Review

Climate change, drought and desertification

Henry N. Le Houérou

327, rue A.L. De Jussieu, F-34090 Montpellier, France

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The definition of desertification accepted in the *ad hoc* conference held by UNEP in Nairobi in 1977 and confirmed at the Earth Summit on Environment and Development held in Rio de Janeiro in 1992 is: 'arid, semiarid and dry-subhumid land degradation'. There is no global long-term trend in any rainfall change over the period of instrumental record (*c.* 150 years), but there has been an increase of 0.5° C in global temperature over the past 100 years. This increase seems partly due to urbanization, as there is no evidence of it resulting from atmospheric pollution by CO₂ and other warming gases (SO₂, NO₂, CH₄, CFH etc.). On the other hand, the thermal increase is uneven, increasing with latitudes above 40° N and S. The increase is only slight or non-existent in subtropical and inter-tropical latitudes where most arid and semi-arid lands lie. This, incidently, is consistent with Global Circulation Models (GCM) — derived scenarios. The study of tree-rings, lake level fluctuations and pollen analysis confirm the existence of climatic fluctuations, but with no long-term trends over the past 2000 years.

A possible increase of 1–3°C in arid lands over the next 50 years due to a doubling of the CO₂ content of the lower atmosphere to 700 p.p.m., as assumed by most scenarios stemming from GCM, would increase global potential evapo-transpiration (PET) by some 75–225 mm year⁻¹. The ratio of mean annual precipitation to PET would then decrease by about 4–5%, assuming that no substantial changes in rainfall took place in arid and semiarid lands. However, the impact of CO₂ on plants would boost photosynthesis and, therefore, primary productivity; it would also increase wateruse efficiency via the reduction of stomatal conductance. It is therefore at present difficult to predict the net balance of these two opposite consequences or to prophesy which phenomenon would prevail: increased aridity or higher productivity and more efficient water use. At all events, the possible effect of a climatic fluctuation (or change) of the magnitude envisaged would have a trivial consequence on arid environments, as compared with the past and present impact of humans and their livestock.

Drought has always been a normal recurrent event in arid and semi-arid lands. Strategies and tactics to mitigate its consequences via improved landuse and management practices are analysed.

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Keywords: arid lands; bioclimatology; land degradation; vegetation depletion; drought mitigation; land management; range management; desertization; erosion

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Introduction

The present study was carried out within the framework of IPCC (Intergovernmental Panel on Climate Change, Working Group II on Impacts, Drought and Mitigation), to which the author was appointed as co-ordinator of the topic 'Climate Change, Drought and Desertification' (CCDD) in September 1993. After two previous drafts submitted to some 52 peer reviewers in 1993 and 1994, the final report was completed and submitted to the IPCC governing body in August 1995. The present review, however, only reflects the author's standpoint which does not necessarily coincide with official IPCC views on every item, but it does claim to represent a consensus of the many scientists who actually carried out field work on many aspects of the subject in various arid zones of the world.

Fluctuations and trends in rainfall and temperature in desert, arid, semi-arid and dry sub-humid lands of the world, since instrumental recording began

Definitions

The terms hyperarid, arid, semi-arid and dry sub-humid are hereafter understood as the meaning in the *World Atlas of Desertification* (UNEP, 1992), i.e. slightly different from those used in the UNESCO *World Map of Arid Zones* (1977). In other words, on an annual basis, using Penman's standard equation to evaluate potential evapo-transpiration (PET) (which should not be confused with potential evaporation (PET); PET = 0.65 PE \pm 0.05 approximately, when PE is evaluated via the class A pan device (Le Houérou *et al.*, 1993). We then derive the threshold values shown in Table 1 for the ratio between mean annual precipitation (P) and mean annual PET (Le Houérou *et al.*, 1975, 1993; UNESCO, 1977; Le Houérou, 1989*a*; UNEP, 1992).

The surface of land covered by hyperarid, arid and semi-arid climates is shown in Table 2. Altogether, they represent about one-third of the earth's surface area but, if one is to include dry sub-humid zones, the area concerned with the present report would represent over 47% of the land mass of the planet (Tables 1 and 3). The term desert, meaning 'true desert' or 'climatic desert' is here regarded as a synonym for the hyperarid zone. Dry-land (DL) connotes the hyperarid, arid, semi-arid and dry sub-humid zones, while the expression 'World Arid and Semi-Arid Lands' (WASAL) excludes the dry sub-humid zone.

The word desertification was defined as follows at the U.N. Desertification Conference (UNCOD), held in Nairobi in 1977: 'A reduction of the land production potential in arid, semi-arid and dry sub-humid zones, that may ultimately lead to desert-like conditions'. This definition was later accepted at the 'Earth Summit', the

 Table 1. Bioclimatic aridity zoning of world dry-lands, based on the P/PET ratio (After UNEP, 1992)

Bioclimatic Zones	Area (10 ³ km ²)	%	P/PET ratio
Hyperarid	9781	7.5	< P/PET < 0.05
Arid	15692	12.1	0.05 < P/PET < 0.20
Semi-arid	23053	17.7	0.20 < P/PET < 0.45
Dry sub-humid	12947	9.9	0.45 < P/PET < 0.65
SuĎ-humid	25843	19.9	0.65 < P/PET < 0.75
Humid and hyper-humid	42811	32.9	0.75 < P/PET

Regions and	Geographica surface	1	Bio	climatic z	one		
countries	area	Eremitic	Hyperarid	Arid	Semi-arid	Total	%
Aridity Index (I) (P/PET × 100		I<3	3 <i<6< td=""><td>6<i<30< td=""><td>30<i<50< td=""><td></td><td></td></i<50<></td></i<30<></td></i<6<>	6 <i<30< td=""><td>30<i<50< td=""><td></td><td></td></i<50<></td></i<30<>	30 <i<50< td=""><td></td><td></td></i<50<>		
P (Approx. mm)		P<50	50-100	100-400	400-600		
Africa	30312	6232	3017	3570	2951	15770	52
North Africa	6019	3952	1137	505	248	5842	97
Algeria	2381	1562	438	210	90	2300	97
Egypt	1001	685	286	30	-	1001	100
Libya	1760	1435	230	90	2	1757	99
Morocco	713	240	150	120	130	640	90
Tunisia	164	30	33	55	26	144	88
West Africa	8722	2120	1475	1250	955	8500	67
Burkina Faso	274	_	_	10	70	80	29
Chad	1285	370	230	125	100	825	64
Mali	1240	380	370	185	120	1055	85
Mauritania	1030	375	330	300	25	1030	100
Niger	1267	435	355	225	95	1110	88
Nigeria	924	_	_	_	185	185	20
Senegal	197	_	_	30	110	140	71
Sudan	2505	560	190	375	250	1375	55
Sahara	8684	6010	2612	62	_	8684	100
East Africa	3641	40	215	898	622	1775	49
Ethiopia	1222	25	35	310	250	620	51
Djibouti	22	5	10	5	2	22	100
Somalia	638	10	170	393	65	638	100
Kenya	583	_	_	185	120	305	52
Uganda	236	_	_	5	30	35	15
Tanzania	940	_	-	-	155	155	16
Southern Africa	5428	120	190	900	1095	2305	43
Angola	1247	_	_	15	65	80	6
Botswana	600	_	_	290	400	600	100
Mozambique	783	_	_	_	70	70	9
South Africa	1222	15	45	375	250	685	56
Madagascar	587	_	_	15	30	45	8
Cape Verde	4	_	-	2	1	3	75
Extra tropical A	frica 8112	3952	1193	899	529	6572	79
Inter tropical Af		2280	1814	267	2422	9199	42
North and Sou	th America						
Northern Ameri		10	90	1025	1935	3060	14
Canada	9976	_	_	_	30	30	0.3

Table 2. Size and distribution of the world's arid lands (10^9km^2) (After Le Houérou, 1992a)

		Table 2	2. (Continue	ed)			
Regions C and	Geographic surface	al	Bioc	limatic	zone		
countries	area	Eremitic 1	Hyperarid	Arid	Semi-arid	Total	%
North and South	n America	continued					
Mexico	1973	5	75	570	230	880	45
U.S.A.	9373	5	15	455	1675	2150	23
Temperate		_	_	460	1640	2100	69
Mediterranean		10	10	75	70	165	5
Tropical & subt	ropical	-	80	490	225	795	26
Southern America	17818	275	116	967	13268	2626	14
Argentina	2777	215	110	720	720	1451	52
Bolivia	1099	_	-	53	42	95	9 9
Brazil	8512	_	_	120	330	450	5
Chile	757	185	75	40	12	430 312	41
Colombia	1139	165		40	9	10	41
Equador	285	_	-	3	9 15	10	6
		_	_				0 12
Paraguay	407	-	-	-	50	50	
Peru	1285	90	30	25	65 95	210	16
Venezuela	912	_	_	5	25	30	3
Temperate		_	_	438	445	883	34
Montane		-	-	120	100	220	8
Tropical & subtrop	pical	138	70	359	669	1236	47
Mediterranean		137	35	55	60	287	11
Asia	43770	1595	3225	5415	4817	1502	34
Near East	4593	919	1873	938	272	3992	87
Egypt (Sinaï)	60	20	35	5	-	60	100
Iraq	435	-	96	291	48	435	100
Israel	21	4	3	5	9	21	100
Jordan	98	18	25	40	15	98	100
Kuwait	18	-	_	18	-	18	100
Oman	212	107	91	12	2	212	100
Qatar	22	-	22	_	-	22	100
Saudi Arabia	2150	700	1250	200	10	2150	100
Syria	185	_	10	157	18	185	100
Turkey	781	_	_	50	130	180	23
UAE Č	84	_	84	_	_	84	100
Yemen	527	70	257	160	40	527	100
Middle East	6035	20	306	1497	1277	3100	51
Afghanistan	647	-		220	155	375	58
India	2973	_	_	280	400	680	23
Iran	1636	20	306	685	375	1386	85
Pakistan	779	-	-	312	347	659	85
Central &							
Middle Asia	33142	656	1056	2960	3268	9740	24

 Table 2. (Continued)

		Table		eu)			
Regions	Geographica surface	ıl	Bio	climatic	zone		
and countries	area	Eremitic	Eremitic Hyperarid		Semi-arid	Total	%
Asia continued	1						
China	9305	656	776	1375	1293	4100	44
Mongolia	1565	_	80	105	625	810	52
	S.S.R. 22272	-	200	1480	1350	3030	14
Australia	7618	_	_	3250	1375	4625	61
Europe (Spain, Greec	e, Italy) 500	_	_	100	300	400	80
World*	130737	7500	7059	14330	12651	41540	32

U.N. Conference on Environment and Development (UNCED, Agenda 21) in Rio de Janeiro in 1992 in the following form: 'Desertification means land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors including climate variation and human activities'. These definitions were agreed at the Intergovernmental Convention to Combat Desertification (ICCD, 1994). We have retained them, although many scientists would have preferred to have connotations to irreversibility and desert landscapes included in the definition. Many specialists consider them to be the result of political compromises whose goals are not scientific. Under this meaning, desertification may be equated with land degradation under arid to dry sub-humid climates. Many scientists prefer to use the latter terms because, unlike desertification, the expression 'land degradation' does not have emotional connotations.

The term drought is taken in the WMO (1975) definition of agricultural or ecological drought. That is: 'A deficit of rainfall in respect to the long term mean, affecting a large area for one or several seasons or years, that drastically reduces primary production in natural ecosystems and rainfed agriculture'.

Hydrologists may define drought in a somewhat different way as: 'Drought means the naturally occurring phenomenon that exists when precipitation has been significantly below normal recorded levels causing hydrological imbalance that adversely affects land resource production systems' (ICCD, 1994; Williams & Balling, 1994).

Aridity differs from drought in that it refers to a negative ratio between mean annual rainfall (P) and mean annual potential evapo-transpiration (P/PET). The degree of aridity is inversely related to the magnitude of this ratio, but drought is more or less related to aridity because arid regions experience frequent droughts; however, non-arid regions may also undergo infrequent droughts.

Instrumental weather records began approximately 150 years ago. All world arid and semi-arid land (WASAL) records show fluctuations of periods with average values above and below the long-term means (Le Houérou, 1959, 1962*b*, 1968, 1979*b*;

^{*}These figures depart from those of Tables 1 and 3 because of a different definition of the zoning. The total area of the Sahara within the 100 mm MAR isohyet limit, for instance, is 8-1 million km² (Le Houérou, 1990, 1995*b*) or 8-6 (Popov *et al.*, 1991); whereas the whole world hyperarid zone is only 9-8 million km² below the P/PET ratio of 0-05, which also includes the Atacama, Namib, Takla Makan, Chinese, Persian, Arabian and a few other minor desert areas, according to UNEP (1992).

992)	Total %	7650 13.6						130127 100.0
., 1990; UNEP, 1	South America	377	11881	2070	2645	445	257	17675
Table 3. Regional distribution of world dry-lands (10 ³ km ²) (After Oldeman et al., 1990; UNEP, 1992)	North America	6169	8385	2315	4194	815	31	21909
y-lands (10 ³ km ²)	Europe	279	622	1835	1052	110	0	9505
tribution of world dr	Australasia	0	2189	513	3090	3030	0	8822
ole 3. Regional dis	Asia	1082	12243	352	6934	6257	2773	42560
Tab	Africa		—		5138			29656
	Zone	Cold	Humid	Dry sub-humi	Semi-arid	Arid	Hyperarid	Total

Krishnan, 1977; Meher-Homji, 1977; Tyson, 1978, 1980, 1987, 1990; Parry *et al.*, 1988; Gadgil *et al.*, 1988; Hobbs *et al.*, 1988; Nicholson *et al.*, 1988; UNEP, 1992; Daget, 1992; Kharin *et al.*, 1993; Babaev *et al.*, 1993; Balling, 1994*a*; Harsh, 1994; Wang Lixian & Ci Long-Jun, 1994, etc.). Some regions, however, have experienced medium-term trends either upward or downward or, alternately, both. Variability usually increases with aridity, with clear-cut negative correlations between the means and their coefficients of variation. There are, however, some exceptions to this rule. These included NE Brazil and Baja California where the variability appears to be 'extreme and little correlated to the mean' (Le Houérou, 1989*c*,*d*).

Rainfall

Rainfall variability and fluctuations are inherent to arid and semi-arid lands (Le Houérou, 1959, 1989*b, c, d*, 1992*b*; Rosenan, 1961; Katsnelson, 1964; Le Houérou & Norwine, 1985). There are no indications of any long-term trends in rainfall, either from the global view point (Houghton *et al.*, 1990, 1992; Folland *et al.*, 1990, 1992; Nicholls *et al.*, 1994), or in WASAL (Parry *et al.*, 1988; UNEP, 1992; Balling, 1993, 1994*a, b*; Williams & Balling, 1994). There are, however, local medium-term trends. There is, for instance, a clear-cut decline in rainfall since the beginning of this century in Central Chile, approximately between latitudes 30 and 40° S, i.e. in the Mediterranean-climate zone of that country between Copiapo and Valdivia (Burgos *et al.*, 1991; Santibanez & Uribe, 1994).

The African Sahel, between latitudes 10 and 20° N, is experiencing a 25-year drought which began in the late 1960s and is still in progress (Nicholson & Entekhabi, 1985; Nicholson et al., 1988; Hulme, 1989, 1992; Morel, 1992; Le Houérou et al., 1993; Nicholson, 1993; Hulme & Kelly, 1993). In virtually none of these 25 years did the rainfall reach the 1931–1960 mean. Dendrochronological studies, pollen analysis and lake level surveys suggest that such long droughts have occurred on several occasions during the past 2000 years, in addition to prehistorical and geological times. More information is provided below for the period prior to instrumental records. Moreover, no other region in Africa is undergoing a fluctuation of the magnitude recorded in the Sahel, nor synchronous with it (Tyson, 1978, 1980, 1987, 1990; Ogallo, 1979, 1987, 1989*a*, *b*; Nicholson *et al.*, 1988; Downing *et al.*, 1988; Shinoda, 1990*a, b*; Tyson & Lindesay, 1992; Hare & Ogallo, 1993; Jury & Levey, 1993; Jury & Pathack, 1993; Kinuthia et al., 1993; Muturi, 1994). In view of its length, the Sahel drought could scarcely be ascribed to the El Niño Southern Oscillation (ENSO) (Rasmusson, quoted by Glantz, 1987), but it does seem to be associated with sea surface temperatures (SST) in the central and southern Atlantic and with upwellings in the Gulf of Guinea, themselves linked to the activity of the Benguela current system. This particular point will be examined later.

Another clear-cut example comes from Argentina. There has been an indisputable downward trend in rainfall over most of Argentina from the beginning of the present century until about 1945; then the trend reversed. This mid-century reversal may locally have reached 10 to 30% of the previous long-term mean during the following 30 years. The increase was highest in northern Patagonia and in NE Pampa, with a trough close to zero along the mid-lower Rio Colorado valley (Forte Lay *et al.*, 1987, 1989; Burgos, 1988, 1991; Canziani *et al.*, 1990; Burgos *et al.*, 1991; Castaneda & Barros, 1994).

Typical regional fluctuations are experienced in the Mediterranean Basin with two opposite semi-secular fluctuations. In the Iberian Peninsula, there was a decrease in rainfall in the south-east, together with an increase in variability particularly between 1890 and 1940, while in the north-west an opposite trend occurred but with a slight overall decrease over the past 15 years (Maheras, 1988; Font Tullot, 1988; Brandt *et*

al., 1991; Conte, 1993; Mendes, 1993; Onate Rubalcaba, 1993; Palutikof, 1993; Puigdefabregas & Aguilera, 1994). At the level of the Mediterranean basin a so-called Mediterranean East–West Oscillation (MEWO) has been described. An oscillation of the 500 hPa field takes place, in nearly perfect opposition in the east and west parts of the Basin showing a mean period of 22 years (Conte, 1993, p. 386). The positive trend of MEWO is associated with an increase and persistence of high pressure systems and low rainfall values, while the reverse occurs with the negative trend. MEWO has been detected over the 1949–1989 period (Palutikof *et al.*, 1992).

No similar trends were apparent in southern France, perhaps due to the utilization of different analysis methodologies, but a marginally significant trend towards a periodicity of some 35 years was found with periods of low rainfall in the 1870s, 1950s and 1980s and high precipitation in the 1910s and 1970s (Daget, in Corre, 1992). There appears to be no consistent trends or periodicities overall, as far as precipitation is concerned. Examples of rainfall fluctuations in WASAL are very abundant in the literature, leaving little doubt over the issue.

Temperature

The situation is different, but somewhat less clear, in WASAL as far as temperature is concerned. The global planetary temperature has increased 0.45° C per 100 years \pm 0.15 since 1860, and 0.53° C per 100 years \pm 0.18 since 1880 (Kukla *et al.*, 1977; Jones *et al.*, 1986*a, b*, 1988; Houghton *et al.*, 1990, 1992; Folland *et al.*, 1992; Nicholls *et al.*, 1994), but there are quite different regional patterns and trends. In Kenya, for instance, Kinuthia *et al.* (1993) found inconsistent results in different areas, with perhaps an overall, marginally significant, warming trend of approximately 0.4° C between 1942 and 1991, which may be associated with urbanization. Their study showed that air temperature and annual rainfall fluctuations, depicted by smooth curves, have been out of phase with each other in most stations since 1960, a phenomenon also found in the Mediterranean Basin (Palutikof *et al.*, 1992; Palutikof, 1993).

Studies of temperature in Southern Africa (Mühlenbruch-Tegen, 1992) i.e. monthly minimum, maximum and mean at 18 main weather stations over 50 years (1940–1990), have been inconclusive about trends, with quite different results when mean, minimum and maximum were considered, and in different seasons and locations.

In Central Asia, the data provided by Kharin (1994) do not show any definite or consistent trends at the three major weather stations where data were analysed over the period 1900–1980. Data from southern France do not exhibit any definite trends in temperature, either in absolute terms or in range (Daget, in Corre, 1992).

The trend in NW China's arid and semi-arid lands, recorded at 15 major weather stations, showed a rise of about 1°C in winter temperatures between 1970 and 1985, but either little change or a decrease in summer temperatures and a mean annual increase of the order of 0.2°C (Yoshino, 1994*a,b,c*; Wang Lixian & Ci Long-Jun, 1994; Yatagai & Yasunari, 1994). Yatagai & Yasunari (1994) found no increase of annual temperatures in north China between 1951 and 1990, south of latitude 40° N, but an increase of 0.4°C per 10 years north of latitude 45° N. In North American arid and semi-arid lands, Balling (1994*a*) found a global increase of 0.8°C over the past 100 years (Fig. 1). There was a positive correlation between the rate of increase and latitude (Fig. 2), except for little increase, if any, in latitudes below 40° N (Fig. 3).

In Argentina, Hoffmann (1990) found a global increase in mean annual temperature between 1903 and 1989 at 23 major weather stations distributed between latitudes 22 and 64° S, but the change was uneven. Again, there appeared to be a positive correlation between latitude and temperature rise, with the exception of Buenos Aires

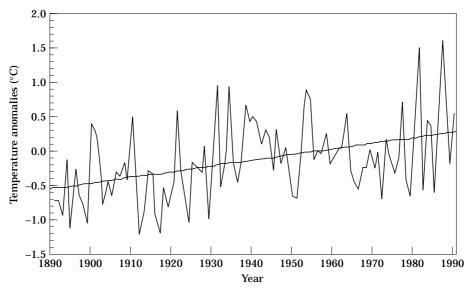


Figure 1. Temperature anomalies for the dry-lands of Mexico, the United States and Canada for the period 1891–1990. The linear trend line reveals a statistically significant warming of 0.86° C over the study period (Balling, 1994*a*).

(again perhaps because of urbanization). There was virtually no increase north of latitude 40° S; south of 40° S the increase was proportional to latitude, reaching 1°C south of latitude 60° S. In central and northern Patagonia (latitude 40–50° S), Labraga (pers. comm., 1994) found a consistent increase of about 0.5°C at five main weather stations between 1900 and 1980. The latitudinal distribution of thermal increase found in the WASAL of North America, northern China and in Argentina are fully consistent: virtually no increase of temperature in latitudes below 40° and a gradual

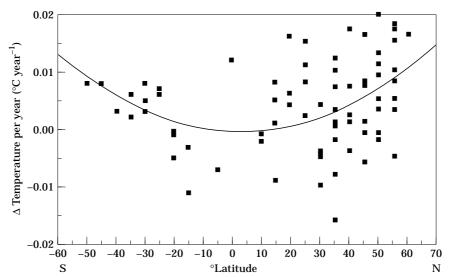


Figure 2. Relationship between latitude and temperature increase in the American dry-lands, by 5° latitude point grid. Data base from Jones *et al.* (1986*a*,*b*), courtesy of R.C. Balling Jr, Laboratory of Climatology, University of Arizona, Tempe, AZ.

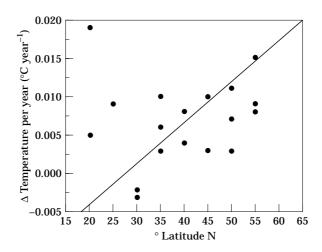


Figure 3. Relationship between latitude and temperature increase in North American drylands, as defined by UNEP (1992) by 5° latitude and 10° longitude grid points. Correlation coefficient + 0.28. Data base from Jones *et al.* (1986*a*), courtesy of R.C. Balling Jr, Laboratory of Climatology, University of Arizona, Tempe, AZ.

increase above. Moreover, these findings are fully consistent with most GCM scenarios. In the Mediterranean Basin there seems to be an E–W fluctuation of rainfall and temperature in opposite phasing, tied to MEWO as mentioned above, but no long-term trend.

From the data available at present it would seem that the order of magnitude of temperature increase in WASAL would be, at the maximum, similar to or lower than the global figure of 0.005°C per annum. It would also seem that the magnitude of the trend is directly related to latitude, increasing poleward, particularly in WASAL located above latitude 40° N and S with little or no increase below these latitudes. This, incidently, is globally coherent with most scenarios elaborated from GCMs. Moreover, the present global increase of 0.5° C per 100 years still remains well within the fluctuations observed over the past 2000 years: *c*. + 1°C (Mediæval Optimum) and *c*. – 1.5° C (Little Ice Age) (see below).

Wind

Other climatic factors pertinent to the phenomena of desertification are wind and radiation. The impact of wind may be an overriding factor, both locally or regionally, in the processes of desertification such as in Patagonia (Movia, 1972; Soriano, 1983), NW China and Mongolia (Chao Sun Chiao, 1984*a,b*; Zhu Zhenda, 1984; Liu Shu, 1984; Zhao Songqiao, 1985; Le Houérou, 1987*a,b*; Yoshino, 1992, 1994*a*), and in the Sahel (Mainguet & Canon, 1976; Mainguet, 1984; Morel, 1992; Le Houérou *et al.*, 1993). These three regions are characterized by strong and persistent winds throughout the long annual dry season: $W \rightarrow E$ winds in Patagonia, NW \rightarrow SE in China and Mongolia and NE \rightarrow SW, (the 'Harmattan') in the Sahel. The consequence of possible climatic change on the strength, direction and persistence of winds is not documented, except for their past events: dune and loess deposits. The impact of global radiation is obviously important. It shall be examined below. The role of wind on arid land geomorphology, on aeolian deposits, and on the mineral aerosol content of the atmosphere, hence on its opical properties and therefore on its temperature and rainfall, are also mentioned below.

Potential evapo-transpiration

Potential evapo-transpiration (PET), i.e. the evaporative demand of the atmosphere on plants, depends to a large extent on temperature and radiation (Table 4) and, to a lesser extent, on wind speed, saturation deficit and a few other parameters (Penman, 1948; Thornthwaite, 1948; Monteith, 1964, 1973; Mather, 1974). As a matter of fact, there is a straight and fairly tight correlation between temperature and PET in a given location over a given period of time. A large number of equations (over 80) have been worked out to predict PET, either from global radiation, from net radiation or from temperature, on various time scales (Budyko, 1958, 1974; Damagnez & de Villèle, 1961; Damagnez et al., 1963; Le Houérou, 1972, 1989a; Riou, 1980; Schneider & Rosenberg, 1988; Le Houérou et al., 1993; McKenney & Rosenberg, 1993). Furthermore, the much utilized empirical equation (P = 2 t) of Bagnouls & Gaussen (1953), (where P is the mean monthly precipitation in mm and t the mean monthly temperature in °C), popularized by Walter & Leith (1960), for determination of the threshold between the dry and rainy season, has been shown to be approximately equal to one-third PET, as measured in lysimeters or estimated via the Penman equation (Le Houérou & Popov, 1981; Le Houérou et al., 1993). From some 500 weather stations belonging to hyperarid, arid, semi-arid and dry sub-humid zones of 20 countries in Africa, it was found that PET, estimated by the Penman-Monteith equation, is equivalent to 77.5 t \pm 2.3, (Table 4) (where PET is the average annual potential evapo-transpiration in mm and t the mean annual temperature in °C, and 2.3 the standard error). In other words, every 1°C of temperature increase corresponds to an annual PET rise of approximately $5\cdot 25\% \pm 1\cdot 55$ (Table 5). A hypothetical rise of 3° C in global temperature in WASAL by the year 2050 as a result of the doubling of atmospheric CO₂ would thus correspond with an increase of PET by about 15.75% \pm 4.65, i.e. between 11.1 and 20.4% when PET is estimated using the Penman-Monteith equation, and 10-19% when estimated by the standard Penman equation (Le Houérou et al., 1993; Table 5). These figures are fairly consistent with the 17-24% bracket for an increase of 3°C, as mentioned by Schneider & Rosenberg (1988) in the U.S.A. We shall examine further the consequences of a possible increase of PET on aridity, drought and desertification.

Fluctuations and trends in historical times, before instrumental records

Tree-ring and pollen analysis data

Data from dendrochronological studies, pollen analyses, lake level surveys, glacier advance and retreat, crop distribution surveys and grape harvesting dates suggest important fluctuations over the past 2000 years, besides the well known Mediæval Optimum (800–1200 A.D.) and the Little Ice Age (1450–1850 A.D.) (Lamb, 1965, 1966, 1977, 1988; Le Roy Ladurie, 1967; Parry *et al.*, 1988).

Dendrochronological studies over the past 75 years have produced convincing conclusions regarding climatic fluctuations since about A.D. 500 (Douglas, 1919; Schulman, 1951, 1956; Fritts, 1965, 1976; Jacoby, 1989). For example, tree-ring studies of cedar trees (*Cedrus atlantica* (Endl.) Carr.) from the Atlas mountains of Morocco showed random fluctuations of rainfall above and below the long-term mean. Dry periods lasting 20 to 50 years occurred on at least six occasions between A.D. 1100 and 1850 (Munaut *et al.*, 1978; Berger *et al.*, 1979; Stockton, 1985; Serre-Bachet & Guiot, 1987; Guiot, 1990; Till & Guiot, 1990; Naciri, 1990; Serre-Bachet *et al.*, 1992). These sites are of particular significance to WASAL because some of them are only a few kilometres in horizontal distance from a sub-desert zone at the northern rim of the Sahara. Similar results were registered in Israel on *Juniperus phoenicea* L. and

Country	No. of stations	PET/t	S.D.	CV	SE
North Africa					
Algeria	22	80.8	7.4	0.09	1.6
Egypt	27	81.9	9.2	0.11	1.8
Libya	17	84.8	15.1	0.18	3.7
Morocco	13	76.4	16.4	0.21	4.6
Tunisia	19	72.8	7.8	0.11	1.8
Total	98	396.8	55.9	0.70	13.5
Weighted mean	-	79.7	11.2	0.14	2.7
The Sahel					
Burkina Faso	7	72.3	$6 \cdot 6$	0.09	2.6
Cape Verde	3	74 .1	3.7	0.05	$2 \cdot 1$
Chad	12	71.9	11.5	0.16	3.5
Mali	18	88.6	11.4	0.13	4.2
Mauritania	13	83.4	9.3	0.11	2.6
Niger	11	95.6	10.1	0.10	3.1
Senegal	14	69.6	7.7	0.11	3.7
Sudan	63	79.2	9.5	0.12	2.2
Total	141	635·4	69.8	0.87	23.0
Weighted mean	-	79.2	9.0	0.11	2.7
East Africa					
Ethiopia	94	76.2	8.6	0.11	0.9
Kenya	40	77.2	9.4	0.12	1.5
Somalia	24	75.7	16.4	0.22	3.3
Tanzania	40	67.3	9.7	0.14	1.5
Total	198	296.4	44.1	0.59	7.2
Weighted mean	_	74.1	11.0	0.15	1.8
Southern Africa					
South Africa	42	86.5	14.0	0.16	$2 \cdot 2$
Botswana	8	76.6	3.9	0.05	1.4
Namibia	6	80.0	14.9	0.18	6.1
Total	56	243.1	32.8	0.46	14.7
Weighted mean	-	84.4	12.6	0.15	2.5
African dry-lands	493	77.5	10.6	0.14	2.3

Table 4. Relationship between mean annual temperature and mean annualPET (mm) (Penman/Monteith) and mean annual temperature (°C) in variousregions of Africa (Data from Le Houérou et al., 1993)

			Т	èmperatu	ure incre	ase assui	nptions	
Present rainfall	Present PET	Present	1	°C	2	C	3	°C
	(mm year ⁻¹)	1 1 00 0110	P/PET	Dec %	P/PET	Dec %	P/PET	Dec %
800	1200	0.66	0.63	4.5	0.59	10.6	0.56	15.2
600	1400	0.43	0.41	4.7	0.39	9.3	0.37	14.0
400	1600	0.25	0.24	4.0	0.23	8.0	0.22	12.0
200	1800	0.11	0.11	3.0	0.10	7.2	0.10	10.0
100	2000	0.05	0.048	4.0	0.047	6.0	0.045	10.0

 Table 5. Examples of Change in PET and P/PET ratio under various temperature increase scenarios

*Dec% = Percentage decrease in the P/PET ratio under the temeprature rise assumption considered.

Acacia tortilis (Forssk.) Hayne subp. raddiana (Savi) Brenan from the Negev and Sinaï, and on Pistacia atlantica Desf. from the northern Sahara of Algeria (Fahn et al., 1963; Shanan et al., 1967; Waisel & Liphschitz, 1968; Liphschitz & Waisel, 1973). In southwestern Europe, analysis of tree rings of Pinus nigra L. and P. uncinata DC. for the period between A.D. 1200 and 1980 shows clearly the cooler, moister period of the Little Ice Age, with greater variability and a maximum effect in the second half of the 17th century when temperature was c. 0.5° C lower than the Mediæval Optimum in that region. Since that time, temperature seems to be slowly growing and autumnwinter precipitations decreasing, with the exception of a small rise at the beginning of the present century (Creus & Puigdefabregas, 1983; Creus, 1992). Analysis of tree rings of Podocarpus falcatus (Thunb.) R.Br. and Widdringtonia cedarbergensis Marsh. in South Africa shows slow growth before A.D. 1600 and between 1870 and 1930, and faster growth between A.D. 1780 and 1870, and from 1930 onwards (Tyson, 1987). The difficulty with tree rings is that it is not always obvious, in spite of all precautions, whether the variation in width of the rings is related to variations in rainfall or in temperature or both. Variation could possibly be due to other causes, such as the thinning and felling of trees which boost the growth of the survivors by reducing competition.

Data from lake level fluctuations

Lake surface levels show wide fluctuations over the past 2000 years. Lake Chad, for instance, fluctuated far below its 1900–1950 mean level on six occasions between A.D. 1000 and 1990, but dropped only once below its present 278 m low level for some 25 years in the 15th century (Maley, 1989*a*,*b*). On two occasions during the last millenium, the surface level increased to its historical maximum of 284–286 m. High levels corresponded with the Mediæval Warm Period (800–1200 A.D.), while the Little Ice Age of Europe corresponded with alternately high and low levels (Maley, 1981, 1989*a*,*b*; Pouyaud & Colombani, 1989). Similar conclusions emerge from the study of the Dead Sea levels (Klein, 1961), and of the many lakes of East Africa (Street & Grove, 1979; Street-Perrott & Harrison, 1985; Street-Perrott & Perrott, 1990; Bonnefille, 1991, 1993) and of Southern Africa (Van Zinderen Bakker, 1978; Tyson, 1987).

Nature, causes, severity and extent of desertification: the respective roles of climate and human activities

General

According to the definitions mentioned above, desertification appears as land degradation under arid, semi-arid and dry sub-humid climates, whatever the cause, but land degradation occurs under all sort of climates. Some types of erosion and deposition are particular to WASAL (although dune formation, for instance, also occurs in humid climates under particular circumstances). Land degradation through salinity, water logging and faulty irrigation practices, albeit common in dry-lands and developing countries, is by no means restricted to these countries. Saline land occupies 10^6 km^2 (Dudal & Purnell, 1986) while 0.1% of the $2.4 \times 10^6 \text{ km}^2$ of land under irrigation is being lost annually due to secondary salinity, sodicity and water logging (Kovda, 1964, 1977, 1980, 1983).

Arid, semi-arid and dry sub-humid lands which, for one reason or another, are kept free from human and livestock interference, do not usually undergo any kind of degradation-desertification: there are many examples in all parts of the world (e.g. uninhabited areas, areas of difficult access, national parks and other private or public protected areas, lightly stocked ranches, etc.). A good example is provided by the Sahel. In several Sahel countries there are a number of state-owned ranches, established in the 1950s and 1960s, covering several tens of thousands ha each. These have been stocked according to rates determined by pre-investment surveys, based on the estimated long-term carrying capacity of the rangelands. As a consequence, these have undergone 25 years of drought without any visible long-term harmful consequences (Le Houérou, 1989*b*, 1992*a*; Achard & Chanono, 1995). During this time, virtually no year received the 1931-1968 mean annual rainfall. The 1969-1985 mean actually varied between 56% (Cape Verde) and 91% (Chad) of the 1950-1967 average (Morel, 1992; Le Houérou et al., 1993). Nevertheless, lightly stocked rangelands were almost undisturbed, and no desertification occurred. Desertification cannot therefore be ascribed to climatic conditions alone, nor to a worsening of them. It has been agreed (UNCOD, 1977) that desertification results from a combination of drought with human mismanagement of the land.

Can desertification occur without the impact of drought?

Drought is relative to the 'normal' or statistical average. Desertification may therefore result from land abuse alone, without drought. Similar land abuse results in comparable land degradation under humid climates. Desertification occurred in the Sahel as well as in North Africa during the 1950s and 1960s (Le Houérou, 1959, 1962*b*, 1968, 1969, 1977), in spite of the fact that rainfall was well above long-term average. During periods of high rainfall, grazing and cultivation are usually expanded to an extent that provokes desertification when the moist spell comes to an end (this does not necessarily mean 'drought', but simply the return to 'normal'). Most people have short memories, however, and tend to believe that favourable weather spells are 'normal', whereas records show that drought normally recurs in all arid lands.

Desertification is caused primarily by human abuse of the land, but adverse climatic conditions, including drought, may trigger or accelerate the phenomenon. The same conclusions can be reached from a study of central Asia (Rozanov, 1990; Babaev *et al.*, 1993; Kharin *et al.*, 1993; Kharin, 1994), from NW China (Zhu Zhenda & Liu Shu, 1983; Chao Sung Chiao, 1984*a,b*; Zhu Zhenda *et al.*, 1988; Zhu Zhenda & Yang Youlin, 1988; Yoshino, 1994*b*; Wang Lixian & Ci Long-Jun, 1994), East Africa (Lamprey, 1975; Lusigi, 1981; Oguntoyimbo, 1986; Warren & Agnew, 1988; Darkoh,

1989; Odingo, 1990; Grainger, 1990; Warren & Khogali, 1992; Muturi, 1994), from South Africa (Acocks, 1952; Roux & Vorster, 1987; Hoffman & Cowling, 1990; Palmer *et al.*, 1990; Dean & McDonald, 1994; Milton *et al.*, 1994; Hoffman *et al.*, 1994; Dean *et al.*, 1995), from Australia (Perry, 1977; Mabbutt, 1978, 1984, 1986; Pickup & Stafford-Smith, 1995), Southern America (Roig, 1975; Mabbutt & Floret, 1983; Soriano, 1983; Rostagno, 1994), Northern America (Sheridan, 1981; Sabadell *et al.*, 1982; Dregne, 1983), the Mediterranean Basin (Le Houérou, 1959, 1968, 1979*b*; Pabot, 1962; Pearse, 1970; Floret & Le Floc'h, 1973; Floret & Pontanier, 1982; Floret *et al.*, 1986, 1995; Bedrani, 1994), and the Sahel (Depierre & Gillet, 1971; Boudet, 1972; Le Houérou, 1989*b*; Le Houérou *et al.*, 1993) and SW Europe (Lopez-Bermudez *et al.*, 1984; Rubio, 1987; Lopez-Bermudez, 1990; Puigdefabregas & Aguilera, 1994). Direct and indirect causes of desertification can be distinguished.

Direct causes of desertification

The direct causes of desertification and arid land degradation, in general, stem mostly from drastic reduction or destruction of the perennial plant cover and simplification of the vegetation structure (one-layered open vegetation vs. multilayered closed patterns) (Le Houérou, 1959, 1968; WMO, 1983). Soil surface not protected by permanent vegetation becomes subject to erosion by water and wind, crusting by raindrop splash and trampling by animals, salinization by evaporation, and water logging in topographic depressions since water is no longer extracted by permanent vegetation. The causes are mainly the following (Le Houérou, 1995*a*, 1996): (i) reduction in the organic content of the soil due to a lower permanent biomass and decreased production of litter. (ii) Decreased organic matter reduces the stability of soil aggregates and thus renders the soil structure more fragile and prone to destruction. (iii) Unstable and poorly developed structure results in higher apparent density (compaction), lower porosity, lower permeability to air and water, lower water storage and reduced oxygenation. (iv) Lower permeability, water intake and storage result in increased edaphic aridity and hence reduced productivity. (v) Reduced organic matter and a fragile structure leads to soil surface crusting by raindrop splash which may increase runoff by 30-50% or more. This in turn reduces water intake in the same proportions, which again increases edaphic aridity. (vi) Decreasing organic matter content in the soil also results in lower biological activity from micro-, meso- and macroflora and fauna, and particularly symbionts. This in turn reduces the turnover of geobiogene elements (N, P, K, S, Ca, Na, Mg, Fe, Cu, Zn, Co, etc.) causing reduced fertility and therefore productivity. (vii) Lower water and nutrient availability causes lower fertility and productivity, hence lower biomass production and plant cover. The self-catalytic spiral of land degradation/desertification is thus set in motion. (viii) There may, in addition, be possible establishment of a biological crust of cyanobacteria and/ or lichens and mosses. This may drastically reduce soil permeability and boost runoff, leading to lower water availability and further erosion (Verrecchia et al., 1995). (ix) Greater runoff results in more frequent and more devastating flooding in topographic depressions, hence more water logging, more salinity, and more encrusting salinity. (x) Destruction of the permanent vegetation cover, particularly shrubs and trees and/or perennial grasses, reduces the shading of the soil surface and increases its temperature so that more evaporation takes place as soil surface temperature in WASAL may rise to over 70°C. (xi) Reduction or destruction of the perennial plant cover also decreases the rugosity of the landscape resulting in higher wind speeds at the soil surface and hence higher rates of evapo-transpiration and increased aridity.

All these combined causes and processes, as well as others, constitute a complex and intricate process of depletion. This is not fully understood, but the functioning of the

ecosystems is deeply affected (sometimes in an irreversible manner) and only the disastrous results are apparent. Many processes are individually well known and have been successfully modelled (i.e. validated) but the global misfunctioning of disturbed ecosystems still requires investigation, particularly in WASAL.

Indirect causes of desertification

Indirect causes are human activities that reduce or destroy vegetation cover thus provoking soil surface denudation for prolonged periods of time, and hence triggering or expanding water and wind erosion. They are the same all over the world under any climate type; they are generated by the ever-increasing pressure on the land from exponentially growing human and livestock populations without adapting management practices: clearing of land which is not appropriate for rain-fed cropping for reasons of climate, soil, topography, etc., over-cultivation, long standing continuous overgrazing and overstocking, water logging, salinization and sodization due to faulty irrigation, poor drainage, etc., expansion of dune fields and sand-seas, poorly planned or executed irrigation schemes and/or urbanization and communication systems, uncontrolled tourism development, excessive wood collection and deforestation. Most of these causes are shared by developing and industrial countries alike, albeit some are more common and detrimental in one category than in the other. These activities are not necessarily harmful per se, but their excessive intensity is at fault. The respective role of these various types of activities may change greatly from one region or country to another, as shown in Tables 6-13. The correlation between desertification hazards and the density of rural human and livestock populations is clear-cut in most developing countries; but is not necessarily so in industrial countries where no relationship seems to exist between rural population densities (inevitably low) and land management practices.

It should be noted, however, that the estimated percentages of desertification shown do not necessarily represent the importance of the economic loss because the nature of the land largely interferes; land desertification by secondary salinization or sodization, although representing a small percentage in absolute terms, are economically important because these are initially among the lands having the highest production potential, and which, in addition, have undergone heavy investments (in the vicinity of 10,000 US \$ per ha, or more, in 1995).

Wood collection, for example, is very important in many parts of the arid lands in developing countries of Asia and Africa where fuelwood often represents some 90% of family energy consumption among rural populations. There are regional differences, however; wood collection is mainly concerned with fencing in the Sahel, East Africa and the Kalahari (corrals, bomas, zeribas, grichas), and with both fuel and firewood in North Africa, the Near and Middle East and China.

Other regions have desertification patterns similar to those shown in Tables 6–8. The Middle East (Arabia, Iran, Iraq, Afghanistan, West Pakistan) exhibits a pattern similar to that of North Africa and the Near East, whereas NW India resembles more the conditions of the Sahel and East Africa. In southern Africa, the Karoo and Namibia have patterns closer to those of Australia, the western U.S.A. or Patagonia, while Botswana resembles East Africa more. In other words, land tenure, population density, cultural traditions and other socio-economic characteristics play key roles. The extent and severity of desertification in various continents are shown in Table 6 (Oldeman *et al.*, 1990; Le Houérou, 1992*a*; UNEP, 1992; Le Houérou *et al.*, 1993).

Tables 6–13 warrant some comments. Tables 8–13 refer more precisely to soil degradation *sensu stricto* than to desertification. These are not synonymous. Land, for example, may be chemically degraded by nutrient deficiency or exhaustion, without

NW China			Q		CONCEPTION				OHIO	
		45	16		18	6		¢.		14
N Africa and Near East	ar East	50	26		21	2 23		o ←		
Sahel and East Africa	drica	25	65		10	I		I		I
Middle Asia		10	62		I	6		10		6
U.S.A.		22	73		I	5		ذ		I
Australia		20	75		I	2		1		I
		Light*	Moderate	rate	Strong	лg	Ñ	Severe	Total**	*
Region	S	%	S	%	S	%	S	%	S	%
Africa	1180	6	1272	10	707	5	35	0.2	12860	56
Asia	1567	6	1701	10	430	3 S	5	0.1	16718	42
Australasia	836	13	24	4	11	0.2	4	0.1	6633	32
North America	134	2	588	8	73	0.1	0	0	7324	50
South America	418	80	311	9	62	1.2	0	0	5160	29
Total	4273	8	4703	6	1301	2.5	75	0.1	51691	39.7

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er UNEP, 1992)	Total Non v degradation Total	9996	13015	875 5758 6633	2002	6529	4369	10352 41339 51691
(10^3 km^2) (A)	Bio-industry	0		0	-1	0	0	2
Main causes of soil degradation in susceptible dry-lands (10 $^3~{\rm km^2}$) (After UNEP, 1992)	Over-exploitation	540	423	0	0	61	91	1115
of soil degradatio	Agriculture	622	967	48	183	414	116	2350
Table 8. Main causes (Over-grazing Agriculture	1846	1188	785	413	277	262	4771
Tab	Deforestation		1115		398		322	2106
	Region	Africa	Asia	Australasia	Europe	North America	South America	Total

Region	Aridity zones	Light and moderate	Strong and extreme	Total
Africa	Dry sub-humid	252	121	373
	Semi-arid	699	396	1095
	Arid	1052	223	1725
Asia	Dry sub-humid	706	77	783
	Semi-arid	1242	172	1414
	Arid	1319	188	1507
Australasia	Dry sub-humid	42	6	48
	Semi-arid	329	10	339
	Arid	489	0	489
Europe	Dry sub-humid	590	23	613
	Semi-arid	308	26	334
	Arid	48	0	48
North America	Dry sub-humid	150	32	182
	Semi-arid	509	23	532
	Arid	63	16	79
South America	Dry sub-humid	214	23	237
	Semi-arid	439	40	479
	Arid	75	0	75
Total		8976	1337	10352

Table 9. Degree of soil degradation by region in sensitive dry-lands (10^8km^2) (After UNEP, 1992)

strictly speaking being desertified. If the native vegetation or crops present were not well adapted to poor nutrient conditions, very large tracts of the Australian continent could be considered 'desertified'. This is absurd because Australia is perhaps the least spoiled of the continents, as can be seen in Tables 3, 6–13. The causes examined in Table 8 are not identical to those given in Table 6. Both, however, show that overgrazing and overstocking are the first and foremost causes of desertification and land degradation, in terms of the area affected. Second come cultivation and deforestation. The latter, as shown in Table 8, can be equated with fuel collection as shown in Table 6. (There is, generally speaking, little timber available in the arid, semi-arid and dry sub-humid zones, apart from artificially established woodlots.) Over-cultivation in Table 6 can be equated with agriculture in Table 8. These three causes,

 Table 10. Degree of water erosion in susceptible dry-lands (10⁹km²) (After UNEP, 1992)

Degree	Africa	Asia	Australasia	Europe	North America	South America	Total
Light	285	496	675	64	103	128	1751
Moderate	366	912	21	380	239	167	2085
Strong	515	167	0	14	42	52	790
Extreme	25	0	0	23	0	0	48
Total	1191	1575	696	481	384	347	4674

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Degree	Africa	Asia	Australasia	Europe	North America	South America	Total
Light	781	805	159	13	26	188	1972
Moderate	742	629	0	366	336	81	2154
Strong	66	07	1	0	16	0	180
Extreme	10	1	0	7	0	0	18
Total	1599	1532	160	386	378	269	4324

Table 11. Degree of wind erosion by region in susceptible dry-lands (10^9km^2) (After UNEP, 1992)

Table 12. Degree of chemical deterioration by region in susceptible dry-lands $(10^3 km^2)$ (After UNEP, 1992)

Degree	Africa	Asia	Australasia	Europe	North America	South America	Total
Light	102	222	0	15	3	101	443
Moderate	104	111	2	22	13	62	314
Strong	59	165	0	4	6	7	241
Extreme	0	4	4	0	0	0	8
Total	265	502	6	41	22	170	1006

Table 13. Degree of physical deterioration by region in susceptible dry-lands $(10^3 km^2)$ (After UNEP, 1992)

Degree	Africa	Asia	Australasia	Europe	North America	South America	Total
Light	12	44	2	48	2	0	108
Moderate	60	50	0	38	0	2	150
Strong	67	2	10	0	8	2	89
Extreme	0	0	0	0	0	0	0
Total	139	96	12	86	10	4	347

overstocking, deforestation/wood collection and over-cultivation, represent 89% of land degradation in Table 8 and 90% in Table 6. The global degree of consistency of these two independent estimates is amazing. The data in Table 6 are subjective estimates derived from long standing worldwide field experience, Tables 8–13 result from a detailed mapping exercise: the Global Assessment of Soil Degradation (GLASOD). This involved some 350 scientists from all over the world. The data were compiled by ISRIC (Oldeman *et al.*, 1990) for UNEP. The zonal surface area of drylands, in terms of global proportions, with absolute areas are given in Tables 2 and 3. They show that hyperarid zones constitute 7.5% of total land surface; arid zones constitute 12.1% of total land surface; semi-arid zones constitute 17.7% of total land surface; dry sub-humid zones constitute 9.9% of total land surface; cold (= montane and tundra) zones constitute 13.6% of total land surface; humid and hyper-humid zones constitute 39.2% of total land surface.

Dry-lands thus represent a total of 47.2% of the earth's land surface and 39.7% if one excludes the true climatic deserts (the Hyper-Arid Bioclimatic Zone). These, naturally, are not liable to further desertification (Tables 3, 6–8).

Some $19,644 \times 10^3$ km², i.e. 15% of the land surface of the earth, are subject to various degrees of desertification, but 32% of the dry-lands (61,473 \times 10³ km²) are undergoing processes of land degradation. If one discards the hyperarid zone, the proportion of land being desertified is 16% of the overall land area and 38% of the drylands. When the various processes of land degradation are considered globally, water erosion represents some 42% of the areas affected, wind erosion another 42%, physical degradation of the soil structure 3.5% and chemical deterioration (mainly salinization and sodization) 10%. These figures are computed from the ISRIC/GLASOD data. All the above processes are human induced (Oldeman et al., 1990; UNEP, 1992), but there are also cases of desertification being induced by natural causes such as river capture (e.g. the Niger river at Tosseye, east of Timbuctoo, during the Holocene) (Le Houérou, 1979a), the light subsidence and southward dip of the Niger Inland Delta, south and east of the Fala of Molodo, and the subsequent aridization of the Mema Plains, around A.D. 1100 (Le Houérou, 1979a; Haywood, 1981) etc. These, however, represent an infinitesimal proportion of the nearly 20 million km² affected by desertification.

Other causes originate in faulty technology, the so-called 'technogenic desertification' of Russian speaking authors. Typical examples include the Aral Sea Basin, the Niger River Inland Delta, the Gezira of Nile valley, etc. (Glasovsky, 1990; Mainguet & Glasovsky, 1992; Kharin *et al.*, 1993), and the Salton Sea area of SE California. Illplanned or poorly-executed water development schemes are a common-place cause of desertification (Le Houérou, 1994*b*). Land speculation, whereby land ownership is subject to a high turnover may also be a serious cause: each landlord tends to draw the maximum short-term profit before selling again. This occurs in parts of Patagonia, for instance (M.C. Rostagno, pers. comm., 1992).

The role of climate generally reinforces human action: climate is usually not, at present, the triggering factor, as it was during the geological periods of establishment of true climatic deserts. The expansion of desertification has been the subject of such speculation and of many emotional statements and publications. There are, in fact, few well scientifically documented cases. A few long-term studies by qualified scientists, in large areas and over several decades allow, however, scientifically sound conclusions. These include investigations carried out in central Asia by the Desert Institute of Ashgabat, Turkmenistan, the Desert Research Institute of the Academia Sinica in Lanzhou, China, the CEFE/CNRS-Montpellier team and its associates in southern Tunisia and North Africa (already 48 years of continuous field investigation), IEMVT and ORSTOM in the Sahel of Mauritania, Senegal, Mali, Niger, Chad and Burkina-Faso, IPAL/UNESCO in Northern Kenya, CONICET/IADIZA of Mendoza, Argentina, CONICET/CENPAT of Puerto-Madryn in Patagonia, Argentina, the

CONACYT/Institute of Ecology, Jalapa, Mexico, the University of Cape Town and associates in Southern Africa, CSIRO in Alice Springs, Australia, and a few others. These teams have, by and large, utilized the same techniques, i.e. remote sensing, notably with air photos and large scale satellite images (e.g. SPOT) taken decades apart, combined with detailed ground control and comparison with older vegetation, forest or range resources maps etc. These provide indisputable and quantified data over periods of nearly 50 years, since the first sets of aerial photo coverages for civilian purposes appeared in the late 1940s to early 1950s. These large scale, detailed studies came up with almost identical figures for central Asia, NW China, North Africa and the Sahel. The rate of desertification found in these areas in the 1960s to 1980s varied from 0.5 to 0.7% of the arid zone (Le Houérou, 1959, 1962b, 1968, 1976, 1979b, 1989b, 1992a; Depierre & Gillet, 1971; Floret & Le Flo'ch, 1972, 1973; Boudet, 1972; Long et al., 1978; De Wispelaere, 1980; Haywood, 1981; Gaston, 1981; Floret & Pontanier, 1982; Barral et al., 1983; Zhu Zhenda & Liu Shu, 1983; Chao Sung Chiao, 1984*a, b*; Peyre de Fabrègues, 1985; Vinogradov & Kulin, 1987; Grouzis, 1988; Aîdoud, 1989, 1994; Kadomura, 1989, 1992, 1993; Rozanov, 1990; Hiernaux, 1993; Kharin et al., 1993; Babaev et al., 1993; Kharin, 1994). All these investigations were carried out under truly arid conditions, with mean annual rainfalls of 150-450 mm. They could therefore be extrapolated to the same or similar aridity conditions, i.e. over some 16 million km^2 , worldwide. Assuming a conservative rate of expansion of 0.5%per annum we have an annual increment of desertified land of 80,000 km². Taking into account the fact that some 25% of the arid zone is already desertified, we find that almost all the arid zone will have become desertified within a century from now, if the rate of expansion that prevailed over the past 50 years continues. This stage could, however, be reached earlier if we take into account that the phenomenon is gaining momentum as the pressure on the land increases (Figs 4-6).

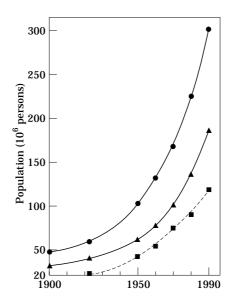


Figure 4. Evolution of the human population in northern Africa (\blacksquare), the Near East (\blacktriangle), and the two combined (\bullet) from 1900 to 1990. Sources: Various, including FAO yearbooks (Le Houérou, 1992*a*).

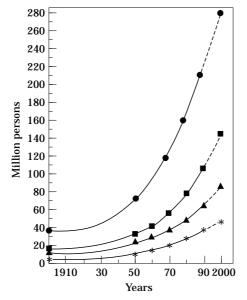


Figure 5. Human population increase in the arid lands of sub-Saharan Africa between 1900 and 1990. The data between 1900 and 1940 are estimates. Sources: Various, including FAO yearbooks (Le Houérou, 1992*a*). (\bullet) = African arid lands (south of the Sahara); (\blacktriangle) = Sahel; (\blacksquare) = Eastern Africa; (*) = Southern Africa; (- - -) = projections 1900–2000.

The role of land surface albedo

In 1974, J. Otterman, the Israeli physicist, formulated the hypothesis that degradation of the vegetation cover by increasing land surface albedo, reducing temperature and hence evaporation, could alter cloud formation and possibly rainfall over arid zones. A similar concept, known as the surface-albedo-desertification-biogeophysic-feedback hypothesis, was then taken up by J. Charney in 1975. It received broad acceptance as a possible explanation of the long standing drought in the Sahel. The idea was accepted at its face value by a number of physicists and modellers (Henderson-Sellers, 1980; Gornitz & NASA, 1985; Cunnington & Rowntree, 1986; Laval, 1986; Hulme, 1989; Lare & Nicholson, 1990); while others denied any such possibility of feedback (Jackson & Idso, 1975; Ripley, 1976*a,b*; Le Houérou, 1976; Idso, 1977, 1980*a,b*, 1989; Norton *et al.*, 1979; Courel *et al.*, 1984; Courel, 1985). Courel made an indepth study of the albedo feedback assumption as regards the Sahel (the grounds on which Charney based his ideas), and showed it was not tenable.

Williams & Balling (1994) made a thorough analysis of the literature on the biogeophysical feedback theory and concluded as follows: '...Numerical modelling studies and empirical measurements have shown both warming and cooling in areas that have been undergoing desertification... Only limited accuracy can be obtained in translating perturbations in the energy balance in dry land regions directly into local or regional temperature or precipitation... Numerical models are improving, but they remain relatively unrealistic...'.

The biogeophysical feedback theory of Otterman (1974) and Charney (1975) has never been indisputably validated. A large artificial body of water such as Lake Nasser, does not increase rainfall in the Nubian Desert, despite its very low albedo, over an area of 5000 km², contrasting with the very high reflectivity of the surrounding desert. Mean annual precipitation in Beer-Sheva was the same for the periods 1920–1948 and 1948–1990: 220 mm, as acknowledged by Otterman himself (pers. comm.). There are many similar cases in WASAL (Le Houérou, 1976, 1993).

Recent progress in drought prediction

Many attempts have been made over the past decade to link drought in various parts of the world with El Niño Southern Oscillation (ENSO) events. These have met with various degrees of success depending on the area concerned (Glantz *et al.*, 1987). Relationships between the 1982–83 ENSO, one of the strongest during the past 100 years, showed good correlations with drought in Australia (Nicholls, 1987; Allan & Heathcote, 1987), in Indonesia (Malingreau, 1987) and in western South America (Serra, 1987), while the correlation was negative with Japan (Yoshino & Yasunari, 1987). In other arid and semi-arid zones the relationship was dubious or had a low statistical level of significance. This included NE Brazil (Gasques & Magalhes, 1987;

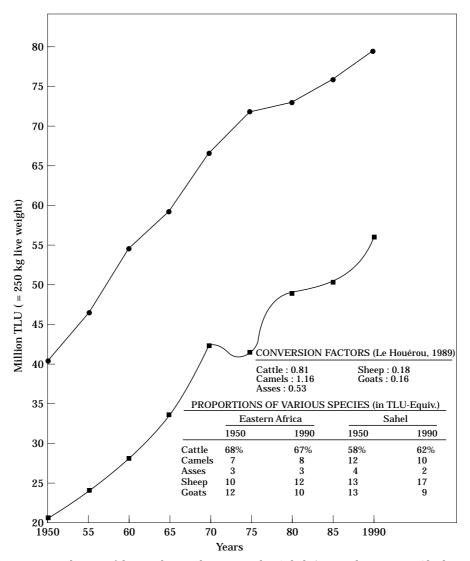


Figure 6. Evolution of livestock populations in the Sahel (\blacksquare ; Burkina Faso, Chad, Mali, Mauritania, Niger, Senegal, Sudan) and eastern Africa (\bullet ; Djibouti, Ethiopia, Kenya, Somalia, Tanzania, Uganda) between 1950 and 1990. Source: FAO yearbooks (Le Houérou, 1992*a*). TLU = tropical livestock unit (=2 normal 250kg liveweight Zebu, kept at maintenance).

Magalhes et al., 1988), India (Sinha, 1987), China (Wang Shao-Wu & Mearns, 1987), eastern and southern Africa (Ogallo, 1987; Tyson, 1980; Nicholson & Entekhabi, 1985; Nicholson et al., 1988). In the Mediterranean Basin the history of drought does not seem to be related to ENSO events. ENSO events occur at fairly regular intervals of some 6.4 years (13 events between 1900 and 1983). The mean period between two consecutive El Niño events is 6.4 years, with extremes of 2 and 12 years (Nicholls, 1987), while Mediterranean drought, particularly in North Africa and the Near East, is totally acyclic and unpredictable. No relation seems to exist between ENSO and the present 25 years of almost continuous drought in the Sahel (Rasmusson, quoted by Glantz, 1987). But there is a clear link between drought in the Sahel, sea surface temperature (SST) and upwellings in the Gulf of Guinea, in turn correlated with the Benguela current. The present drought corresponds with relatively high SST, particularly in the cool season. SST in the 1950s and 1960s was 0.3–0.5°C lower than in the 1970s and 1980s, while the average position of the St Helena high pressure centre moved NE (Lamb, 1977; Hastenrath & Lamb, 1977; Hirst & Hastenrath, 1983; Folland et al., 1986; Demarcq et al., 1988; Janicot, 1990; Janicot & Fontaine, 1990; Fontaine, 1991; Fontaine & Bigot, 1991; Mahé, 1993; Mahé et al., 1993). There seems to be a Southern Atlantic Oscillation (SAO) comparable to ENSO, with many similarities between the Humboldt and Benguela currents, their upwellings and the generation of coastal deserts. The situation in Southern Africa is particularly complex. There is a warm current in the east (Mozambique-Agulhas) and a cold current to the west (Tyson, 1980, 1987, 1990; Jury & Levey, 1993; Jury & Pathack, 1993). Other similarities are found in the northern hemisphere between the California and the Canary currents, their impacts on the climates of Baja California and south Morocco-Mauritania, and the flourishing fisheries in both.

In most WASAL, some droughts may, with various degrees of confidence and various time lags, be correlated with ENSO events: but not all droughts can be ascribed to ENSO, thereby making prediction difficult, if not impossible. Forecasts from SST and other parameters may be feasible in the future, but there is a long way to go before reliable drought forecasts become available. Even so, experience shows that for various political, administrative and other reasons, a reliable forecast is not necessarily followed by appropriate preventive action (Glantz, 1976; Le Houérou, 1992*a*,*c*, 1993).

Impact of drought and desertification on natural ecosystems and rain-fed crops

Consequences of geomorphology

Arid zones have always displayed a tendency to show rapid geomorphological change in response to relatively modest environmental changes. They may well therefore do so in the future, for instance in the Holocene history of lake and *wadi* systems in the Sahara, in the erosional and depositional arroyos of the American SW, or the reactivation of Pleistocene and Holocene clothed/fixed sand dunes in the Sahel and elsewhere (Mainguet & Canon, 1976; Mainguet, 1991; Coudé-Gaussen, 1991; Goudie & Middleton, 1992; Goudie, 1994). On the other hand, sand dune and clay dune (lunettes) deposition and dust (aerosols) transport may have an important impact, not only on the arid lands where they are generated but also several thousand kilometers away, changing the optical properties of the atmosphere and thereby influencing temperature and precipitation (e.g. Saharan dust in north Europe and the Carribean) (Carlson & Prospero, 1972; Morales, 1979; Middleton, 1986; Prospero & Nees, 1986; Pye, 1987; Coudé-Gaussen, 1991; Goudie & Middleton, 1992).

Drought and desertification

There are many differences between drought and desertification. Drought, being a normal feature of arid climates, is typically of a temporary nature usually leaving little permanent aftermath. It affects production, not productivity in the long-term. Desertification is the opposite; it has a long lasting effect with permanent and sometimes irreversible consequences on productivity. Desertification may be triggered by drought, but not necessarily so. It may occur, and has done in the past, in areas undergoing periods of higher than usual rainfall. This situation, however, implies that land abuse has steadily increased.

The impact of drought on natural ecosystems is essentially concerned with plant cover and biomass production, particularly among annual plants. Arid land perennials are much less affected on account of their deeper rooting systems and because of their anatomy and physiology; they are adapted to drought by xeromorphism and various physiological drought-tolerance mechanisms. For this reason, physiologists and ecologists call them drought-enduring species. Annuals, conversely, do not usually exhibit xerophytism, have short life cycles and, for that reason, are called droughtevading species. Drought reduces their number, ground cover (leaf area index) and phytomass; but when 'normal' weather conditions return they resume their usual role in the ecosystem, provided that the seed bank in the soil has not been depleted or exhausted. Some arid zone annuals have a very short life cycle (the tachytherophytes, Nègre, 1959) of only a couple of weeks or less. This appearance is called 'Aacheb' in the Sahara and 'Gizzu' in north Sudan (Baumer, 1968, 1987; Wilson, 1978; Le Houérou, 1987b). These may remain inconspicuous for many years and reappear when suitable rain falls. Dry-land annual crops (e.g. barley, sesame and millet) behave like native annual species: water shortage, i.e. drought, will reduce their size, their phytomass and they may not reach maturity, resulting in crop failure or low yields. But the seed bank is not then in the ground, it is in the farmer's barn. Perennial crops behave as perennial native plants if they are well adapted to the situation in which they are placed. Production may be reduced or eliminated, but the plant will usually survive; if the perennial crop is not well adapted to the environment to which it has been introduced, it may not survive drought.

Desertification, naturally, has much more profound and lasting effects. First, soil surface would have been affected by water and/or wind erosion and would therefore have become shallower and less able to store water and nutrients. Many perennials would have been eliminated by overgrazing, overbrowsing, fuel collection or land clearing for cultivation. At best, useful perennials would have been replaced by perennial weeds of no value either to humans or livestock. Nevertheless, these still may be of value for the protection of the soil surface against the forces of erosion. In the worst case, all perennials will have gone and the land surface left to wind and water erosion. The land may also be invaded by undesirable shrubs, such as mesquites or algarrobos (e.g. *Prosopis glandulosa* Torr.), the spiny cacti (e.g. chollas) in southern U.S.A. and northern Mexico, or the creosote bushes (*Larrea* spp.) of the Chihuahua 'desert' of Mexico and Monte province of Argentina.

Erosion rates of 200–300 tonnes ha⁻¹ year⁻¹ have been reported from several countries under such conditions (1 t ha⁻¹ year⁻¹ corresponds to a nominal abrasion rate of 0.07 mm of soil surface removal; a nominal abrasion rate of 1 mm equals about 15 t ha⁻¹ year⁻¹) (Fournier, 1960, 1972; Hudson, 1987; Lal, 1988; Roose, 1994). The soil surface, not being permanently protected, is eroded by running water, sealed and crusted by raindrop splash and thus made increasingly impervious. This leads to further runoff and more erosion (Valentin, 1985). Most nutrients and the macro- and microfaunas and floras of the soil die or are removed by water or wind, reducing the soil's ability to sustain plant growth (Le Houérou, 1995*a*, 1996). Soil surface sealing

and encrustation reduce water intake and result in a drier environment; a whole spiral of edaphic aridity is triggered which continues by a self-catalytic effect (Le Houérou, 1969; Floret & Pontanier, 1982, 1984).

The trend may or may not be reverted. When all the soft layers of the top soil have been removed, plant life becomes untenable through the dry season due to lack of water. As long as some soft top layers are present, the trend may be reversed by various methods. These include total protection and/or soil and water conservation techniques, contour pitting, furrowing, banking, etc. All these techniques are costly, including total protection which implies fencing and/or guarding the area.

Rain-fed cropping and agricultural production systems

The impact of drought and desertification on rain-fed cropping is important because these croplands occupy the most productive soils, usually devoted to subsistence staple food crops in the arid zones, and to food and cash-crops in the semi-arid and subhumid zones. Drought may mean famine where staple crops are concerned and lead to collapse of the society when events recur over several consecutive years. But desertification is worse as it results in emigration because the land cannot sustain the people who formerly lived on it. Production systems are dismantled and there are reports of farmers who have returned to nomadic pastoralism or, still worse, enlarged the slums around the main cities.

Rangelands and animal production systems

Nomadic production systems are more able to cope with drought if grazing lands in non drought-stricken country are within reach. Settled graziers may have mixed farming and livestock production systems. Therefore, because of greater flexibility, they can cope better with drought than farmers who own no stock and stockmen who do not farm. Rangelands, however, are usually second or third class quality land in terms of production potential and, therefore, more prone to the consequences of drought and desertification than farmland.

Wildlife and tourism

These are the rural activities least affected by drought, and even less by desertification. We are not aware of any report describing reduced tourism due to drought in national parks or game reserves, either in eastern Africa, in Southern Africa or in other WASAL where these activities are of great economic significance. Nevertheless, drought obviously has an important effect on wildlife numbers but perhaps less than in the case of livestock. The main reason why these activities are little affected by desertification is because they are usually managed rationally and the land stocked to carrying capacity. Consequently no desertification occurs, even when there is drought. Wildlife concentrations around permanent water may, however, provoke land degradation (e.g. by elephants in the Tsavo park of Kenya in the 1980s).

Socio-economic conditions

The socio-economic consequences of drought and desertification depend, to a large extent, on the type of economic system involved. In the large ranches of industrial countries such as U.S.A., Australia, Southern Africa or Argentina, drought and

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desertification are very serious to the ranchers and farmers. But, in these countries, there are various types of compensation so that drought and desertification are not a matter of life and death as they are in densely populated developing countries. The relative importance of drought and desertification tends to be inversely related to the development of the economy, to the GNP per capita, and directly related to the density of the rural population, its standard of living and demographic growth. Some of the traditional social systems of pastoralists used to achieve *de facto* population control through social structures and rules engineered over the centuries. These are illustrated by the age-group structure of the Boran of Kenya and Ethiopia and other social practices among the Masai, Tuareg and Kababish (Le Houérou, 1985). Unfortunately these have often become obsolete at a time they are most needed.

Differential impact of a possible warming

Rainfall amount and variability

GCMs differ widely in a given region and, naturally, between regions within WASAL, as pointed out by Parry *et al.* (1988), Parry (1990), Balling (1994*a,b*), Williams & Balling (1994) and Hoffman *et al.* (1994). Some GCMs predict a slight increase in rainfall variability, others not. Some indicate an increase in winter rain and a decrease in summer precipitation, others suggest the opposite. The resolution of GCMs is too broad for accurate prediction of rainfall. We shall therefore assume there will be no significant change, as occurred over the past 150 years, in rainfall patterns, amount and variability within WASAL for the next 50 years. Moreover, as we have seen, there is no overall trend in rainfall change over the past 150 years, unlike the trend that has taken place with temperature.

Temperature

In contrast to rainfall, there is good agreement between GCMs on temperature, although not on the seasonal distribution of the increase. Most GCMs reckon a 2-3°C increase in subtropical regions and 1-2°C in the intertropical zone, but only with a 50% confidence level. We may assume that temperature might increase by $1-3^{\circ}$ C in WASAL and that this increase would, in addition, be uniformly distributed throughout the year. The impact of a temperature rise on ecosystems and crops would be different in various ecological zones. In the intertropical lowlands, the differential impact would be slight if not negligible as low temperatures are usually not a limiting factor to plant growth and production. In the intertropical midlands and highlands the impact would be noticeable, native vegetation and cropping zones would shift upward and poleward by $1^{\circ}C \times (100/0.55) = 182$ m in altitude and 182 km in latitude, for each degree of temperature rise, the altitudinal lapse rate of temperature being 0.55°C for each 100 m of increase of elevation. The increase would be about the same for each kilometre in latitude at any given elevation on a continental scale (Idso & Quinn, 1983; Le Houérou, 1991). The shift in the intertropical zone would thus be 182-364 m upward and 182-364 km poleward, depending on latitude and elevation. An upward and poleward slide of vegetation belts would therefore take place. Lowland crops would thus be grown in the lower midlands and temperate crops would encroach on the tropical-alpine zone. In the Mediterranean and subtropical regions, the upward shift would be 364-546 m and the poleward slide would reach 364-546 km. Such shifts of the vegetation belts may actually be occurring in Patagonia where the temperature has increased by 0.5°C since the beginning of this century between latitudes 40 and 50°S (Labraga, pers. comm., 1994). The 'Monte' Biome of Northern Patagonia (Neuquen & Rio Negro), characterized by several species of creosote bushes (*Larrea* spp.), is thus likely to encroach into the Patagonian Subdesert Biome of Chubut, if this trend persists (Rostagno, 1994, *in litt.*), since the border between the two biomes is controlled by temperature (the annual isotherm of 13°C) (Cabrera, 1951, 1971; Soriano, 1983).

Such movements of thermal belts may have very important economic consequences on the expansion of cold-sensitive crops such as citrus, banana and avocado to areas such as parts of southern Europe, southern Asia, and southern and northern America where they cannot be grown at the present time. Vegetable crops would be little affected as they are mostly grown under controlled conditions (in greenhouses or under plastic sheets).

Temperature increase would also expand the growing/cropping season in cool arid lands (Great Basin, Central and Middle Asia, NW China, Tibet, Patagonia and the Andean Puna). In other areas where winter temperature is a factor limiting the length of the growing season (e.g. the tropical and subtropical highlands) this would, in most cases, be favourable. Over how long a period of time such shifts would take place is very difficult to predict. Most probably they would not occur abruptly, but by steps, and an increased frequency of formerly unusual events. Pollen analysis shows that a quick change may take a century or less, whilst slow evolution might need a millenium or more.

Potential evapo-transpiration and climatic aridity

As mentioned above, evaporation and transpiration, depending on the energy budget, necessarily increase with temperature (Tables 4,5). Statistical analysis of temperature and PET shows that each degree of temperature corresponds with 59 mm year⁻¹ of PET when calculated using the Thornthwaite formula (Holdridge & Tosi, 1967), and with 72 ± 5 mm year⁻¹ when calculated by the Penman standard equation. It would possibly reach 77.5 mm \pm 2.3 when evaluated using the Penman–Monteith formula or measured experimentally (Griffiths, 1972; Le Houérou, 1972, 1989a,b; Riou, 1980; Le Houérou & Popov, 1981; Le Houérou *et al.*, 1993). A temperature rise of $1-3^{\circ}$ C would therefore correspond with a PET increase of *c*. 72 to 232 mm year⁻¹. Thus, assuming no significant rainfall change would take place, the P/PET ratio, a generally accepted aridity index, would decrease by approximately 4 to 15% as shown in Table 5; see also Schneider & Rosenberg (1988) and McKenney & Rosenberg (1991). Such a temperature change, however moderate, would correspond with a significant increase in climatic aridity. The impact of increased aridity on natural ecosystems and crops would be moderate and in most cases manageable by improved agricultural and management practices including the selection of more drought-tolerant species and cultivars, shorter cycle annual crops, better tillage practices, soil conservation practices, more timely agricultural operations, more water-conserving tillage, more water-conserving crop rotation, and the utilization of water-efficient crops. In natural ecosystems such as rangelands, increased aridity could be mitigated using lower stocking rates and more balanced grazing systems, such as deferred grazing, the concurrent utilization of various kinds of stock species and breeds, game ranching, mixed stock-and-game ranching, and commercial hunting.

Edaphic vs. climatic aridity

There are large differences in water availability in soils within a given land system or landscape. These depend on topography, geomorphology, the nature of the soil and its depth, and the presence of runin or runoff. Many surveys show that water availability

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in contiguous soils on the same site may vary by a factor of 1 to 10 or even more (Le Houérou, 1962*a*; Floret & Pontanier, 1982, 1984). The actual distribution of soil water may thus be considerably modified by tillage and mulching practices, soil and water conservation techniques, runoff farming, water harvesting, *wadi* diversion and the like. Most of these have been known for some 3000 years in the Near and Middle East and also by some Amerindians. There are many techniques that could counteract a moderate increase in climatic aridity, but, naturally, they also tend to increase the cost of production and hence to change the conditions for the commercial competition of WASAL products. The option has then to be a compromise between what is technically possible and economically feasible.

Dry-land agriculture

Dry-land agriculture may or may not suffer from increased climatic aridity, depending on the technical skill of the farmers. In the intertropical lowlands, increased aridity would necessarily require more skill to achieve a given result in a given situation. But poorly skilled farmers living on subsistence crops would certainly suffer from more frequent crop failure, and the sustainability of the land would decline. But the situation would be different in cool and temperate arid lands and in the intertropical highlands where the combined effect of CO_2 , increased water-use efficiency (WUE), higher temperatures and expanded growing seasons would result in substantially greater plant production.

Irrigated farming

Irrigated farming would suffer least from increased aridity, even if water availability were reduced. Increased temperature would in many areas permit the introduction of new cash-crops, not utilized before because of their sensitivity to low temperatures. A doubled CO₂ content in the atmosphere would significantly enhance photosynthesis, particularly in C_3 species, and increase plant productivity, perhaps by a factor of up to one-third, as suggested by greenhouse and growth chamber experiments. A CO2enriched atmosphere would also increase WUE by perhaps another one-third. Improved irrigation practices (e.g. generalized drip irrigation and underground irrigation) may, on the other hand, save up to 50% water as compared with traditional or conventional irrigation systems. One may thus realistically expect a very large increase in irrigated agriculture production and productivity, not to speak of the expansion of controlled farming, crop genetic improvement and the expansion of winter crops that are much less demanding on water. Salt-tolerant crops and cultivars, allowing the utilization of water and soils which cannot be used in conventional farming, should expand substantially. Better water/land management might also reduce the rate of 0.1% of the 1 billion ha of world irrigated land annually lost to salinization, sodization and water logging (Kovda, 1964, 1977, 1980, 1983).

Carbon fertilization

The effect of a CO_2 -enriched atmosphere on photosynthesis and plant growth has been known for almost a century. More than a thousand laboratory and field experiments have been carried out on the subject over the past 20 years or so (Cure & Ackocks, 1986; Idso, 1989). The subject has two main aspects: (i) enhanced photosynthesis, plant size and overall productivity; and (ii) reduced stomatal conductance, transpiration, and improved WUE.

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Comprehensive reviews (Kimball & Idso, 1983; Kimball, 1985, 1986; Kimball *et al.*, 1993) point out that a doubling of CO_2 in the atmosphere from 330 to 660 p.p.m. in volume increases the harvestable yield of plants by an approximate average of 34% with a 95% confidence interval of $\pm 6\%$ for both herbaceous and woody species. It was first thought that C_3 plants would benefit more from CO_2 enrichment than C_4 and CAM species. More recent data show contradictory results, suggesting that this categorization might be simplistic. Moreover, some species are able to shift from one pathway to another (Beer, 1986). Most of the data available, however, comes from experiments carried out in growth chambers and greenhouses. But more recent field experiments seem to confirm boosted productivity (Oechel & Strain, 1985; Schneider & Rosenberg, 1988; Mooney *et al.*, 1991; Oechel *et al.*, 1995).

A word of caution, however, is in order at this stage. The increase in biomass resulting from a CO_2 -enriched atmosphere does not necessarily affect overall plant productivity in the same proportions as the final commercial product which is sought by the farmer (Bolin *et al.*, 1979; Lemon, 1983; Mortensen, 1983; Crane, 1985; Shugart & Emanuel, 1985; Morison, 1985, 1987; Houghton, 1986; Trabalka & Reichle, 1986). This is due to the fact that extra photosynthates from CO_2 enrichment may be allocated differently than under normal concentrations. The determinism governing allocation is poorly understood. It seems that plants grown under a CO_2 -enriched atmosphere tend to allocate more resources to structural compounds poor in N such as lignin, fibre, cellulose and starch (hence there would be taller plants, larger and thicker leaves etc.). The quality of commercial production might thus decrease in the case of some non-fibrous and non-starchy plant products such as some fruits and vegetables.

The second aspect of CO_2 increase relating to the reduction of stomatal conductance has also been known for decades (Morison, 1985, 1987; Cure & Ackocks, 1986). Stomatal conductance (i.e. water loss by transpiration) is reduced to an average 66% of normal conditions, without any significant difference between C_3 and C_4 species (Kimball & Idso, 1983; Schneider & Rosenberg, 1988). Thus a production increase of 1.33 and transpiration reduced by 0.66 would provide a theoretical boost to WUE by a factor of 1.33/0.66 = 2.02, in a $2 \times CO_2$ atmosphere (Idso, 1989).

Two questions then arise: (i) would increased productivity and WUE persist under conditions of water stress, and (ii) do these conditions apply to crops in open, natural ecosystems and native vegetation? Increased WUE enhances plant productivity under water-limiting conditions (Idso *et al.*, 1987; Schneider & Rosenberg, 1988). Some highly water-efficient species, however, such as maize, can scarcely withstand any water stress whilst others tolerate various degrees of water limitation, including sorghum, barley and millet, in that increasing order. Experiments on water-stressed native vegetation, such as the California chapparal in summer time, tend to show that both productivity and WUE are boosted by a CO_2 increase, even under water stress conditions (Jenkins & Oechel, 1991; Oechel *et al.*, 1995).

It would, however, be unwise to assume that a doubled concentration of CO_2 in WASAL atmosphere in the middle of the next century would double plant production in these regions. As the percentage of increase in WUE will, most probably, be greater than the increase in water demand stemming from a rise of about 5–15% in PET (depending on the temperature rise), the net global result would be beneficial. If higher productivity, increased WUE, expanded growing season and higher temperature are combined, one may reasonably expect an increase in plant productivity in the cool and temperate arid lands such as the Great Basin, Central and Middle Asia, NW China, Tibet, Patagonia, the Andean Puna and other tropical and subtropical arid highlands. In the subtropical and intertropical lowlands, plant productivity might increase to a limited extent, as long periods of water stress, high temperatures and very high PET remain permanent features and limiting factors in these regions, depending on bioclimatic aridity zoning from dry sub-humid to arid.

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Conversely, in sub-humid and humid climates with irrigated agriculture, CO_2 increase would be positive, particularly when combined with a temperature rise. This would expand the cropping season in both the temperate and subtropical regions as well as in the tropical highlands; but here we are not dealing with WASAL any more. One may also speculate on the possible change in competition between C_3 , C_4 and CAM species in WASAL in a $2 \times CO_2$ atmosphere, and therefore on the subsequent evolution of natural vegetation and particularly rangeland. This topic is extremely complex, however, and still poorly understood.

Productivity and variability

All productivity studies in WASAL show that range productivity, while affected by rainfall, is dependent on the dynamic status of the ecosystem. A good way to evaluate this fact is by using the concept of rain-use efficiency RUE (Le Houérou & Hoste, 1977; Le Houérou, 1984; Le Houérou *et al.*, 1988). The average world value, based on 1000 pairs of rainfall/production data in 80 series, is a RUE of 4.0 kg DM ha⁻¹ year⁻¹ mm⁻¹ with extreme values of 0.1 and 10.0, and a standard error of 0.5. Non-degraded ecosystems in desert and sub-desert conditions may have a RUE up to 4–6, particularly in sandy habitats. Degraded ecosystems may have a RUE of 0.1–2.0, even under conditions of fairly high rainfall. Productivity per unit of water available is therefore tied not only to aridity but also to ecosystem functioning and balance. An increase of aridity may not therefore necessarily decrease productivity per unit of water available if the increase in aridity is compensated for by better management and a healthier, more balanced and more efficient ecosystem.

Another useful notion for evaluating productivity, rangeland degradation and desertification is the production to rain variability ratio (PRVR). This is the quotient between the coefficient of variation of annual production and the coefficient of variation of annual rainfall (Le Houérou *et al.*, 1988; Le Houérou, 1992*b*). In non-depleted rangelands PRVR varies between $1\cdot2-1\cdot5$ (in a few cases, notably in runin depressions, PRVR may drop below $1\cdot0$). Annual primary production is therefore 20-50% more variable than annual rainfall. In depleted rangelands PRVR rises to $2\cdot0-3\cdot0$ and in desertified conditions, above 5. Not only does the overall production decrease dramatically, but its variability increases three- to five-fold when the land is desertified. This is one more outstanding difference between the impacts of drought and desertification.

Adaptive strategies for mitigating the impact of possible climate change, drought and desertification

General

In the worst case scenario, that is a rise of temperature of 3°C in WASAL by the mid-21st century, a moderate increase in climatic aridity due to a 5–15% drop in the P/PET ratio (Table 5) would be envisaged. Thus there could be a slide of the hyperarid zone into the arid, the latter into the semi-arid, and the semi-arid into the sub-humid zone. These encroachments would equate to a nominal loss of rainfall of some 15 mm year⁻¹ at the limit of the true deserts, 50 mm year⁻¹ at the upper limit of the arid zone and some 70 mm year⁻¹ at the upper limit of the semi-arid zone (Le Houérou, 1992*a*). Calculated for the Sahel and the arid zone of North Africa, from a latitudinal N–S lapse rate of 1 mm km⁻¹ (Le Houérou, 1980*a*), the areas affected would be *c*. 100,000 km² to the north of the Sahara and 385,000 km² to the south. The area affected would thus be about 10% of these arid zones (Le Houérou, 1992*a*). If we transpose these

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assumptions to WASAL, as shown in Tables 2 and 3, we would find that 1.3 million km^2 of sub-humid land would become semi-arid, 2.3 million km^2 of semi-arid land would be in the arid belt and 1.5 million km^2 of arid land would become hyperarid, i.e. 5.1 million km^2 out of a 51 million total, in the worse case scenario. As we have seen above, *edaphic aridity* might be reduced by increased plant productivity and WUE stemming from increased CO₂. This would be particularly true in temperate and cool arid lands where the temperature rise would, in addition, expand the length of the growing season.

Is desertification irreversible?

Irreversibility is arbitrarily understood as the inability of a degraded ecosystem to recover its pristine condition after a period of 25 years of total protection: one human generation (Floret & Pontanier, 1982). Irreversible situations are created when all soft material in the soil has been eroded by water or blown away leaving a bare, hard substrate such as calcrete, a gypsum or iron pan or hard rock on which no perennial plant can become established. There is, therefore, no direct answer to the question. Irreversible situations, e.g. tank tracks from World War II are still visible in the vegetation, 53 years later, in parts of Egypt (El Alamein), Libya (Bir Hakeim) and south Tunisia (Ksar Rhilane and Bir Soltane) in areas protected from grazing by mine fields or lack of water. Irreversibility is naturally more frequent when the environment is drier and the soil more shallow (Le Houérou, 1968; Floret *et al.*, 1986, 1995; Grainger, 1990).

Managerial adaptation in natural ecosystems and rangelands, restoration and rehabilitation

Adaptation to drought and desertification has challenged pastoralists, ranchers and farmers for centuries. The nomadic pastoralists have a drought-evading strategy whilst farmers and ranchers have a drought-enduring strategy. This includes methods of coping with different plants, water shortage, with infertile soils or with all three. The first category includes the adoption of a light stocking rate that preserves the dynamics of the ecosystem and its ability to recover after drought. Recent data show that the socalled proper-use factor (i.e. the proportion of range biomass herbivores are permitted to levy on an annual basis) is often in the vicinity of 25-30% in arid zones, rather than 40-50% as thought to be the case for decades on the basis of data and experience in temperate zones (Le Houérou, 1989b). Together with these tactics is the utilization of agroforestry techniques whereby fodder shrubs and trees, which can store large amounts of feed over long periods of time, are planted in strategic locations in order to provide an extra source of feed when drought strikes. Among these are saltbush (Atriplex spp.): North America, South America, South Africa, North Africa, the Near East, Southern Europe, Australia; the spineless fodder cacti (Opuntia spp.): North and South America, North Africa, South Africa, and Southern Europe; century plants (Agave americana L.) in the same areas as cacti; Australian wattles (phyllodineous acacias subgenus Racosperma), mesquites (algarrobos = Prosopis spp.), acacias (Acacia spp.) and other wood-and-fodder 'TRUBS' (trees and shrubs). These compensate for the disappearance of nomadism and transhumance, since permanent feed and water is ensured throughout the seasons without the necessity of moving away from the homeland, even when the range is dry and parched. This strategy constitutes a kind of 'drought insurance' (Le Houérou, 1994*a*).

Another strategy utilized in the U.S.A. and South Africa is ranching of game animals that are better adapted to dry conditions than livestock: cervidae, gazelles, various antelopes, Camelidae (vicuña, guanaco, llama), ostriches and other Ratites. There are at present over 20 million ha of game ranching in Southern Africa: South Africa, Namibia, Botswana, Zimbabwe (Le Houérou, 1994a). The utilization of stock species and breeds which are better adapted to dry conditions, such as Karakul and Dorper sheep vs. Merino and Angora goats, can be promoted. Many East African pastoralists (Somali, Rendille, Gabra, Samburu) have recently shifted from cattle husbandry to camel rearing in response to the deterioration of their environment as a result of an excessive number of cattle. Others (e.g. Turkana) have increased the proportion of goats to sheep. Another strategy is concerned with water use, the techniques of water harvesting, of river diversion, and runoff farming, which were in existence as early as 2600-2800 B.P. (Evenari et al., 1982). A third strategy to cope with drought and desertification is the application of soil conservation techniques: contour furrowing, pitting, banking, terracing and benching. Most of these techniques have been known to some ethnic groups and in some regions since time immemorial; yet they have rarely been extended outside their region of origin. But artificial range or pasture reseeding is usually not feasible either technically or economically in the arid zone sensu stricto, unlike the semi-arid and sub-humid zones. It would not do any good, anyway, unless the management of the range were improved and the causes of its deterioration discontinued.

Adapting land-use and farming systems, erosion control, runoff farming, and water harvesting

Some strategies and tactics of adaptation have been alluded to above. The overall strategy should be the development of multiple diversified systems including livestock production and game ranching, commercial hunting, various tourist activities including so-called green-tourism, runoff farming, poultry/rabbit production and non-agricultural activities such as handicraft. These activities are developed in a number of countries including the dry-lands of the U.S.A. (west of 100° W), Australia, South Africa, Namibia, Botswana, Zimbabwe, Kenya and Tanzania. They could well be developed elsewhere, but this may require a strong political will, government incentives and appropriate legislation.

The technique of runoff farming dates back nearly 3000 years in west China, Iran, south Arabia, Yemen, Jordan, North Africa and Spain as well as in the pre-Colombian Andes and northern Mexico. But, as mentioned above, they have scarcely been used outside their region of origin; they are virtually unknown in sub-saharan Africa and large parts of the Americas (with the exception of the Andean highlands and the SW U.S.A. and NW Mexico). As they are very demanding in labour, they are being abandoned in countries such as south Tunisia, Libya, north Egypt, Yemen, Iran and SW Europe where they have been in use for centuries.

The technique of water harvesting was extremely well developed in the Near East and North Africa during Roman and Byzantine periods (200 B.C. to 650 A.D.). Some structures are still in operation or could be developed again within and outside these regions and in parts of Latin America where they have not yet been used. These techniques are not operative under all conditions. For instance, they could not be developed in most parts of the Sahel on account of the nature of the terrain and the climate (9–10 months of continuous annual dry season with an evaporation rate of 2–3 m year⁻¹).

Water saving; utilization of water-efficient and drought-tolerant crops, of drainage and other waste water

In most arid and semi-arid countries water is frequently wasted, particularly in agriculture, due to over-irrigation, poorly designed canals and inefficient irrigation systems. The percentage of wasted water often reaches 50%. Such waste is easy to prevent by adopting appropriate techniques of channelling and irrigation. Saving may also be encouraged by appropriate water rights and fees. Water will continue to be a rare commodity, not only in WASAL, and may be the cause of warfare between upstream and downstream countries, and over the utilization of particular aquifers. In many countries, including industrialized ones, most of the resources are already being tapped to their maximum sustainable level and sometimes beyond in the case of both shallow water tables and deep aquifers. Future developments in many countries will have to come primarily from savings.

Another way to save water is to utilize plants which are water-efficient and to develop winter-growing crops. Alfalfa, for instance, is extremely water-demanding. It requires 700 to 1000 kg of water to produce 1 kg of dry fodder, while other fodder crops may use only 25 to 30% of that for the same yield. They include millet, barley, saltbushes and cacti, and in the case of agave much less (10-15%) is required (Nobel, 1988; Le Houérou, 1994*a*). Again, winter crops consume much less water than summer crops as PET in winter is only a fraction of the summer amount.

Although drainage water has a high concentration of salts, it can be used to grow salt-tolerant crops. Some of these, such as asparagus, are cash-crops, others, such as sugar beet are industrial crops. Drainage water may also be used to grow timber and fodder. Some timber and fuelwood species produce high yields with water having half the salt concentration of sea water, as so do a number of fodder crops such as saltbush, fleshy sainfoin, tall fescue, strawberry clover, sweet clover and the like (Le Houérou, 1986). Using saline water requires skill, in particular perfect drainage. It can, therefore, only be utilized under specific conditions of soil and topography. The side-effects of CO_2 enrichment also have to be taken into consideration, although it seems that CO_2 increase enhances salt-tolerance (Idso, 1989).

Given rapid urbanization and the large amounts of water required, recycling of effluents and their use in agriculture will have to be pursued energetically over the next decades. The process has been initiated in a number of countries but currently seems to be developing rather slowly.

The role of agrofestry

Agroforestry may play an extremely important role in WASAL development and in policies against desertification (Le Houérou, 1980*b*; Baumer, 1987; Le Houérou & Pontanier, 1987; Joffre & Rambal, 1990). Agroforestry techniques have been developed for time immemorial in some rural civilizations such as Kejri (*Prosopis cineraria* (L.) Druce) in NW India (Rajasthan) (Mann & Saxena, 1980; Tejwani, 1994), *Faidherbia albida* (Del.) A.Chev. in intertropical Africa (Charreau & Vidal, 1965), saltbush throughout the world (Le Houérou, 1992*c*), *Argania spinosa* (L.) Skeels in SW Morocco, evergreen oaks (*Quercus ilex* L. and *Q. suber* L.) in the Dehesa of Spain and in the Montado of Portugal, Espino (*Acacia caven* Mol.) and Algarrobo (*Prosopis* spp.) in Latin America (Aronson *et al.*, 1994). They may permit high rural population densities in arid zones e.g. 60–80 rural people km⁻² with the millet/*Faidherbia* system in the south Sahel, similar densities in the Rajasthan with the millet/*Prosopis cineraria* system and in south Morocco with the barley/*Argania* system (under 150–300 mm of mean annual rainfall, and almost no irrigation for the latter region).

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Agroforestry should therefore be an integral part of any dry-land development strategy for a sustainable agriculture. These development endeavours should include village woodlots which, when located in strategic situations, on deep soils benefitting from some runoff, may produce very high yields as long as the right species of tree is selected, then rationally managed. Such woodlots could and should be an important part of the combat against desertification, since fuel-wood collection and feed shortage are among the major causes of land degradation in many developing countries.

Energy efficiency and savings

As fuel-wood collection and deforestation are a major cause of desertification, energy saving ovens are being developed and popularized in some countries, as well as solar energy appliances, windmills and biogas devices. All these should be encouraged. But progress is desperately slow as it always takes a long time before people relinquish their old habits and traditions, which, at times, conflict with new technology and devices. It is a duty, and should be a policy, to provide incentives to speed up the necessary changes.

Multiple land-use and income-diversification, sustainable development policies

As suggested above, drought mitigation, sustainable development and the struggle against desertification are various facets of the same thing (IPED/INCD/ICCD, 1994). Development policies should aim at sustainable agriculture. This includes education and social security in order to discourage large families. The core cause of desertification is extreme pressure on the land resulting from high demographic growth, often 3% per annum and up to 4% in some cases (which correspond to a doubling period of 23.3 and 17.5 years, respectively). Any sustainable development strategy should therefore include an education programme aimed at reducing demographic growth. Sustainable development with high demographic growth cannot be supported by agriculture alone, and the extra rural population generated in WASAL must move to industry and services. Sustainable development is thus a package deal that needs a fast growing economy to absorb most of the population growth. But this may remain a pious wish for the foreseeable future in countries where the population grows faster than the economy.

Conservation and biodiversity

WASAL harbour many species of plants and animals which are useful to mankind and may be the wild relatives of crop species and domesticated animals. Moreover, a number of native plants contain chemical molecules with potential use in industry and health services. Due to the fast expansion of desertification, many of these are either endangered or soon will be. The best, if not the only, way to preserve this biological capital for the benefit of mankind is by *in situ* conservation projects. Most people would agree on this; but conservation is expensive, particularly in areas where the demand on the land is acute because of high demographic growth. Most of the national parks and reserves established in Africa and Asia in the 1950s and 1960s could not be established today because the pressure on the land has increased so much. On the other hand, most developing countries have not the resources to develop or even manage such conservation projects, because there are many more pressing issues and priorities on their budgets. The only possible solution appears to lie in co-operation with and financing by industrial countries.

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Conclusions and recommendations

Desertification continues to progress at a steady pace while anti-desertification programmes have achieved little. New political committment by the countries concerned, channelled through the ICCD, could improve the situation in the not too distant future.

Would any climatic fluctuation or change of a warming earth change anything in WASAL? A climate change of the magnitude envisaged in most GCM models would hardly alter the situation in intertropical arid lowlands by the year 2050 because climatic factors play a relatively minor role there, as compared with human activities. The P/PET ratio would decrease by about 5% for each 1°C of mean temperature rise and climatic aridity would therefore worsen. On the other hand, some compensation would come from carbon fertilization and improved WUE and, perhaps, some increase in the drought and salinity tolerance of agriculture crops. The temperate and subtropical arid lands (above *c*. lat. 40°) and the intertropical highlands may undergo substantially improved primary productivity due to the combination of enhanced photosynthesis, greater WUE, higher temperature and expanded growing season. Irrigated farming would become substantially more productive as a result of CO_2 increase, enhanced WUE, more salt-tolerant plants and new technical and biological developments including generalized drip irrigation and new cultivars of crops.

Desertification could probably be prevented in industrial countries and cured by legislation. The Australian type of legislation (e.g. long-term lease of state-owned land, subject to monitoring) could be a source of inspiration in this respect. In the U.S.A., the Taylor Grazing Act, passed in 1934, immediately after the dust bowl phenomenon, resulted in a considerable improvement of the U.S. public rangelands. In developing countries, desertification could be prevented and cured **if** the demographic growth were lowered and **if** the other sectors of the economy could absorb the surplus of the dry-lands population, which is often not the case. These are two big **ifs** that many developing countries could scarcely overcome in the next few years. But some of them are changing: demographic growth rates have been drastically curbed in countries like Mexico, Tunisia and Turkey over the last 20 years (dropping just below 2%). One may hope that other countries will follow suit.

Sustainable and diversified development is the key to combat desertification. Any climatic change of the envisaged magnitude would have little bearing on the situation. In the worse case scenario, about 10% of the various bioclimatic zones within drylands would retrogress into the adjacent climatically drier belts; but the worst is never predictable, as the proverb goes. Warming would, most probably, be beneficial in the semi-arid and sub-humid zones, in the intertropical highlands and in the temperate and subtropical lowlands where the increased temperature would expand the growing season and, in some cases, allow for the introduction of frost-sensitive cash-crops.

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Symbols and acronyms

A.D. = *Anno Domini*, i.e. of the present era

AGRHYMET = Centre for Agriculture, Hydrology and Meteorology, WMO/FAO/ UNDP. Niamey, Niger

Albedo = Reflectivity

A S O = Atlantic Southern Oscillation

B C = Before the present era (= Before Christ)

B.P. = Before Present, i.e. before A.D. 1954

CCDD = Climate Change, Drought and Desertification

CEFE = Centre d'Ecologie Fonctionnelle et Evolutive L. Emberger, Montpellier, France

CENPAT = Centro Patagonico, (of the CONICET), Puerto-Madryn, Chubut, Argentina

CILSS = Comité Inter-Etats de Lutte contre la Sècheresse au Sahel (Ouagadougou, Burkina-Faso)

CNRS = Centre National de la Recherche Scientifique, France

CONACYT = Consejo Nacional de Investigaciones Científicas y Tecnicas, Mexico

CONICET = Consejo Nacional de Investigaciones Científicas y Tecnicas, Argentina

CSIRO = Commonwealth Scientific and Industrial Organization, Australia

DL = Dry-lands (= hyperarid, arid, semi-arid and dry sub-humid bioclimatic zones)

DTFS = Drought Tolerant and Water Efficient Fodder Shrubs

ENSO = El Nino Southern Oscillation

FAO = Food and Agriculture Organization of the United Nations

GCM = Global Circulation Models

GDP = Gross Domestic Product

GLASOD = Global Assessment of Soils Degradation

GNP = Gross National Product

hPa = Hectopascal = Millibar

IADIZA = Instituto Argentina de Investigaciones de las Zones Aridas, Mendoza

ICCD = Intergovernmental Convention to Combat Desertification (Paris, 1994)

IEMVT = Institut d'Elevage et de Medecine Vétérinaire des Pays Tropicaux, France

INCD = Intergovernmental Negotiating Committee for a Convention to Combat Desertification

IPAL = Integrated Project in Arid Lands (UNESCO)

IPED = International Panel of Experts on Desertification, within INCD

ISRIC = International Soil Reference and Information Center (Wageningen, The Netherlands)

MEWO = Mediterranean East-West Oscillation

ORSTOM = Office de la Recherche Scientifique et Technique d'Outre-Mer, the Institut Français de la Recherche Scientifique et Technique pour le Développement en Coopération, Paris

P = Long-term mean annual precipitation

- PE = Potential evaporation
- PET = Potential evapo-transpiration
- PRVR = Production to Rain Variability Ratio (coefficient of variation of annual production/coefficient of variation of annual rainfall)
- RUE = Rain-use efficiency (primary production kg DM ha⁻¹ year⁻¹ divided by rainfall mm year⁻¹)
- SAO = Southern Atlantic Oscillation
- SPOT = Satellite Pour l'Observation Terrestre, CNES = Centre National d'Etudes Spatiales Toulouse, France
- SST = Sea Surface Temperature
- TRUBS = Trees and shrubs
- UNCED = United Nations Conference on Environment and Development (Rio de Janeiro, 1992, Agenda 21)
- UNCOD = United Nations Conference on Desertification (Nairobi, 1977)
- UNDP = United Nations Development Programme, New York
- UNEP = United Nations Environment Programme, Nairobi
- UNESCO = United Nations Education Science and Culture Organization, Paris
- UNSO = United Nations Sahel-Sudan Office
- WASAL = World arid and semi-arid lands
- WMO = World Meteorological Organization of the U.N., Geneva
- WUE = Water-use efficiency (units of DM produced per 1000 units of water evaporated and transpired e.g. mg g^{-1} , g k g^{-1} , kg t^{-1})

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