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:

ATI = 0	[Tday <= T0 or Tday >= Tx]
ATI = Tday – T0	[Tday > T0 and Tday < T_{opt1}]
ATI = $(T_{opt1} + T_{opt2})/2$ - T0	[Tday >= T_{opt1} and Tday <= T_{opt2}]
ATI = Tx – Tday	[Tday > T_{opt2} and Tday < Tx]

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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