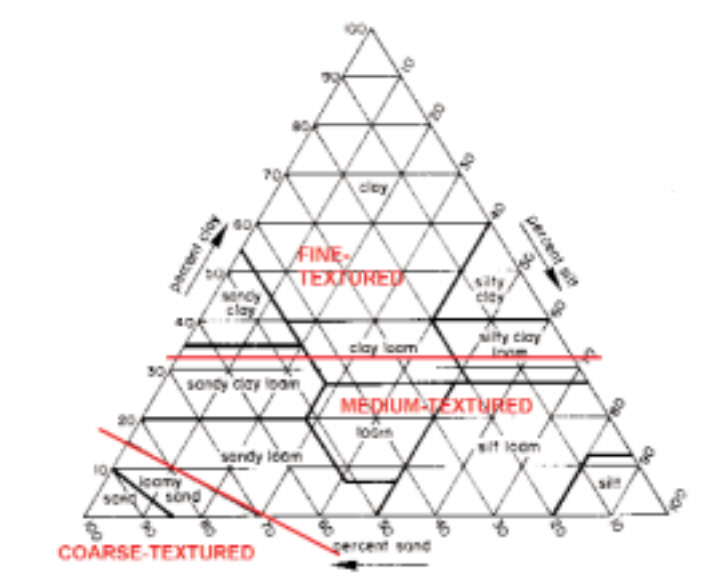

Fig 35: USDA textural triangle and simplified textural classes

Soil texture is a key management property. It determines the amount of water a soil can hold and make available to plants. In dry areas, soil texture is a key determinant of irrigation management. Clayey soils are suitable for different types of flood irrigation. They retain water very well, but are subject to high evaporation losses. Silty soils can be irrigated fairly infrequently, but

have high percolation losses. Sandy soils demand very frequent irrigation, usually by sprinkler or drip systems, or, if very coarse, cannot be irrigated. Soil texture is also a determinant of soil structure and surface properties. Silty soils tend to form a surface seal, which reduces infiltration capacity and promotes runoff even on gentle slopes. In contrast, water infiltrates sandy soils and no evaporation losses occur. As a result, higher biomass productivity of natural vegetation is in the Arabian Peninsula often associated with sandy soils.

Figures 36-38 show the distribution of the coarse-textured, medium-textured, and fine-textured soils, respectively, in the Arabian Peninsula.

These figures demonstrate that the prevailing perception of the Arabian Peninsula as a sandy desert is incorrect. Most soils are medium-textured, with silt as dominant soil component. Sandy soils are common, particularly in the drier interior basins, but clayey soils are fairly uncommon.

5.2.2. Soil depth and stoniness

Soil depth and the related attribute, stoniness, are important management properties, since they determine the feasibility of mechanization and the soil

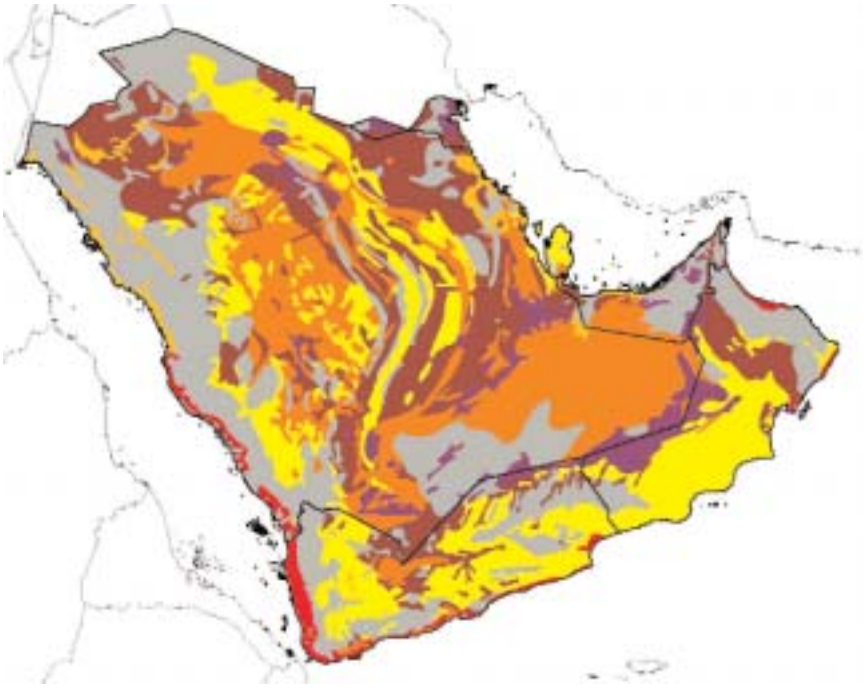

Fig. 36: Distribution of coarse-textured soils(Note: for legend see Fig. 34)

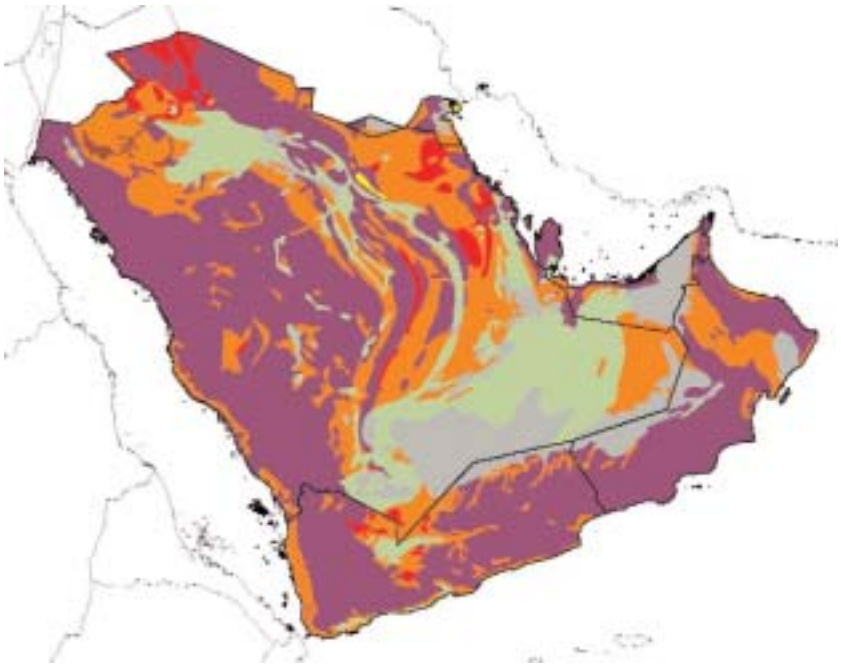

Fig 37: Distribution of medium-textured soils(Note: for legend see Fig. 34)

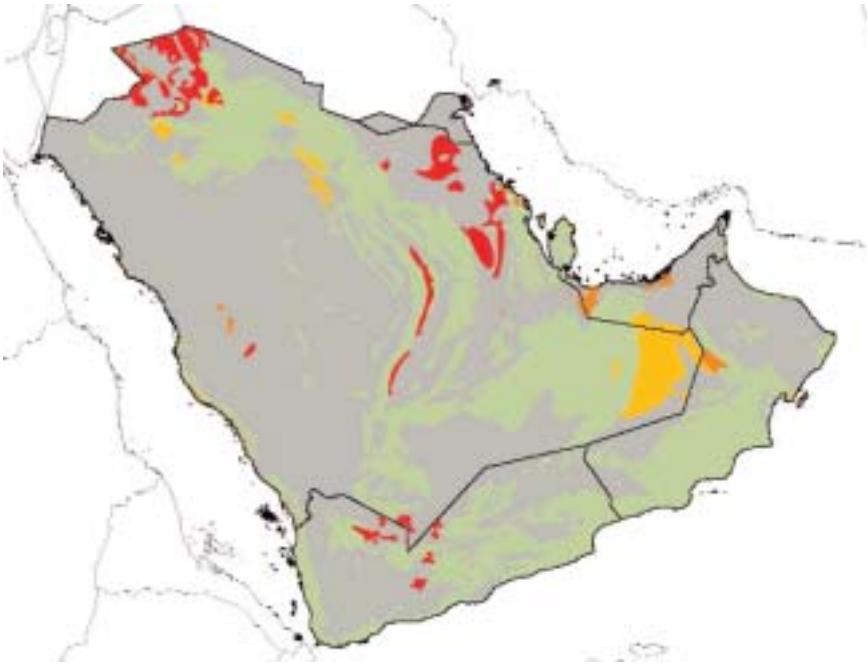

Fig 38: Distribution of fine-textured soils(Note: for legend see Fig. 34)

moisture storage capacity. Very shallow or stony soils do not have sufficient soil volume in which to store moisture, and therefore dry out more rapidly than deep soils, or soils of similar depth without stones. For the same reason, these soils have more difficulty absorbing rainfall during storms and thus generate much runoff.

The distribution of soil depth and related attributes are shown in Figures 39-41. The map of the dominant soil depth (Figure 39) is an oversimplification, but shows a clear pattern. Mountain areas are invariably associated with high levels of shallow (Figure 40) and stony soils (Figure 41). They occur mainly in the western highlands of the Midian, Hejaz, and Asir, the escarpment of the Yemen high plateau, and the Hajjarr and Mussandam mountains in Oman. In addition, there are interspersed but fairly large areas of gravel plains throughout the Peninsula. The most important ones occur in eastern Kuwait and south of the Hajjar mountains.

5.2.3. Soil fertility indicators

As mentioned earlier, the fertility status of soils is, in general, so site-specific and determined by management that any region-wide assessment is

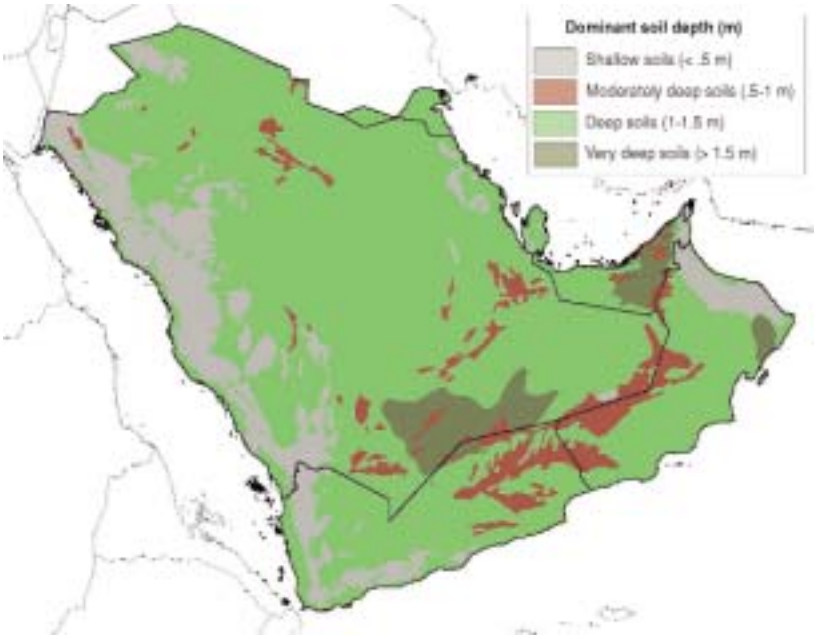

Fig 39: Dominant soil depth

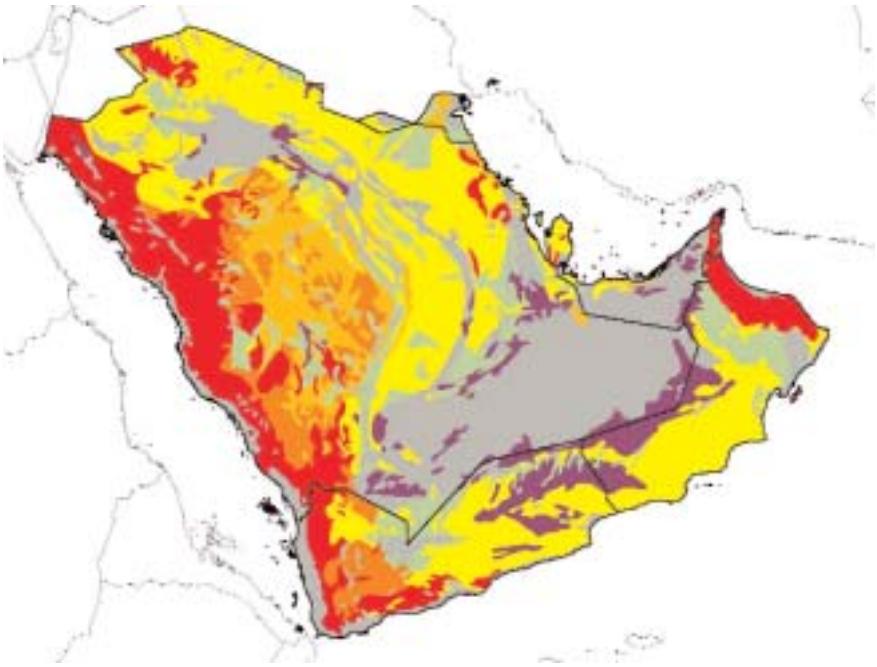

Fig 40: Distribution of shallow soils(Note: for legend see Fig. 34)

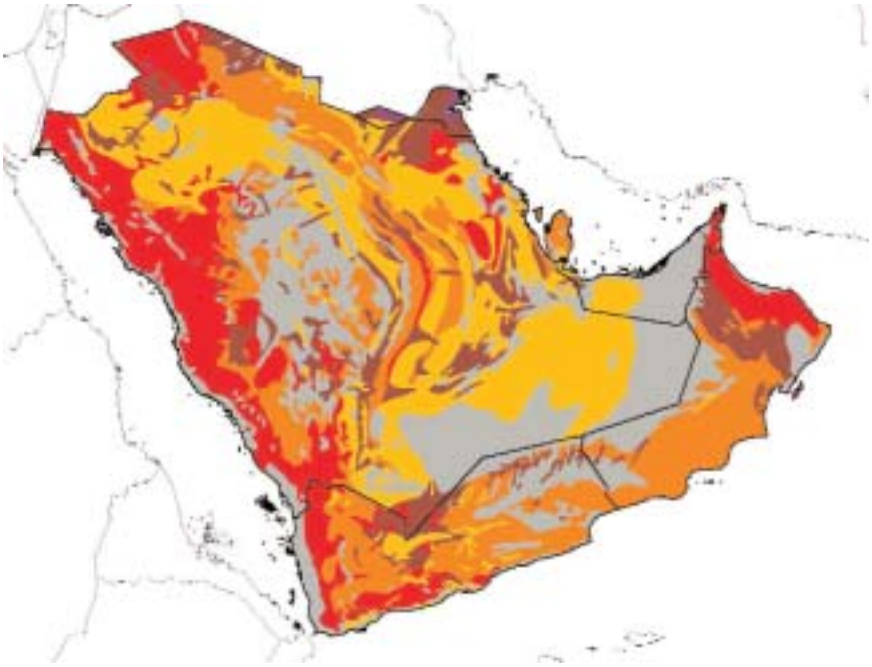

Fig 41: Distribution of gravelly and stony soils(Note: for legend see Fig. 34)

meaningless, especially in a part of the world where moisture availability is the prevailing constraint. However, certain soil characteristics, such as organic carbon content, pH, CEC, and lime content, are indicative of the fertility status and are more static and spatially invariant, being mostly determined by climate.

The organic matter content is the most important indicator of the general fertility status of a soil. Although the composition of organic matter is also important, soils with a high organic matter content are usually productive. Dry and hot climates, which do not support a dense cover of vegetation, do not promote organic matter decay and accumulation. As a result, the organic carbon levels are very low in the Arabian Peninsula (Figure 42). Most of this organic matter is concentrated in the topsoil. The subsoils are virtually devoid of organic carbon, and, as a result, the total organic carbon pools are very low (Figure 43). Given the considerable overgrazing and vegetation degradation that has occurred during the last 30 years, it is suspected that even these low levels of organic carbon quoted are optimistic estimates.

Soil pH controls availability and eventual deficiency or toxicity of certain micronutrients, which are needed by plants in very small amounts but which are essential for plant growth, such as zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), and boron (B). At high pH, Zn might be deficient in sensitive plants. B-

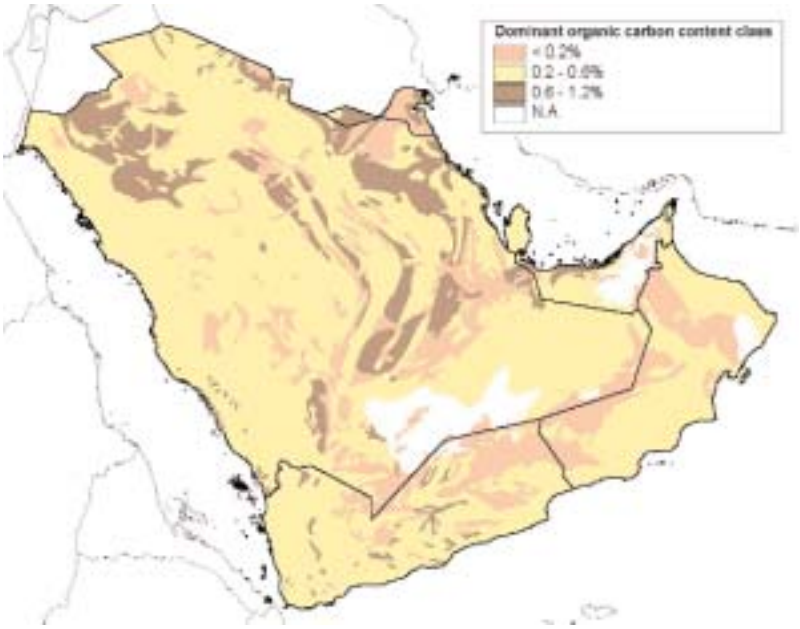

Fig. 42: Dominant organic carbon levels

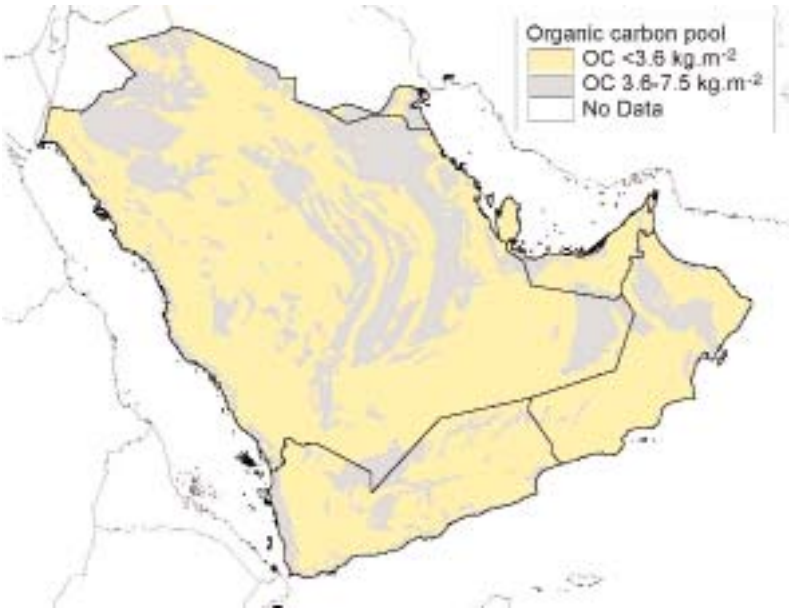

Fig. 43: Organic carbon pool

toxicity might occur in soils of volcanic origin, in other areas it might be deficient (Ryan et al., 1997). The soil pH hovers in the Arabian Peninsula around neutral or above (Figure 44). It is mainly controlled by the presence of free calcium carbonate (see further), and is not limiting to plant growth, except where it is the consequence of high soil salinity (pH >8.2).

Cation exchange capacity (measured in milliequivalents per 100 g soil) quantifies the clay fraction's capacity to retain nutrients, and is a measure of resilience against nutrient depletion. In dry climates, the CEC is generally high for most soils, with the exception of sandy soils, which do not have high enough clay content. The CEC is therefore related to soil texture, particularly the content of clay, sand, and coarse fragments. The patterns in Figure 45 reflect broad textural groupings rather than particular soil characteristics, with high CEC values associated with medium-and fine-textured soils.

The soils of the Arabian Peninsula are well supplied with free calcium carbonate ($CaCO_3$) as a result of inheritance from calcareous sediments and rocks, but also due to the lack of leaching and weathering (Ryan et al., 1997). Apart from its control on soil pH and availability of certain micronutrients, $CaCO_3$, within reasonable amounts, is not an impediment to crop productivity. The distribution of calcareous soils is shown in Figure 46.

The same qualification applies to gypsum ($CaSO_4.2H_2O$), which can be present in substantive amounts, particularly in the Gypsic Yermosol subgroup. Gypsum, like $CaCO_3$, is another soluble mineral of sedimentary origin that is very common in arid regions. Gypsiferous soils have special management

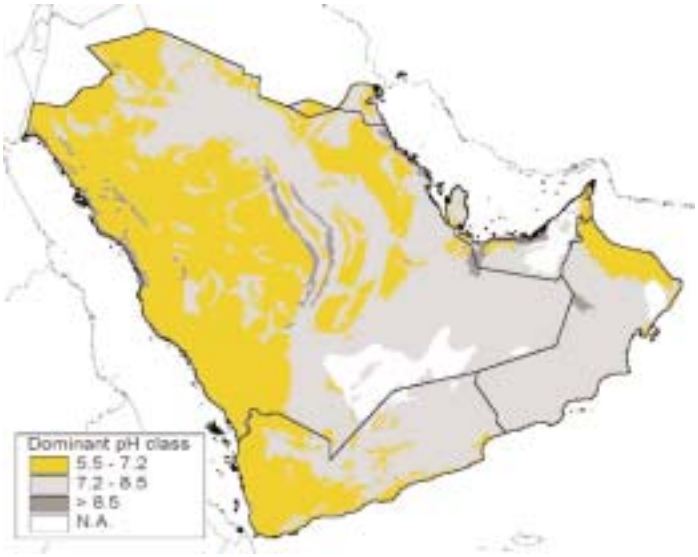

Fig. 44: Dominant soil pH

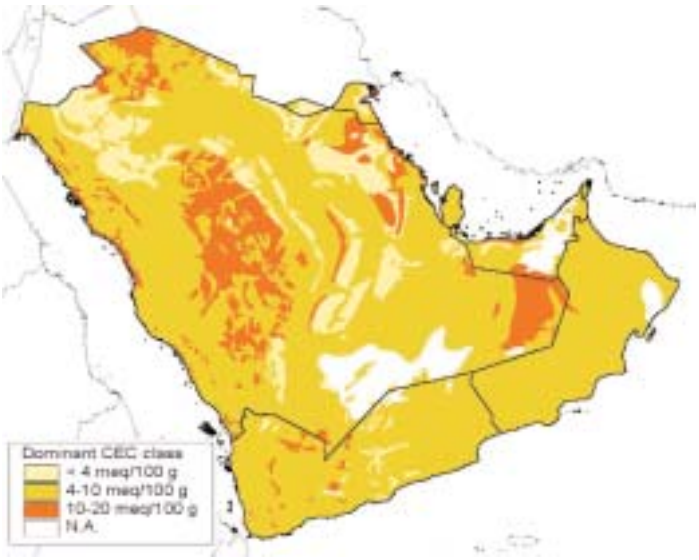

Fig. 45: Dominant cation exchange capacity

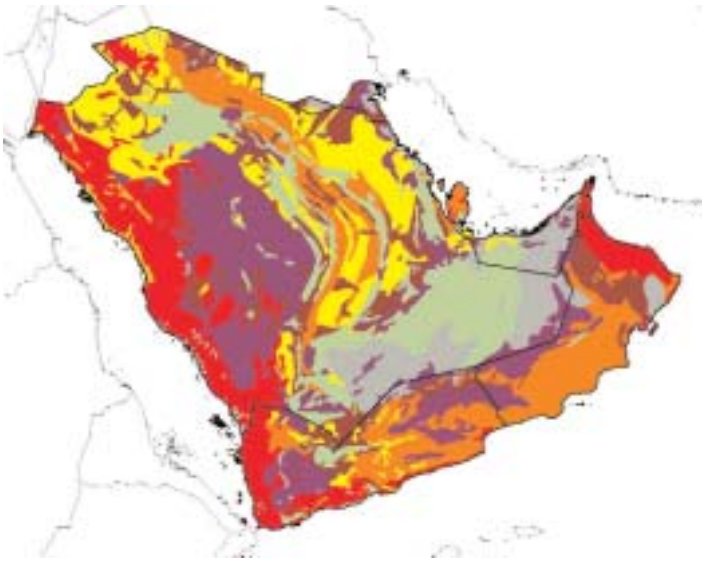

Fig. 46: Distribution of calcareous soils(Note: for legend see Fig. 34)

properties. They can be irrigated with fairly saline water without causing salinity build-up. However, inefficient irrigation with high percolation losses, can cause the gypsum to dissolve, and the soil to collapse (possibly taking with it irrigation canals).

In some soils, lime or gypsum have built up massively to form hard banks. These 'indurated' soils are called 'petrocalcic' or 'petrogypsic' (*petro*, Greek root for 'rock'), depending on whether lime or gypsum is the cementing agent, and are often confused with sedimentary rocks. They are obviously unsuitable for agriculture. Their distribution is shown in Figure 47.

In contrast with most other soil types, saline soils show a great diversity in their appearance. Unless salinity is very pronounced, chemical tests are needed to recognize a saline soil. In order to be recognized as salt-affected, soils must have a minimum concentration of salts at some time of the year within the root zone. Soils are called saline when the total salt concentration, expressed in electrical conductivity (ECe) of a saturated extract, is above 15 deciSiemens per meter (dS m^{-1}) at 25°C within 30 cm of the surface at some time of the year, or more than 4 dS.m^{-1} if the pH (H_2O 1:1) exceeds 8.5. An ECe of 15 dS m^{-1} corresponds with about 0.65% salt (Driessen and Dudal, 1991).

The distribution of soil salinity in the Arabian Peninsula is shown in Figure 48. Most of this salinity is due to primary salinization. This refers to the build-

up of salts as a result of lithological inheritance or topographical position, and is a natural process within arid zones. This map does not provide a good representation of secondary, or human-induced salinity. The latter has significantly increased since the large resource surveys of the 1970s and 1980s, due to the unregulated use of groundwater and large-scale irrigation development, often without adequate drainage.

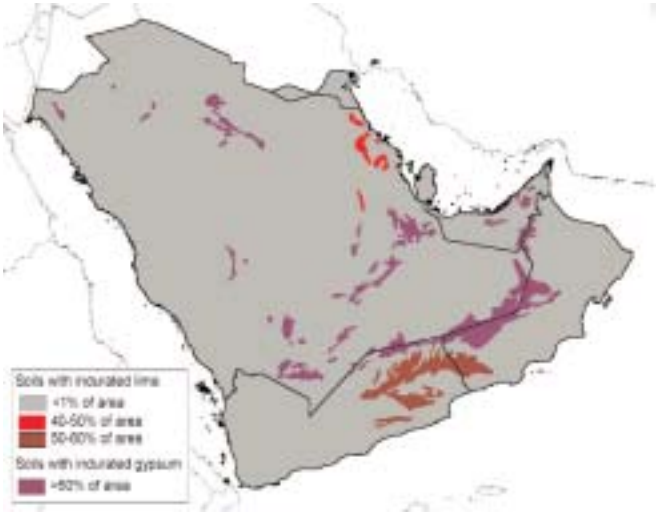

Fig. 47: Distribution of soils with hardened lime or gypsum

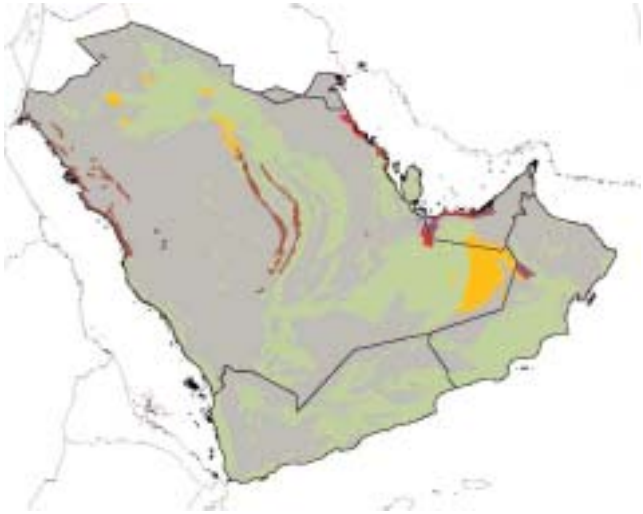

Fig. 48: Distribution of soil salinity(Note: for legend see Fig. 34)

5.3. Conclusions

Soil patterns in the Arabian Peninsula are controlled by the interaction of climate, landforms, and geological parent materials. There is no shortage of good agricultural soils; the obvious limitation to put them into production is water availability. Where irrigation water is available, standard fertility management practices are required, and, if provided, will allow maintenance or enhancement of soil quality. Gypsiferous soils require careful irrigation management, but they can be made productive.

6. Agricultural Production Systems

Notwithstanding extreme aridity and limited renewable water resources, the Arabian Peninsula has developed indigenous agricultural production systems, based on crop production under irrigation, and extensive livestock systems. Rapid economic development in the latter half of the 20th Century has resulted in significant changes in the traditional agricultural systems of the subcontinent. Increased agricultural production has contributed to economic growth, but at the price of degradation of natural resources, particularly the rangelands and the non-renewable groundwater aquifers.

Country-level data indicate that the cropland areas are very limited in the Peninsula (Table 10). With the exception of Saudi Arabia and Yemen, the

Table 10. Cropland in the Arabian Peninsula

Country	Surface [a]	Crop [b]	Irrigation [c]
Bahrain	680	7.0	100
Kuwait	17,820	0.4	71
Oman	212,460	0.3	98
Qatar	11,000	1.5	76
S. Arabia	2,149,690	1.8	42
UAE	83,600	1.0	89
Yemen	527,970	2.9	31

Base year for statistics: 1997

[a] Country area in km^2

[b] Crop: % of country area that is cropland (defined as sum of arable land and permanent cropland)

[c] Irrigation: irrigated land as a % of cropland area

Source: World Resources Institute, URL: http://earthtrends.wri.org/country_profiles

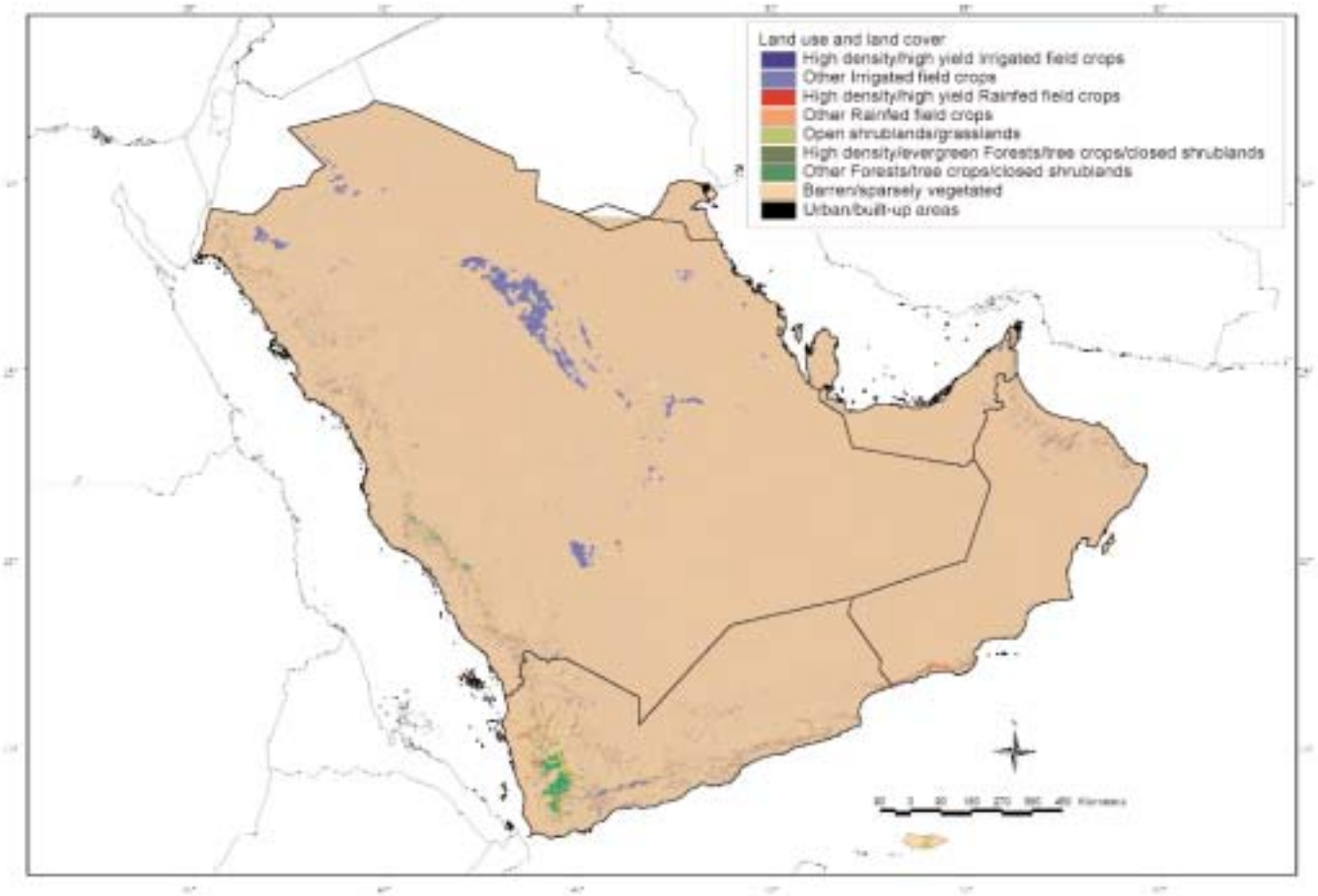

Fig. 49: Land use and land cover

majority of areas under crops are irrigated. Both statistics underscore the critical limitation of water, since soil resources for agriculture are much less limiting (see Section ‘Soils’).

The land use and land cover of the Arabian Peninsula are shown in Figure 49. It is clear that most of the subcontinent is either bare or under very sparse vegetation. The lack of vegetation is probably as much the result of overgrazing as aridity. Between 1980 and 1996 the livestock numbers nearly doubled, from about 15 million to about 28 million sheep and goats, and from about 550,000 to 850,000 camels (FAO, 2001).

The best cover is found in the Yemen Highlands and Asir mountains. It consists of open shrubland and woodland interspersed with rainfed agriculture. (This is the only part of the Arabian Peninsula with a growing period adequate for rainfed agriculture. See Section 4.6.2.)

Between 1980 and 1996, area under irrigation more than doubled, aided by the use of modern irrigation technology, such as center-pivot and drip irrigation (Figure 50). Some large areas in the deserts of Saudi Arabia are irrigated, as are some valleys in Yemen (Figure 49). The spectacular growth in irrigated agriculture in the center of the Arabian Peninsula between 1983 and 1993 is shown in the four scenes from the 8-km resolution AVHRR (Advanced Very High Resolution Radiometer) satellite (Figures 51a-51d). The areas with high biomass productivity are shown in red or brownish colors. The rainfed areas of the Yemen Highlands show up clearly, as do some coastal flats with halophyte vegetation. All other inland areas in red or brown are irrigated. In 1983 (Figure 51a) there were barely any irrigated areas. Ten years later they reached their maximum extent (Figure 51d).

The changes in biomass productivity as a result of irrigation in the desert (and some crop area increase in the rainfed areas of Yemen and the Asir) are shown in Figure 52. It should be noted that the small spots scattered across the image are probably artifacts due to errors in processing the satellite signal.

Since most of the irrigated agriculture is fed by fossil aquifers, which are barely recharged, this type of agriculture is obviously not sustainable.

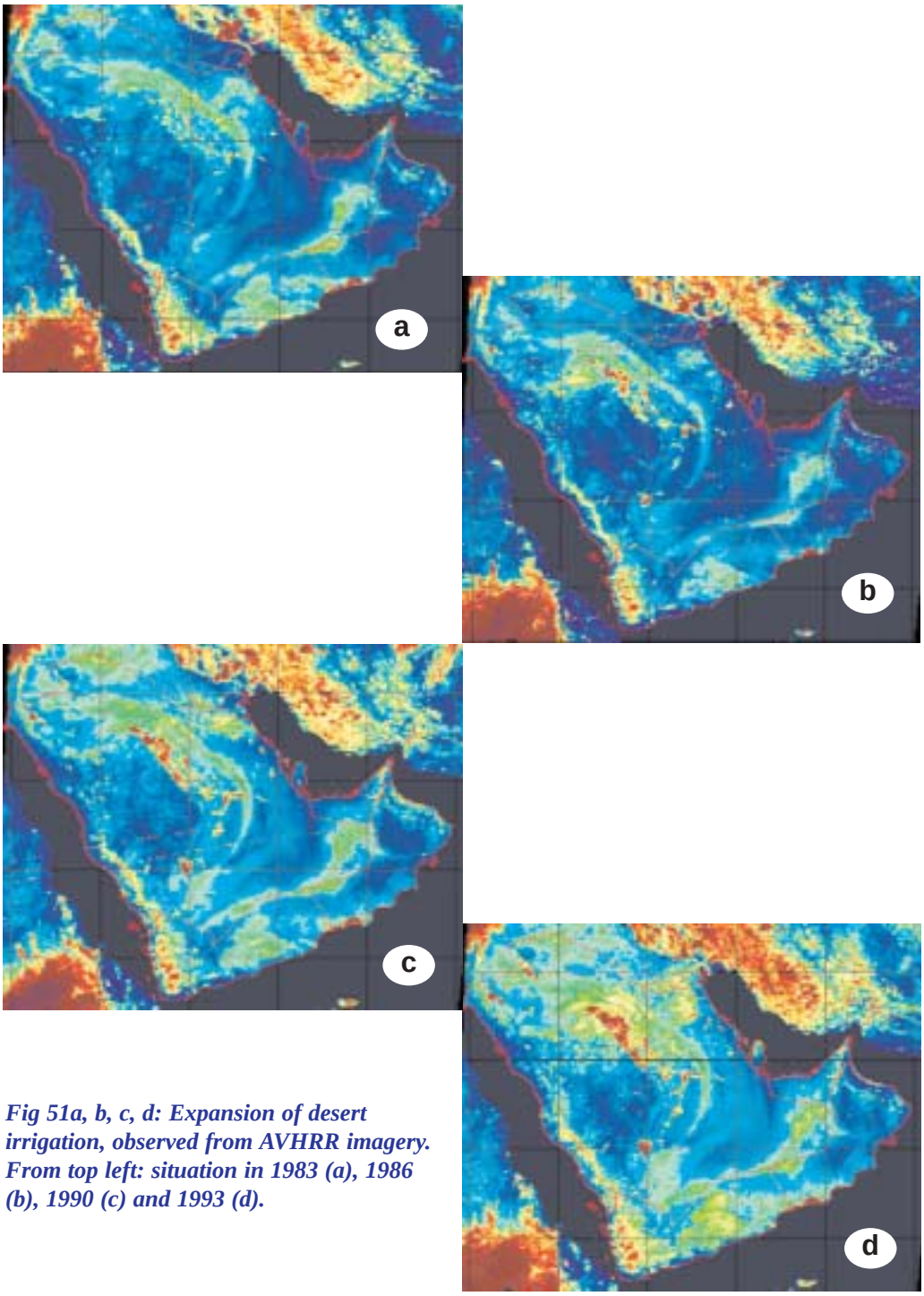

Fig 51a, b, c, d: Expansion of desert irrigation, observed from AVHRR imagery. From top left: situation in 1983 (a), 1986 (b), 1990 (c) and 1993 (d).

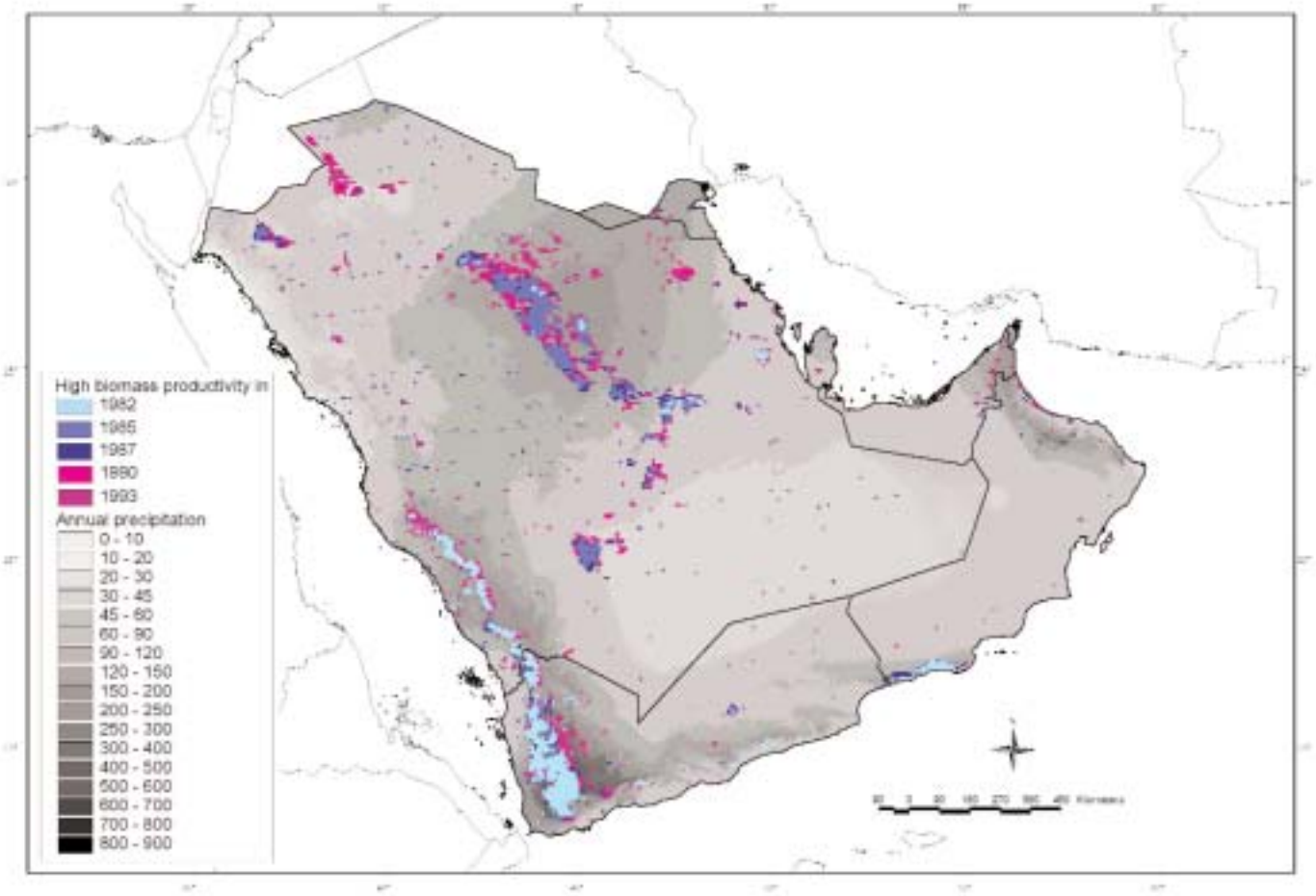

Fig. 52: Evolution of desert irrigation 1982-1993

7. Research Priorities in Agroecological Characterization

The Arabian Peninsula suffers from a public perception that it is a subcontinent of limited heterogeneity, poor agricultural potential, and low population densities. This view is oversimplified, and the Peninsula is far from monolithic in its agroecological characteristics. In fact, some agroecological niches, admittedly small, have high agricultural potential. The subcontinent also has important potential as a source of genetic diversity and abiotic stress resistance. In order to realize this potential, there is a clear need for better agroecological characterization of the Peninsula. Numerous thematic surveys in the form of soil survey reports, climatic maps, and groundwater surveys exist, therefore, the need for new resource inventories is probably limited. The real need is to integrate this information in the form of agroecological frameworks for development. Specific methodologies, models, and decision-support systems must be developed to achieve and make use of this integration.

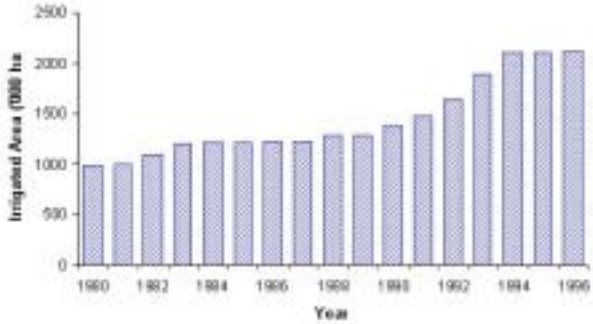

Fig. 50: Evolution of irrigated areas in the Arabian Peninsula (1980-1996)

The number of synoptic and climatological stations for a subcontinent of this size is inadequate to map the variations in agroclimatic conditions, particularly in very dry, hot, and mountainous areas. With the exception of a few areas, time series of climatic data are generally short and often interrupted. As well, the temperature, radiation, moisture, humidity, and wind regimes in the Peninsula's agroecological niches will need to be properly characterized. This will require a network of well-monitored, integrated research sites.

The following research priorities in agroecological characterization have been identified for the Arabian Peninsula (De Pauw, 1998):

- Regional assessment of crop water requirements for enhancing water use efficiency
- Agroecological zoning for biodiversity conservation, rangeland rehabilitation, abiotic stress identification, and development planning
- Improved climate monitoring

7.1. Regional assessment of crop water requirements

A basic principle behind efficient water use is irrigation to meet the crop water requirement. Crop water requirements can be calculated from climatic and crop data. The main challenge in estimating crop water requirements is extrapolation of climatic and crop coefficient data, obtained by measurement at specific sites, to areas without data. As mentioned earlier, the climatic station network in the Arabian Peninsula is sparse and records are recent. In addition, apart from literature data on crop coefficients, relatively little work has been done on the reassessment of crop coefficients for local crop cultivars under the specific climatic conditions of the subcontinent. As a result, assessment of crop water requirements is usually very site-specific and difficult to generalize to agroecological zones.

Figure 17, which shows mean annual potential evapotranspiration, is a rough basis for estimating regional water requirements. This work needs to be improved, however, by using climatic data on a shorter time scale, and linking this with crop coefficients for specific crops and cultivars, calibrated in representative sites.

7.2. Agroecological zoning

There is considerable data available on climate, soils, and water resources in the Arabian Peninsula. These information sources range from fair to excellent, depending on the country and theme. With the exception of Yemen, little work has been done in the region to integrate these data for targeted agricultural research, ecosystem and biodiversity studies, and development planning. As a result, data that are potentially highly valuable are under-analyzed, under-utilized, and under-valued.

Area profiles (agroecological zones) are required to identify different environments as a basis for a holistic approach to development planning and resource conservation. Modeling, state-of-the-art interpolation techniques, GIS, and remote sensing could be used to integrate climatic, soils, and land cover data into agroecological zones. Agroecological frameworks can form a rational basis for agricultural research priority setting, promote transferability and compatibility across countries of research results, and provide an integrated spatial view of resource availability, quality, use, and degradation risk.

The concept of this research theme is illustrated in Figure 53. A macro-scale agroecological characterization allows assessment of edaphic diversity at the level of broad landscapes. This edaphic diversity is nearly always associated

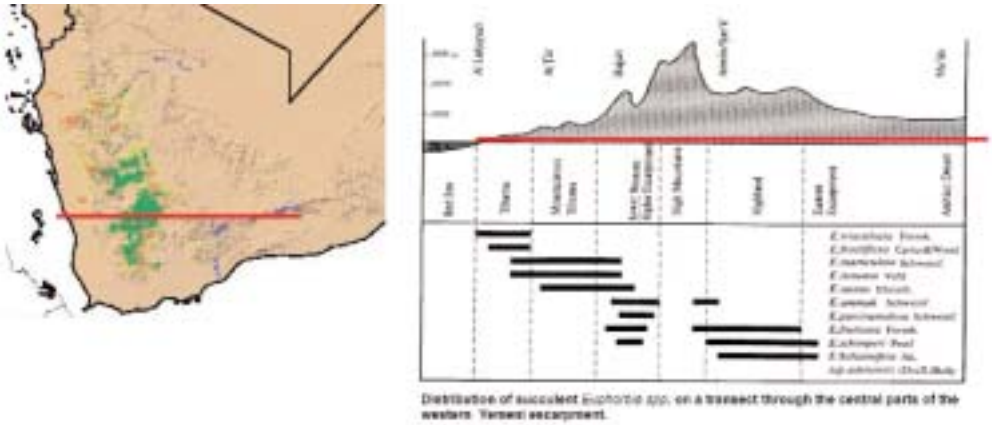

Fig. 53: Mapping the distribution of plant communities or species using landscape frameworks.

with different plant communities. The plants of the Arabian Peninsula have been described in many studies, but they have not been mapped in a consistent framework that allows extrapolation across the region. An agroecological characterization at macro-scale would address the issue of biodiversity assessment by linking landscapes (with their climatic, landscape and soil patterns) to plant communities and species.

7.3. Improved climate monitoring

Techniques of data spatialization and remote sensing, such as those used in this publication, are valuable tools for extracting maximum information content from data sparse areas. However, they cannot compensate fully for the tremendous climatic data gap in the Arabian Peninsula. Meteorological services in the region should make an effort to service the most needy areas, using agroecological frameworks as a basis for siting weather stations in representative locations. Automatic stations, with data loggers and data transmission by telephone or satellite, can overcome the remoteness of such areas.

In addition, different meteorological data networks, including those independent of the national meteorological services, should form partnerships, assisting each other with data collection, pooling, and sharing.

8. Methods and Data Sources

8.1. General maps

Roads and population centers

Obtained from the Digital Chart of the World (ESRI, 1993).
Annual precipitation background: see 'Climatic maps.'

Population density

Obtained from Columbia University's Center for International Environmental Science Information Network (CIESIN) Gridded Population Database of the World (GPW version 2). This database contains estimates of population density (in square kilometers) of the world in 1995.
[On-line document. URL:
http://sedac.ciesin.org/plue/gpw/index.html?main.html&2]

8.2. Relief and geomorphology

Altitude

Derived from 1-km resolution global DEM GTOPO30 (USGS, 1996).

Elevation range

Derived from 1-km resolution global DEM GTOPO30 (USGS, 1996) by applying a range filter on the 8 neighboring cells of each grid cell.

Geomorphological regions

Polyline on-screen digitizing of boundaries from Guba and Glennie (1998) on the elevation range background.

Salt flats: polygon digitizing based on FAO (1995), with corrections based on elevation range background. (Afterwards added as a mask.)
Wadi network: obtained from the Digital Chart of the World (ESRI, 1993).

8.3. Climatic maps

All climatic maps were prepared by converting point data into grid datasets (with 1 km resolution) through spatial interpolation methods. The point data were obtained from an international climatic database, FAOCLIM (FAO,

1995b), supplemented with data obtained from meteorological records of the region. (Particularly for Oman, Qatar, the United Arab Emirates, and, to a lesser extent, Yemen, stations could be added to the FAOCLIM database.)

The basic climatic variables processed were mean maximum and minimum monthly temperature (Tmax and Tmin), mean monthly precipitation (Prec), and mean monthly potential evapotranspiration (PET). The latter parameter was pre-processed for the stations of the FAOCLIM database using the Penman-Monteith method (Allen et al., 1998). For stations with only temperature data available, but not the other variables required by the Penman-Monteith formula (sunshine/radiation, wind, humidity), a two-step approach was followed to estimate PET according to the Penman-Monteith method by regression:

1. Calculate PET according to the Hargreaves method (Choisnel et al., 1992):

$$PET_{HG} = .0023 * Ra * (T_{mean} + 17.8) * \sqrt{(T_{max} - T_{min})}$$

With:
Ra: extraterrestrial radiation (calculated from latitude and time of year);
Tmean: mean temperature
Tmin: minimum temperature
Tmax: maximum temperature

2. Estimate Penman PET from Hargreaves PET using regression equations for climatically homogeneous regions. The regions were obtained from the Köppen climatic classification and the regression equations used are shown in Table 11.

Table 11. Conversion equations from PET (Hargreaves) to PET (Penman-Monteith)

Köppen region	Description	Equation	r^2
BSs	Semi-arid climate with summer drought	$PET_{PM} = 1.1058\ PET_{HG} - 14.909$	.90
BSw	Semi-arid climate with winter drought	$PET_{PM} = 0.1478\ PET_{HG}^{1.3689}$	.85
BW	Arid climate	$PET_{PM} = 1.1594\ PET_{HG} - 7.3988$	.81

PET_{PM}: PET calculated according to the method of Penman-Monteith (mm)
PET_{HG}: PET calculated according to the method of Hargreaves (mm)
TP: mean monthly temperature (°C)

From these four **basic** climatic parameters, the following **derived** climatic parameters were calculated: mean average monthly temperature (Temp), and the mean average temperature in summer (Tsum) and winter (Twin).

The interpolation technique used was a thin plate smoothing spline using the method of Hutchinson (1995) and the software package ANUSPLIN. This

method is essentially a radial basis interpolation function of the type:

$$B(h) = (h^2 + R^2) \log (h^2 + R^2)$$

With:
B: weight at the grid node
H: anisotropically rescaled, relative distance from the point to the node
R^2 smoothing factor specified by the user

In the approach of Hutchinson the smoothing factor, or inversely, the degree of complexity of the created 'climate surface,' is determined automatically from the database by minimizing a measure of predictive error of the fitted surface given by the generalized cross validation (GCV). In the surface fitting procedure three independent spline variables were used, longitude, latitude, and elevation above sea level. They were considered the most appropriate for fitting surfaces related to temperature or precipitation parameters.

Twelve monthly climate surfaces were created for each of the basic climatic parameters (Tmax, Tmin, Temp, Prec, and PET), and a surface for Tsum and Twin. These elementary climate surfaces were combined into various *derived climate surfaces* using formulas and models, which will be explained in the following sections.

Aridity index (AI)

$$AI = \sum_{i=1}^{12} prec / \sum_{i=1}^{12} pet$$

with i: month number
prec: total precipitation during month I
pet: total potential evapotranspiration (Penman-Monteith) during month I

Precipitation deficit (PD)

$$PD = \sum_{i=1}^{12} (prec_i - pet_i)$$

Annual heat units (AHU)

$$AHU = \sum_{i=1}^{12} (Temp_i \ x \ NumDays_i)_{Temp>Threshold}$$

with: Temp: mean monthly temperature (°C) during month i
NumDays: number of days in month i
Threshold: temperature below which no accumulation is done (in this study: 0°C)

Climatic growing period (GP)

$$GP\_ON = (Date)_{aet/pet>Threshold}$$

$$GP\_END = (Date)_{aet/pet<Threshold}$$

$$LGP = GP\_END - GP\_ON$$

with: GP_ON: growing period onset date
GP_END: growing period end date
LGP: length of growing period

In the Arabian Peninsula low temperature is not a significant limiting factor, therefore only the moisture limitation is considered to determine the growing period.

The criterion used for the definition of a moisture-limited growing period is whether the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET) for any particular month is higher than a user-defined threshold. If it is, that month is part of a growing period, if it is not, that month is not part of the growing period. The start date of the growing period is obtained from linear interpolation of the AET/PET ratios between the last month that is part of the growing period, and the first month that is not part of the growing period. The end date, inversely, is obtained by linear interpolation of the AET/PET ratios between the last month that is part of the growing period, and the first one that is not part of the growing period.

$$GP\_ON = M\_Start + NDays \frac{Thre - R_0}{R_1 - R_0}$$

$$GP\_END = M\_End + NDays2 \frac{Thre - R_{n-1}}{R_n - R_{n-1}}$$

with: M_Start: the number of days from 1 January up to the end of the last month that is not part of the growing period

M_End: the number of days from 1 January up to the end of the month preceding the last month of the growing period
NDays: number of days in the first month of the growing period
NDays2: number of days in the last month of the growing period
Thre: |AET/PET threshold for defining a growing period (user-defined; for this study set to .5)
R_0: AET/PET ratio for the month preceding the first month of the growing period;
R_1: AET/PET ratio for the first month of the growing period;
R_{n-1}: AET/PET ratio for the month preceding the last month of the growing period;
R_n: AET/PET ratio for the last month of the growing period.

If more than one growing period occurs, a distinction is made between the first and the second growing period, but the calculation procedure is the same.

Similarity index

A combined temperature-precipitation based similarity index is calculated as follows[1]:

1. For each grid cell the 12 monthly mean temperature (Temp) and precipitation values (Prec) are taken;
2. The square deviations with the match locations are summed:

$$Tr = \sum_{i=1}^{12} \left[10\left(Temp_i - T_i\right)\right]^2$$

and

$$Pr = \sum_{i=1}^{12} \left(Prec_i - P_i\right)^2$$

3. The deviations are sorted and ranked into arrays $[Tr]_n$ and $[Pr]_m$.
4. The similarity index for temperature in a grid cell j is then calculated as:

$$Ts_j = 100\left[1 - \frac{1 - rank\left(Tr_j, \overline{Tr}\right)}{N-1}\right]$$

[1] Procedure developed by Dr. F. Pertziger, SANIGMII, Tashkent, Uzbekistan.

and similarity in precipitation as:

$$Ps_j = 100\left[1 - \frac{1 - rank\left(Pr_j, \overline{Pr}\right)}{M - 1}\right],$$

in which *rank* $\left(b, \overline{A}\right)$ is a ranking number of *b* in array $\overline{A}$.

5. The combined temperature-precipitation similarity is calculated as:

$$S = 100\sqrt{\frac{(T_S W_T)^2 + (P_S W_P)^2}{W_T^2 + W_P^2}},$$

where the W_T and W_P are the weights assigned to temperature and precipitation, respectively. In this study, equal weights have been used for W_T and W_P.

Biomass productivity indices

A distinction is made between biomass productivity indices for natural vegetation/rangeland and for crops.

One rangeland biomass productivity index (RBPI) is defined as follows:

RBPI = AHU x AI

with: AHU: annual heat units (°C days)
AI: aridity index

The RBPI can, therefore, be considered as the atmospheric energy available for biomass production, as expressed by accumulated temperature, adjusted for the moisture regime.

Biomass productivity indices for crops can be developed using the same principle, except that temperature outside the time bounds of the moisture-limited growing period are not considered.

The first step is to calculate a daily adjusted thermal increment (ATI) as a function of the adaptability range for each crop group.

Table 12. Adaptability to temperature for different crop groups (adapted from FAO, 1978)

Crop group	T_0	T_{opt1}	T_{opt2}	T_x
I	5	15	20	33
II	10	25	30	45
III	15	25	35	50
IV	10	20	30	45

Adaptability expressed in relation to four cardinal temperature points (all in °C):

T_0 : the daytime temperature below which no assimilation takes place (cold-limited);

T_{opt1} : the lower daytime temperature threshold above which maximum assimilation takes place;

T_{opt2} : the higher daytime temperature threshold above which assimilation rate declines;

T_x : the day-time temperature above which no assimilation takes place (heat-limited)

For a particular daytime temperature Tday (as assimilation takes place during the day), ATI can be defined as follows:

$$
\begin{aligned}
ATI &= 0 && [Tday <= T0 \text{ or } Tday >= Tx] \\
ATI &= Tday - T0 && [Tday > T0 \text{ and } Tday < T_{opt1}] \\
ATI &= (T_{opt1} + T_{opt2})/2 - T0 && [Tday >= T_{opt1} \text{ and } Tday <= T_{opt2}] \\
ATI &= Tx - Tday && [Tday > T_{opt2} \text{ and } Tday < Tx]
\end{aligned}
$$

The concept of ATI is thus related to the concept of heat units, but the accumulation is weighted according to the distance of the real daytime temperature from the optimal daytime temperature for each crop group.

The daytime temperature is estimated from the minimum and maximum temperature as:

$$Tday = T_{mean} + \frac{T_{max} - T_{min}}{\pi}$$

The ATI values are summed for each crop group on a daily basis between the onset and end dates of the growing period. Since daily data are needed for operational reasons, and the interpretation derived from this exercise does not require high precision, the daily values can be interpreted from the monthly temperature values through linear interpolation.

The biomass productivity index for each crop group can then be defined as:

$$CBPI_j = \sum_{i=GP\_ON}^{GP\_END} (ATI)_{i,j}$$

with: j: crop group
I: day number
ATI: adjusted thermal increment (°C)
GP_ON: growing period onset date
GP_END: growing period end date

8.4. Soil maps

All soil information was obtained, directly or indirectly, from the FAO Soil Map of the World (SMW).

Soil associations

Obtained directly from the digital version of the SMW (FAO, 1995).

Derived soil properties

The original resolution of the derived soil property maps on the Digital SMW is 5 arc-minutes (about 10 x 10 km). To allow mapping of the derived soil properties at 1 km resolution, the original *Soil Associations* vector file was converted to a 30 arc-second grid. The QuickBasic code of the viewing program IMAGES.BAS was then modified to allow operation on a 30 arc-second grid and to export the generated maps as ASCII grids.

8.5. Land use and cover maps

Land use/cover

Map clipped from CWANA map in Celis and De Pauw (2001).

Irrigated areas

NDVI (Normalized Difference Vegetation Index) from AVHRR 8 x 8 km downloaded from Goddard DAAC as monthly datasets for period 1981-94. (URL:

http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/LAND_BIO/GLBDST_Data.html)

Threshold of NDVI > 0.46 used to superimpose masks for years 1982, 1985, 1987, 1990, and 1993 representing expansion of irrigated areas.

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