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Agrometeorological aspects of agriculture and forestry in the arid zones

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Abstract

The arid zones of the world are all characterized by a large deficit of rainfall in relation to the potential evapotranspiration. Their distribution around the world is governed by the interaction of global atmospheric circulation patterns, the distribution of land and sea, and local topography. Countries that have substantial areas with arid conditions belong to very different groups in terms of resource availability, agricultural productivity, population density and wealth. Most are poorly endowed with good agricultural land. Water resources vary tremendously, both in terms of reserves and consumption. Agriculture is in most cases the main consumer of water. Most arid zone countries have high population growth, and rural population densities are generally much higher than overall population densities. They have a wide disparity in wealth. The arid zones have a surprising diversity of agroecological niches, with edaphic conditions that can deviate substantially from those of surrounding areas. These niches often have a higher biomass or agricultural productivity. At the same time they are vulnerable to natural processes such as primary salinization, wind and water erosion. Increasing pressure of human and livestock population make that these natural environmental stresses lead to accelerated degradation and depletion of soil and water resources. As they exploit the various agroecological niches, the production systems of the arid zones are equally diverse, and cover the full spectrum of land use intensification from pastoral or transhumant livestock systems to rainfed or irrigated cropping systems. These production systems show rapid change under the pressures of environmental degradation, increasing land and water shortage, and the needs of expanding populations. With the exception of irrigation management, the agrometeorological needs of the arid zones have been insufficiently addressed in the past. Perceptions of homogeneity, low agricultural potential, low population density and the logistical problems of providing maintenance and collecting data from remote stations are largely to blame for this situation. Agrometeorological research can have a positive impact on the productivity, resource-efficiency and environmental sustainability of the arid zones by supporting a better characterization of the agricultural environments. Research targeted towards data spatialization and integration of meteorological and remote sensing information will help to alleviate the handicap of sparse meteorological data networks. At the same time these networks will need to be improved through installation of automatic stations and by establishing new partnerships with land users. © 2000 Elsevier Science B.V. All rights reserved.

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1. Arid zones of the world

The term ‘arid’ in the English language is synonymous for ‘dry’. Possibly this is one reason why these terms are often used as interchangeable, not only by the general public, but by scientists as well. ‘Terms like desert, drought, dryland, desertification, semi-desert, sahel, steppe, arid, semi-arid, dry sub-humid have been variously and loosely used, understood, and defined by different people and by scientists’ (Noin and Clarke, 1998).

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It is therefore not surprising that this situation has led to considerable confusion in international agricultural research planning. For example, the International Center for Agricultural Research in the Dry Areas (ICARDA) still defines its 'dry' mandate region as one where the growing period is less than 180 days (ICARDA, 1996). This, of course, seems a fairly generous interpretation of dryness.

To avoid such confusion in what constitutes 'dry' or 'arid' regions, and to allow a better agroclimatic characterization of these regions, UNESCO (1979) has proposed a worldwide classification of the arid zones of the world. The latter is based on the value of the ratio of annual precipitation to annual potential evapotranspiration, calculated by the standard Penman method (see Table 1).

This classification has been widely adopted as an international standard. Its major advantage, apart from the standardization of terminology, is that the degree of aridity can be assessed by a simple relationship between rainfall and reference water demand, which is more appropriate than using absolute rainfall amounts.

The elements needed to classify an area into one of these four categories are easily obtainable from the many world meteorological databases.

By necessity, the UNESCO classification is macro-scale and low resolution, and is unable to capture the fine detail of landscape-climate interactions, which, as will be discussed later, are of such fundamental importance in the arid regions. According to this classification, rainfed agriculture is only feasible starting with the semi-arid zone, and then only with great yield fluctuations as a result of rainfall variability (Table 1).

This interpretation of the land use potential of the arid zones is relatively restrictive and, while correct at macro-scale, leads to contradictions at meso-scale. Firstly, it is contradicted by the evidence that cereals and legume crops are grown at the upper limit of the arid zones (300–350 mm) under winter rainfall. It is for this reason that some authors have raised this upper limit. For example, Le Houérou (1993) puts the upper limit of the arid zone at a P/PET ratio of 0.28, or an annual rainfall of 400 mm.

Table 1
UNESCO classification of the arid zones of the world

Zone	P^{a}/PET^{b} ratio	Characteristics
Hyper-arid zone	<0.03	Very low and irregular rain which may fall in any season Interannual variability of rainfall can reach 100% Almost no perennial vegetation, except some bushes in river beds; annual plants can grow in good years Agriculture and grazing are generally impossible
Arid zone	$0.03<P/\mathrm{PET}<0.2$	Annual rainfall of 80–150 mm up to 200–350 mm Interannual rainfall variability 50–100% Scattered vegetation including bushes, small woody, succulent, thorny or leafless shrubs Very light pastoral use possible, but not rainfed agriculture
Semi-arid zone	$0.2<P/\mathrm{PET}<0.5$	Mean annual rainfall from 300–400 to 700–800 mm in summer rainfall regimes, and from 200–250 to 450–500 mm in winter rainfall regimes. Interannual rainfall variability 25–50% Steppe zone with some savannas and tropical scrub Sometimes good grazing areas and rainfed agriculture is possible, although with great yield fluctuations due to great rainfall variability
Semi-humid zone	$0.5<P/\mathrm{PET}<0.75$	Interannual rainfall variability is less than 25% Includes tropical savanna, maquis and chaparral, steppes, etc. Agriculture is the normal use

[a] P: annual rainfall.

[b] PET: annual potential evapotranspiration.

Secondly, the relationships established by Le Houérou et al. (1993) between the annual precipitation/potential evapotranspiration ratio and the length of the rainy season, would indicate for the upper limit of the arid zones a maximum length of rainy season, according to the particular climatic regime, of 67–90 days. If one considers the role of soil moisture, which may add to the available growing season, rainfed agriculture appears therefore feasible at the upper rainfall limit of the arid zones, although with severe constraints.

In this paper, the agrometeorological aspects of the 'hyper-arid' and 'arid' areas will be discussed.

2. Geography of the arid zones of the world

At the most generic level arid conditions are created by the interaction between global atmospheric circulation patterns, the distribution of land and sea and the local topography.

The air that is heated at the equator rises and cools, loses its moisture in the tropical belt, subsides towards subtropical latitudes 30°N and 30°S and heats up, creating two subtropical high pressure belts from which trade winds blow hot and dry air back towards the equator (Ahrens, 1993).

Where the trade winds blow overland, they are responsible for the major desert belts and arid fringes of the world. To this category belong the Sahara, the Arabian and Iranian deserts in the Middle East, the Turkestan desert in Central Asia, the Namib and Kalahari deserts in southern Africa, the Australian desert and the Atacama-Peruvian desert in South America (UNESCO, 1953).

On the other hand, where the trade winds blow onshore, such as on the east coasts of Africa, South America and Australia, they bring moisture and preclude the existence of arid conditions.

Other arid zones, such as the Gobi and Takla Makan in Central Asia, are created simply by their central position within a huge landmass, which isolates them from oceanic sources of moisture (Fig. 1).

Outside the subtropical belt extensive arid belts may occur within the high latitudes as a result of rain-shadow effects. They are typically located on the leeward side of huge topographical barriers. This is the case for the North American and Patagonian deserts which are in the rain shadows respectively of the Sierra Nevada and the Andes.

As will be discussed later, topography is a key factor determining arid conditions at finer resolution and the diversity of agrometeorological conditions within the arid zones.

The arid zones are unevenly distributed across countries. Given the physical principles that govern the occurrence of aridity, countries in subtropical belts are more prone to arid conditions. However, there is no simple way to classify countries into either humid or arid groups.

A summary inventory of countries with a substantial share of arid zones is shown in Table 2. This table, derived from the UNESCO World Map of Arid regions (UNESCO, 1979), evidences the extent of aridity across the globe in terms of affected countries and land surface.

This table also indicates that it is difficult, if not impossible, to put entire countries within a single classification unit. In most cases, arid countries are composed of areas with different degrees of aridity. This has important consequences for economic development. In countries where a complementary mix of different climatic zones exists, a higher diversity of agricultural production systems is possible, and compensation for the physical constraints related to aridity, as compared to countries where arid zones dominate. In the latter case the contribution of agriculture to the national economy is by necessity limited.

3. Development indicators for arid zone countries

Table 3 summarizes some relevant indicators related to land and water resources, agricultural production, population and wealth for the countries that have at least 20% of their land surface classified as 'very dry areas' according to the FAO soil criteria 'occurrence of Xerosols and Yermosols' (FAO, 1995). These countries are henceforth labeled 'arid zone countries' (AZCs).

3.1. Land resources

Most AZCs have a low proportion of cropland, in the majority less than 10%. Where cropland is more

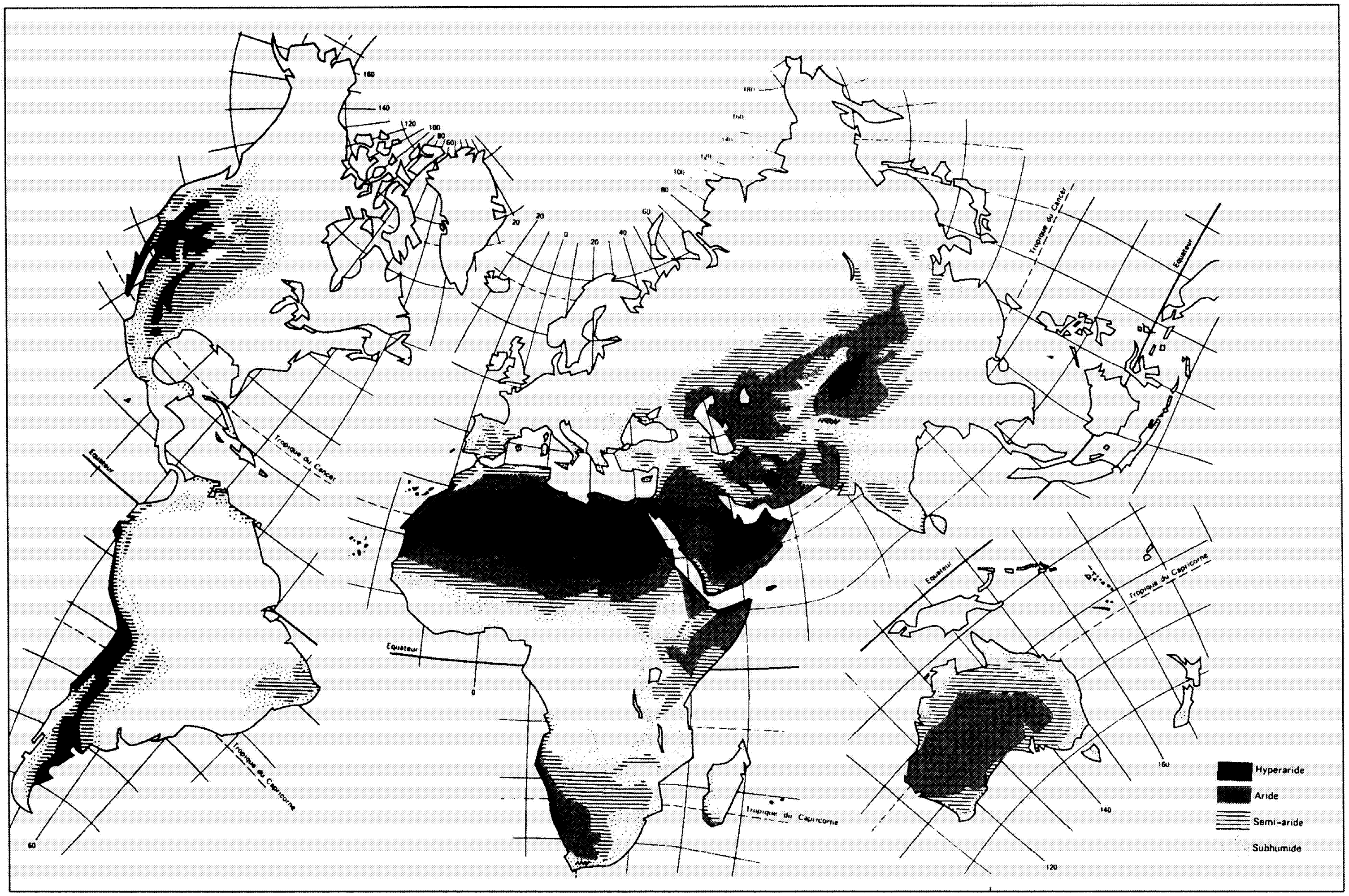

Fig. 1. Distribution of arid zones (from UNESCO, 1977).

Table 2
Countries with arid zones[a]

Continent	Country	Degree of aridity[b]					Very dry areas[c]	
		HA	A	SA	SH	H	Sq. km	%
N. America	Mexico		In	As	Do	As	329000	16.8
	USA	In	In	As	As	Do	901000	9.5
S. America	Argentina		As	As	As	As	701000	25.2
	Bolivia		In	In	In	Do	71000	6.5
	Chile	As	As	In	In	As	126000	16.5
	Colombia				In	Do	10000	0.9
	Ecuador			In	In	Do	2000	1.0
	Paraguay			As	As	Do	14000	3.5
	Peru	In	In	In	As	Do	13000	1.0
Africa	Algeria	Do	As	As		In	1245000	53.8
	Angola		In	In	As	Do	65000	5.2
	Botswana			Do			63000	11.0
	Chad	As	As	As	As	In	161000	12.5
	Egypt	Do	In				508000	50.9
	Eritrea	As	Do	As				
	Ethiopia		As	As	As	As	226000	18.1
	Kenya		As	As	In	As	92000	15.5
	Libya	Do	As	In		In	1162000	71.9
	Mali	As	As	As	As	In	218000	17.4
	Mauritania	As	As	In			733000	69.8
	Morocco		As	As	In	In	110000	26.9
	Namibia	As	As	Do			247000	30.2
	Niger	As	As	As			283000	23.9
	S. Africa		As	As	As	As	155000	12.8
	Somalia	In	Do	As			256000	40.1
	Sudan	As	As	As	As	As	511000	20.5
	Tunisia		Do	As		In	72000	46.9
Asia	Afghanistan		As	As	As	In	236000	36.9
	Azerbajan		Do	As			36000	44.9
	Bahrain		Do					
	China	As	As	As	As	Do	1192000	12.7
	India		In	As	As	As	145290	4.9
	Iran	In	Do	As	As	In	774000	47.7
	Iraq		Do	As	As		217000	50.3
	Israel	As	As	As			6000	29.9
	Jordan	In	Do	In			50000	55.6
	Kazakstan		As	As	In		1449000	53.4
	Kyrgyzstan			As	As	As	21000	10.3
	Kuwait		Do				13000	72.3
	Lebanon			Do			1000	11.4
	Mongolia	As	As	Do	As		416000	26.7
	Oman	As	Do	In			221000	70.5
	Pakistan		As	Do	In	In	263000	33.1
	Qatar	As	Do				8000	66.9
	S. Arabia	As	As	In			1370000	70.3
	Syria		As	As	In		115000	61.4
	Tadjikistan		As	As	Do	As	36000	17.3
	Turkmenistan		Do				351000	86.2
	UAE	Do	As				64000	81.6
	Uzbekhistan		Do	In	In		324000	72.9
	Yemen	In	Do	As			287000	68.4
Australasia	Australia		Do	As	As	As	2115000	27.5

[a] The symbols used refer to relative importance within the country: In: inclusion (<5% of the country); As: associated (at least 5–10% of country); Do: dominant (>50% of country).

[b] Degree of aridity: HA: hyper-arid; A: arid; SA: semi-arid; SH: semi-humid; H: humid.

[c] The category 'very dry areas' is derived from the FAO Soil Map of the World as areas where Xerosols and Yermosols occur. This is a valid approach since the latter soils are defined in terms of their soil moisture regime, which is arid (Xerosols) or very arid (Yermosols).

Table 3
Land and water resource, population, wealth and agricultural productivity indicators of countries with arid zones[a]

Country	Surface	Land		Water				Population					Wealth	Production		
		CROP	IRRIG	PCAW	WCI	WATA	WATD	RPOP	PDNS	RPDN	PGRW	LAI	GDPC	GDPA	LABR	AII
Afghanistan	652090	12.4	34.8	2482	74	99	1	18559	34	226	2.8	0.43	n.a.	n.a.	70	5
Algeria	2381740	3.3	6.9	528	34	60	25	12631	11	164	2.3	0.62	4591	13.0	26	17
Argentina	2736690	9.9	6.3	28739	4	73	9	4300	12	17	1.3	6.33	8861	6.0	12	11
Australia	7644440	6.1	4.5	18963	5	33	65	2721	2	6	1.0	17.08	17824	3.3	6	32
Azerbajan	86100	23.2	50.0	4364	52	74	4	3367	85	207	1.0	0.59	1980	20.7	31	27
Bahrain	680	2.9	100.0	n.a.	n.a.	n.a.	n.a.	91	778	5789	3.4	0.02	15397	0.9	2	350
Botswana	566730	0.7	0.2	9886	1	48	32	991	2	157	2.5	0.42	7060	4.9	46	2
Chile	748800	32.7	29.7	32814	5	89	6	2005	18	56	1.7	12.22	9525	n.a.	19	10
Egypt	995450	2.8	100.0	923	104	85	6	32324	56	1094	2.1	0.09	2499	16.7	40	357
Ethiopia+Eritrea	1101000	12.7	1.6	1998	3	86	11	50268	53	414	2.9	0.28	437	58.7	86	6
Iran	1636000	11.1	39.3	1746	78	87	4	26434	36	144	2.6	0.69	5300	20.8	39	52
Iraq	437370	12.5	64.7	5340	86	92	3	5388	45	100	2.8	1.01	n.a.	n.a.	16	52
Israel	20620	21.1	44.1	382	107	79	16	433	255	142	2.7	1.00	15708	n.a.	4	225
Jordan	88930	4.6	17.3	314	55	65	29	1357	44	371	4.5	0.30	3102	6.0	15	34
Kazakstan	2669800	13.0	6.4	9900	23	79	4	6988	6	20	−0.1	4.98	3927	17.2	22	9
Kuwait	17820	0.3	n.a.	103	508	4	64	48	82	1017	2.7	0.10	n.a.	0.3	1	200
Libya	1759540	1.2	21.7	111	793	87	11	758	3	43	2.5	2.86	n.a.	n.a.	n.a.	49
Mauritania	1025220	0.2	23.6	5013	18	92	6	1079	2	547	2.5	0.19	1704	26.7	55	22
Mongolia	1556500	0.9	5.9	10207	3	62	11	976	2	71	2.1	1.44	1667	35.1	32	0
Morocco	446300	22.2	12.7	1110	38	92	5	14594	57	137	2.0	0.68	2955	14.7	45	29
Namibia	823290	0.8	0.9	29545	1	68	29	1166	2	139	2.7	0.57	4589	10.6	49	8
Oman	212460	0.3	95.2	892	63	94	3	1582	9	3759	6.4	0.04	9398	n.a.	45	143
Pakistan	770880	27.6	80.0	3331	62	98	1	88148	159	393	2.9	0.24	1439	24.8	52	101
Qatar	11000	0.6	n.a.	n.a.	n.a.	n.a.	n.a.	42	53	667	8.5	0.17	18394	n.a.	3	286
S. Arabia	2149690	1.7	34.3	254	195	47	45	3486	8	90	3.2	1.07	10215	n.a.	19	122
Somalia	627340	1.6	19.6	1459	7	97	3	7554	14	646	3.8	0.14	n.a.	n.a.	75	0
Sudan	2376000	5.5	15.0	5481	12	94	4	21833	11	140	2.1	0.59	n.a.	n.a.	69	5
Syria	183780	31.4	17.1	3662	12	83	7	7039	72	122	3.0	0.82	2708	n.a.	33	65
Tunisia	155360	31.9	7.8	443	86	89	9	3665	56	116	1.9	1.35	4429	14.7	28	22
Turkmenistan	488100	3.0	87.8	17573	36	91	1	2159	9	170	6.6	0.69	2800	n.a.	37	97
UAE	83600	0.5	89.3	1047	84	80	11	285	27	968	6.8	0.14	17992	2.2	8	710
Uzbekhistan	425400	10.6	88.9	5674	73	84	4	13143	53	316	2.3	0.34	2560	32.2	35	150
Yemen	527970	2.8	29.6	359	93	93	5	9223	27	690	3.3	0.16	744	26.8	61	7

[a] Base year for statistics: 1993. (a) Country area in km^2; (b) CROP: % of country area that is cropland (defined as sum of arable land and permanent cropland) [source: World Resources Institute, 1997]; IRRIG: irrigated land as a % of cropland area [source: World Resources Institute, 1997]; PCAW: per caput available water (m^3) [source: World Resources Institute, 1997]; WCI: water consumption index: water withdrawal as a % of available water [derived from World Resources Institute, 1997]; WATA: water withdrawal by the agricultural sector as a % of total water consumption [source: World Bank, 1998]; WATD: water withdrawal for domestic use as a % of total water consumption [source: World Bank, 1998]; RPOP: rural population (×1000) [source: World Resources Institute, 1997]; PDNS: population density (persons/km^2) [source: World Resources Institute, 1997]; RPDN: rural population density (rural population divided by cropland area) in person/km^2 [source: World Resources Institute, 1997]; PGRW: annual population growth (%) [source: World Bank, 1998]; LAI: agricultural land availability index (cropland area divided by rural population) [derived from World Resources Institute, 1997]; GDPC: per caput GDP adjusted for PPP (purchasing power parity) in current US$ [source: World Bank, 1998]; GDPA: contribution of the agricultural sector to GDP (%) [source: World Bank, 1998]; LABR: labour force employed in agriculture (% of total labour force]; AII: agricultural intensification index (derived as total fertilizer consumption divided by total cropland area, kg ha^{-1}) [derived from World Resources Institute, 1997].

prevalent, this is explained by a high reliance on irrigation (e.g. Azerbajjan, Israel, Pakistan) or the importance within the country of more humid agroclimatic zones (e.g. Chile, Morocco, Syria, Tunisia).

The weight of irrigation varies tremendously between the AZCs, from a fraction of the cropland area to 100%. This range reflects the state or feasibility of irrigation development within each country, rather than the need.

3.2. Water resources

In terms of available water resources there are again huge differences between the AZCs. The per-caput available water varies by a factor 300 between the most and least endowed countries, which results in a highly unbalanced distribution of water resources for economic and social development. These disparities between AZCs are due to differences in population density or compensation within countries that have wetter agroclimatic zones or both. Some countries consume only a small percentage of their water resources (e.g. Botswana, Chile, Ethiopia, Mongolia, Namibia), others consume all (e.g. Egypt, Israel), whereas the most deficient countries import water from non-renewable sources (e.g. Libya) or manufacture it themselves through desalination (e.g. Saudi Arabia, Kuwait).

In the vast majority of arid zone countries agriculture is the main consumer of water. Water is generally not in short supply for domestic use, except in a few countries with an adverse combination of low per-caput availability and high demand for domestic use (e.g. Jordan, Kuwait, Saudi Arabia).

This water picture, which on the whole is not exactly rosy at present, is likely to change dramatically within one generation. The majority of countries currently in the AZC group[1] will by the year 2025 be characterized by absolute water scarcity. These countries will not have sufficient renewable water resources to meet reasonable per caput water needs for their rapidly expanding populations. Given the dominant share of agricultural water use, these countries will almost certainly have to reduce the amount of water used in irrigated agriculture and transfer it to the other sectors, importing more food instead (Seckler et al., 1998).

3.3. Population

In terms of population characteristics the AZCs are a very heterogeneous group, with net population growth rates ranging between 1 and 3% for most countries. The vast majority have high growth rates (>2%) resulting in rapid population increase. Some countries have very high growth rates (e.g. Oman, Qatar, UAE), which are due mainly to a large net immigration of guest workers, rather than an increase in the native population.

The total rural population in the AZCs is nearly 350 million people. Noin and Clarke (1998) reckon that in the 20 most arid countries of the world total population has multiplied more than six times since the beginning of the century. They also estimate that the contribution of these countries to the world population is expected to increase from a base of 4.3% in 1900 to 11.5% in 2025.

The overall population density, which does not distinguish between rural and urban populations, is, with the exception of a few countries (Bahrain, Israel and Pakistan), low to moderate. However, when the rural population density is considered, one finds that the population pressure associated with agriculturally productive areas is much higher, in the majority of countries at least five times more than the overall population density. The absolute values of rural population density are in some countries very high (>300 persons/km^2). This can be explained by high countryside populations (e.g. Egypt, Ethiopia, Jordan, Pakistan), low cropland area and urbanization of the countryside (e.g. Kuwait, Bahrain, Oman, Qatar, UAE) or concentration of population in pockets of cropland (e.g. Mauritania, Yemen).

3.4. Wealth

In terms of wealth, as expressed by per-caput GDP the AZCs include some of the poorest (Eritrea, Ethiopia) as well as some of the richest countries in the world (Australia, Qatar, UAE). However, most of the AZCs would be classified as low-income countries.[2]

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[1] Libya, Saudi Arabia, UAE, Kuwait, Oman, Jordan, Yemen, Israel, Egypt, Tunisia, Iraq, Iran, Syria, Pakistan, and a few outsiders like South Africa and Singapore (Seckler et al., 1998).

[2] With a per-capita GDP adjusted for purchasing power parity of less than US$ 6000 per year.

4. Agroecology and environmental vulnerability of the arid zones

The energy available for evaporation is the controlling factor in the regional hydrology of the arid zones. All arid zones are characterized by a vast surplus of water demand over rainfall. Regional gradients of potential evapotranspiration therefore largely determine the macro-scale aridity. The synchronicity between evaporation and rainfall also determines the effectiveness of the latter. Winter rainfall is more effective in building up a reliable moisture supply for plants than summer rainfall. For this reason the same crop which can grow well under a winter rainfall regime of 300 mm may easily require 500–600 mm under summer rainfall.

Within the general arid setting the ‘soilscape’ (landform-soil complex) is an important determinant of land use potential by its control over runoff and infiltration. Topography plays a major role in modifying the moisture supply, not only by trapping rainfall or attracting occult precipitation, but also by lowering the rate of evaporation at higher altitude.

The arid zones exhibit a tremendous diversity in landscapes, soil, geological substrata, surface water and groundwater resources (Gerrard, 1992). Different landforms, lithologies, the general sparsity of vegetation, and regional tectonics combined with the differential resistance of these parent rocks to stress and shear, create wide differences in the properties of land to generate runoff and to accept and store groundwater.

The diversity of the arid zones thus creates a surprisingly wide range of agroecological ‘niches’, which can be either natural or artificial (e.g. irrigated areas). Agroecological niches are formed by climate-landform–soil interactions that create edaphic conditions that deviate substantially from those of the surrounding areas. ‘Patchiness’ of edaphic conditions is therefore a key characteristic of the arid zones.

This concept of agroecological niche is fundamental to understand why at meso- and micro-scale, and sometimes at macro-scale, the agricultural productivity of the arid zones can be much higher than would correspond with their macro-scale agroclimatic potential and biomass productivity. Large-scale studies of eco-region productivity usually do not consider the numerous sites where natural conditions are more favorable or where appropriate land and water management can substantially raise the production potential. In other eco-regions inclusions of areas with a typical edaphology can be ignored, but not in the arid zones because these pockets constitute the core areas of higher biomass productivity and biodiversity.

Examples of extensive natural agroecological niches with more humid conditions include the large river floodplains of North and West Africa (Nile, Niger) and the semi-arid mountain islands of the Sahara and the Arabian Peninsula (Hoggar, Tibesti, Yemen and Asir highlands). At meso- and micro-scale oases are typical examples of highly productive areas owing to a reliable but highly site-specific water supply from springs.

‘Occult precipitation’ from fog, mist, low clouds or dew has often been mentioned in the literature as a modifying factor of the water budget of the arid zones. An excerpt from this literature can be found in Le Houérou et al. (1993). As a source of moisture, occult precipitation can constitute a significant, or even the dominant, fraction of precipitation. However, given the fact that the reported contributions constitute less than 2 mm per day, in areas where the potential evapotranspiration may easily exceed 5–6 mm per day, the claims of significant impact on the regional hydrology are probably exaggerated. Nevertheless, it is clear that these sources of hidden precipitation are of great importance in creating, at micro-scale, improved conditions that support more productive and diverse plant life.

Whereas all these sources of edaphic diversity in the arid zones create a wide spectrum of agroecological niches, the latter can also be further enhanced or expanded by human intervention. Irrigation development in the arid zones has usually started by diverting water from natural agroecological niches, typically floodplains and oases. As the latter reach their capacity, groundwater is extracted, often to levels that are not sustainable even in the medium-term (Seckler et al., 1998). However, for the time being irrigation development is the single most important factor in creating artificial agroecological niches in the arid zones.

The rapid population increases in the arid zone countries have intensified existing environmental pressures. Within the arid zones natural processes occur that, in the absence of solid benchmarks, can be easily confused with land degradation. The first process, probably the less important, is primary salinization. Primary salinity often occurs in natural soil types due to their lithological inheritance (e.g. marine sands), or a topographical position that favors seepage of laterally moving groundwater, subsequent evaporation and salt deposition. In many arid regions lower footslopes are favored landscape positions for saline seepages (Roberts, 1992).

Wind erosion is a natural process in the arid regions. The detachment, removal, and subsequent deposition elsewhere, of soil particles is a function of wind force, lack of vegetation cover, shelter-exposure effect of different landscape positions and susceptibility of soils to detachment. The latter is inversely related to the silt and clay content (Lorimer, 1985). For this reason dust storms and sand drift have always been characteristic of the sandier parts of the arid zones.

Even water erosion, as expressed by rills and gullies, can be surprisingly severe in the arid zones. The limited vegetation cover and associated low biological activity, can not protect the soils from rainfall impact, which tend to seal up and produce relatively large runoff volumes in relation to the absolute rainfall amounts.

These natural processes have been dramatically accelerated by human intervention. The most widespread expression of land degradation is in the degradation of vegetation cover. Major parts of the arid rangeland vegetation, particularly in North Africa and the Near East, have been significantly degraded in quantity and quality. Vegetation destruction takes place by overgrazing and fuelwood collection, both activities being driven by the needs of growing populations. A less visible form of vegetation degradation is in the change of the plant species composition of rangeland ecosystems. The balance between perennials and annuals is often disturbed, which could be detrimental for the ability of arid ranges to hold soil and water, or the ecosystem becomes dominated by a few unpalatable species.

Continuous cultivation of steppe areas rapidly exhausts the limited stock of organic matter, which glues the topsoil. Under conditions of low moisture, low organic matter and rapid oxidation of humus, soil structure deteriorates more rapidly, particularly under continuous annual cropping using disc and moldboard ploughs. Under these conditions the topsoil becomes denser, less aerated and less pervious to rain and plant roots. At the same time, splash erosion causes crust formation and the capping of the topsoil, sealing the surface and resulting in higher runoff and erosion (Roberts, 1992).

The availability of cheap pumps and lack of regulation of groundwater abstraction, have allowed many farmers in the arid zones to expand irrigation into the arid zones. In many cases this has led to secondary salinization, by importing the salinity associated with the groundwater or, through over-irrigation, by raising the level of shallow water tables until they are near to the surface.

5. Agricultural production systems of the arid zones and their development pathways

A wide range of cropping and livestock or mixed systems exploits the ecological diversity of the arid zones. In increasing order of land use intensity the following are major production systems in these areas:

- pastoral livestock systems;
- transhumant livestock systems;
- rainfed cropping systems;
- partially irrigated cropping systems;
- fully irrigated cropping systems.

5.1. Livestock systems

The pastoral or fully-nomadic livestock systems are characterized by the basic need of pastoralists to move with their herds from one place to another because water and fodder is not sufficiently available to keep them permanently in one place (Ruthenberg, 1980). These systems are undoubtedly the most efficient in exploiting niches of very low productivity within barren land, and are mostly confined to the hyper-arid zones. This confinement to very marginal environments makes it also very difficult to settle nomads, or to transform nomadic systems into more productive ones. Owing to the high variability in rainfall, growing conditions vary tremendously from one year to another, which makes it a highly risky form of production. It is therefore not surprising that this production system is in decline and that this trend will continue in the future.

In areas with good road networks, higher rainfall and better production potential, nomadic systems have been able to evolve into semi-nomadic systems, which are more secure and stable forms of livestock production. Transhumant migrations typically have relatively fixed patterns of seasonal flock movements between established grazing grounds. Usually natural grazing is insufficient in the arid zones, even allowing for crop residues and stubble from neighboring or remote agricultural land, and increasingly herd owners have to resort to feed supplements. In all arid zones, particularly those of Africa and the Middle East, the trend towards an increased contribution of feed grains and other concentrates to the livestock diet is bound to increase (Nordblom and Shomo, 1995).

These modern versions of traditional pastoralism are gaining increasing importance in local and regional economies but they have their own problems. The main one is that they have no control over the quality of the grazing areas. While flock ownership is individual but the range is communal, there is no incentive to avoid overgrazing. Permanent overgrazing, with a gradual displacement of perennial grasses by annuals and unpalatable bushes, is an increasingly common problem in the arid zones. What is worse is that any infrastructural provisions, such as roads and watering points simply exacerbate the negative environmental effects by encouraging further resource use beyond the carrying capacity of the land. No major improvements can be expected without land tenure reforms that change the combination of private flock ownership and communal land (Ruthenberg, 1980).

5.2. Cropping systems

At the higher rainfall margins of the arid zones, rainfed production systems occur especially in winter rainfall areas. These systems are mainly based on wheat or barley rotations with food or fodder legumes, or tree crops, mainly fruits and olives. Given the low absolute amounts and considerable variations in rainfall from year to year, such systems critically depend on soils with favorable moisture storing properties. This can be a high moisture storage capacity, as is the case with the red, well drained, clayey Mediterranean soils,[3] or in landscape positions that benefit from moisture additions by runoff from higher areas. The viability of such systems, which can be highly productive especially for cereals and grain legumes, depends on the high efficiency of water storage which is caused by the combination of winter rainfall, low winter evapotranspiration, high available waterholding capacity and adequate rooting depth.

The main problems of the rainfed production systems are land scarcity, limited growing period and yield fluctuations due to rainfall variability. From the viewpoint of soil and climatic resources these systems occur in the most favored parts of the arid zones and it is therefore not surprising that they are under permanent cultivation. Land scarcity is clear from the lack of natural vegetation and fragmentation of fields, which is due to the tenure system and can be readily observed from satellite imagery (e.g. GORS, 1996).

The growing period, part of which includes the winter with a dormancy period, is too dependent on soil moisture to allow either long-maturing crops with higher yield potential or double cropping. Yield variations can be very substantial as a result of moisture stress at the end of the growing season.

The availability of cheap wells, irrigation water and piping systems has made it possible for many farmers of the arid zones to stabilize production under rainfed conditions, by applying irrigation water at the time that it is critically needed. However, under conditions of unlimited access, supplemental irrigation systems are inherently transitional and tend to evolve into fully irrigated systems, with a higher cropping intensity and new crops that would not be possible under rainfed and supplemental conditions.

Outside major surface irrigated areas, such as the Nile delta in Egypt, or the deserts of Uzbekhistan, where salinity is an increasing problem, groundwater is becoming increasingly important as a source of irrigation water throughout the arid zones. The use of groundwater offers mixed benefits and may in the longer term be a source of severe environmental hazard. Over-extraction of groundwater, fueled by the worldwide explosion in the use of wells and pumps, leads to a rapid drawdown or even exhaustion of the aquifers. This rapid depletion of fresh aquifers is often accompanied by deterioration of the water quality by seawater intrusion, the pumping of deeper saline water to the surface and the contamination of shallow aquifers with more saline water (FAO, 1997). Seckler et al. (1998) consider the mismanagement of groundwater reserves a time bomb for the food security of major countries like India and Pakistan.

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[3] Available waterholding capacities of 150–180 mm/m are common (e.g. Ryan et al., 1997).

Water harvesting, in its various expressions, is likely to expand from the semi-arid to the arid zones. Water harvesting is the collection of runoff for productive purposes from a catchment area to a collection area, usually a cultivated area (Critchley and Siegert, 1991). Floodwater harvesting, also called spate irrigation, can be of particular importance in arid plains dissected by wadis that originate in rainy uplands, such as the Tiama coastal plain in Yemen. These agricultural systems are characterized by diversion of floodwater and spreading through canal systems onto suitable soils with favorable moisture storing properties. The main problems of these systems are inadequate water control and the unreliability of moisture supply, which favor cropping patterns that have to accommodate flood and drought tolerance.

5.3. Forestry

Forestry as a system for the economical production of wood and derivatives is rare in the arid zones, owing to the low growth rates and productivity under non-irrigated conditions, and other associated adverse ecological conditions (shallow soils, salinity, temperature extremes).

Natural trees and shrubs are exploited, such as Acacia senegal for gum arabic or trees of the Boswellia genus for frankincense. Actual afforestation, while limited, is mainly for a conservation or protection purpose, in particular to protect agricultural land against sand dune invasion and to provide shelter against strong winds.

5.4. Trends

The arid zones suffer from a public perception that they are areas of limited heterogeneity (‘all arid zones are deserts, and preferably sandy’), that they have limited agricultural potential and low population densities. This view is likely to change dramatically in the near future owing to the realization that:

- these areas are far from monolithic in their agroecological characteristics;
- they have agroecological niches with high agricultural potential;
- they will become more important as sources of genetic diversity and abiotic stress resistance;
- population densities are increasing rapidly, particularly in urban agglomerations;
- the environmental problems, particularly the decline in quantity and quality of groundwater resources, may reach crisis dimensions.

Together the above factors are bound to transform the existing agricultural production systems of the arid zones within a generation.

A first impact will be on the irrigation systems. Faced with the need to divert more of their water resources to domestic and industrial use, governments will have no alternative but to reduce the share of agricultural water consumption. They can do this by increasing water charges, cutting of price subsidies on irrigated crops, water and pump quota, and other, more restrictive, measures.

These expected water policy changes would provide powerful incentives to boost water use efficiency, water conservation and reutilization.

First of all, irrigation systems in the arid zones are likely to reduce distribution and application losses. In arid climates the efficiency of irrigation can be easily improved to field application efficiency rates of 70% by drip or sprinkler irrigation. Seckler et al. (1998) expect that most AZCs will achieve these efficiency rates by the year 2025. There will also be a trend to change cropping patterns to more water-conserving, drought- or salinity-tolerant rotations. These changes in cropping pattern will be driven by changes in amount and quality of available irrigation water.

In arid zone countries that have the financial resources for wastewater treatment, treated sewage effluent will become a very important source of irrigation water. In others, more use will be made of irrigation return flow runoff, agricultural subsurface drainage water, saline springs and streams, perched water tables and saline groundwater aquifers.

In the cropping patterns emphasis will shift from the more water-demanding, relatively low-value staple crops such as cereals and cotton to vegetables, fruits and other niche crops that will serve the growing needs of nearby urban agglomerations.

It is also likely that in the longer run, when water will be valued at its real opportunity cost, rainfed cropping systems, stabilized through supplemental irrigation, will regain importance.

These pressures to make irrigation systems more efficient may also serve the needs of the livestock sector.

As a result of overgrazing, livestock systems in the arid zones have an increasing need for imported feed to supplement a decreasing range feeding capability (Nordblom and Shomo, 1995). The potential of using indigeneous, heat-, drought- and salinity-tolerant grass and shrub species, grown as irrigated fodder crops for high yield, has been largely unexploited. There are exciting possibilities to select and breed, from the large pool of arid zone genetic resources the fodder crops of the future, with the right mix of high yield, high water use efficiency and abiotic stress tolerance.

Achieving complementarity between irrigated and rainfed crop and livestock production systems is a challenging but necessary developing pathway for ensuring sustainability of agricultural productivity and environmental sustainability of the arid zones.

6. Current and future contributions of agrometeorology to agricultural production systems in the arid zones

Agrometeorology has contributed tremendously to the management of irrigation schemes. The extensive research on methods for calculating potential evapotranspiration has become the basis for managing irrigation scheduling at scheme and field level, both under conditions of unlimited and restricted water supply. The excellent reviews of the literature and resulting guidelines for estimating crop water requirements, contained in various FAO publications (e.g. Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979) have been highly influential in the design and operation of irrigation schemes. They have also created awareness of the indispensability of site-specific agrometeorological data for their management.

The FAO-coordinated work on revising the aerodynamic term of the original Penman formula (Doorenbos and Pruitt, 1977; Frère and Popov, 1979) has been of particular value for the arid zones, because the strong advection effect in these areas could not be properly accounted for by the standard Penman method (Penman, 1948).

Crop coefficients, relating potential evapotranspiration and crop water requirements, have been determined for a wide range of crops and cultivars, in different climatic conditions. As a result a wide body of information exists on site-specific crop water requirements. Local determination of crop coefficients through lysimeter studies is an active area of ongoing adaptive research.

The renewed emphasis on the energy balance for calculating PET (Smith, 1990) using the Penman–Monteith formula, offers the potential of replacing the two-step procedure of estimating crop water requirements (via the potential evapotranspiration and the crop coefficients) by a one-step procedure. As such it would be more suitable for use with crop simulation methods and allow to avoid lengthy experiments to calibrate crop coefficients to local conditions.

With the exception of irrigation management, the contribution of agrometeorology to solving the problems of the arid zones' specific production systems has been suboptimal. In a rapid survey of the journal *Agricultural and Forest Meteorology* it was found that over the last 15 years not a single article was dedicated to research themes specific to the arid zones.

It is therefore not unfair to state that the agrometeorological needs of these areas have up to now not been fully appreciated in the past. The perceptions of low heterogeneity and low agricultural potential, as well as the logistical problems of providing maintenance and obtaining data from remote meteorological stations, are largely to blame for this situation.

Agrometeorology has a significant contribution to make in the transition of the agricultural production systems of the arid zones towards more sustainability. By matching water application to crop water requirement, agrometeorological information is at the heart of cropping systems with high water use efficiency. Agrometeorological data are also necessary to characterize the different agroecological niches in terms of abiotic stresses, particularly extremes of temperature, wind and drought. Relating these data on a spatial basis to plant species distribution will help to identify plants that have high tolerance to the particular stresses. Their genetic resources can then be used to breed the food and fodder crops for the arid zones, that have the right balance between good yield, water use efficiency and stress tolerance.

6.1. Agroecological characterization

The main requirement is for better agroecological characterization of the arid zones. Numerous thematic surveys in the form of soil survey reports, climatic maps, groundwater surveys exist, therefore the need for new resource inventories is probably limited. It is clear that integrated land and water resource information systems, based on GIS-technology will play a major role in linking multidisciplinary, geographically referenced databases at different resolution.

Digital elevation models (DEMs) will play an increasingly important role in this integration of thematic layers in GIS-based land and water resource information systems. DEMs contain topographic information on a grid basis, and are therefore, at least in comparison with climate data networks, very detailed. For example, a global DEM from the US Geological Survey (GTOPO30), available as freeware, provides information on altitude, slope and aspect for every land point with a 1 km resolution. Other DEMs can be generated from digitized topographical maps.

The real need is to integrate this information in the form of agroecological frameworks for development. Specific methodologies, models and decision-support systems will need to be developed for these integration exercises. It will not be enough to overlay, for instance, a rainfall map with a soils map and a DEM to come up with a realistic land use plan.

There is a particular need for a better understanding of the agroclimatic variations within arid zones. Given the diversity in topographic conditions, agroclimatic characterization will be required at different scales. A useful approach to macro-scale agroclimatic zoning can be based on the FAO concept of Length-of-Growing-Period (FAO, 1978). By incorporating temperature thresholds for dormancy and killing frost, and snowfall as a separate sink in the waterbalance, a more refined assessment of growing period could be made that would be of particular relevance to areas where the growing period is limited by either moisture or temperature or both (De Pauw et al., 1996).

In view of the different temperature, radiation, moisture, humidity and wind regimes in agroecological niches, the latter will need to be properly characterized.

6.2. *Spatialization of climatic data*

Given the sparse agrometeorological networks in the arid zones, an area in which agrometeorology can make a much valued and specific contribution is in spatialization of climatic parameters.

Several statistical techniques are already available that make use of DEMs for the spatialization of climatic parameters, such as simple interpolation models, univariate geostatistical and splining methods, multivariate geostatistical and co-splining methods, and composite methods.

Climatic variables are strongly influenced by site altitude and other features of the surrounding terrain. These influences range from more or less purely statistical, to deterministic due to some underlying physical cause-and-effect relationship.

An example of a statistical relationship is the decrease of precipitation with increasing distance from a coast or the increase of rainfall on the windward side of an obstacle (orographic rainfall) with a corresponding decrease on the leeward side (foehn). An example of a deterministic relationship is the variation of solar radiation intensity with slope and aspect.

In view of the strong linkages between climatic variables and topography, the most promising techniques for spatialization in climatology are multivariate approaches, since the latter permit the use of terrain variables as auxiliary variables in the interpolation process. In contrast to the climatic target variables themselves, which are only known for a limited number of sample points, terrain variables have the advantage to be known for all locations in between, which increases the precision of the interpolated climatic variables significantly. Cokriging and co-splining are methods that include the auxiliary information as random quantity, assuming no deterministic relationship between auxiliary variables and target variable. Both methods nearly always lead to robust results. Both are widely used in agroclimatology; various examples are provided by Bogaert et al. (1995), Hutchinson (1995), and Hutchinson and Corbett (1995).

Composite methods exist that combine several statistical techniques that are applied in sequence. Perhaps the best known composite method is the ‘Aurelhy’ method (Benichou and Le Breton, 1987). Terrain information is obtained from a DEM by the average elevation of the central cell of a square matrix of blocks of land, and by the elevation differences between that cell and the other cells in the matrix. The elevation of the central cell and the principal components of the elevation differences are regressed against the target variable in a stepwise regression, the residuals of which are interpolated by simple kriging.

A similar method, but with a different, circular geometry for terrain representation has been employed by Göbel et al. (1996) for the mapping of precipitation in Morocco.

The combination of DEMs and advanced spatial interpolation techniques thus allows to generate 'climate parameter surfaces'. These are raster files that can be manipulated in a GIS with other variables, for instance soil moisture storage capacity, crop calendars and others, to generate spatially or temporally linked derived variables, such as soil moisture, runoff, crop water requirements, potential evapotranspiration.

6.3. Remote sensing

Remote sensing techniques can assist with the interpolation and mapping of climatic variables. The scope ranges from the use of satellite images to guide the manual drawing of isohyets (van der Laan, 1986) to the direct mapping of climatic variables from multitemporal coverages from satellites or ground radar, in which observations from meteorological stations serve mainly for calibration purposes. A few examples are the mapping of precipitation (Barrett, 1986; Dugdale et al., 1991), evapotranspiration and soil moisture near the surface (Bastiaanssen, 1995), or wind speed and direction (Smith and Kelly, 1985).

The major role for remote sensing will be to monitor changes in the edaphic factors. By its synoptic view and rapid refresh capability remote sensing offers a unique ability to integrate the effects of changing weather, vegetation, soil and land use. These changes can be monitored over different spatial and time scales. Especially the use of AVHRR imagery, with low spatial but high temporal resolution, in combination with higher-resolution imagery such as Landsat or SPOT, in representative sample areas, offers cost-effective prospects for monitoring land degradation and climate change impact.

6.4. Improved networks and user access to data

Whereas data spatialization and remote sensing are valuable tools, they can not compensate for the real climatic data gap in the arid zones. Meteorological services should make an effort to service these areas using agroecological frameworks as a basis for citing weather stations in representative locations. The remoteness of such areas can nowadays be overcome by automatic stations with data loggers, and data transmission by telephone or satellite.

In a larger development context meteorological services will need to rethink their role as public institutions that serve different user communities with different levels of purchasing power. The agricultural user community in most developing countries has the highest data requirements but the lowest financial resources.

In order to manage the irrigation projects of the future effectively, site-specific meteorological information is indispensable. The anticipated use of marginal water combined with the need for water conservation will require a level of scheme coordination, that only systems with a large degree of automation in the water scheduling and application will be able to master. Such sophisticated schemes are only feasible if steered by expert systems with meteorological data as driving variables.

The economic pressures on meteorological services to become 'self-supporting' by charging for their data and services should not put a brake on the development of sectors that will increasingly rely on knowledge systems in which meteorological data are a key component.

Meteorological services will need to go in partnership with the private sector, assist them with data collection and find affordable arrangements in an effort to pool and share data. It is not the 'client-server' model that has made meteorology a showcase of international cooperation, but the spirit of unrestricted information access and data sharing.

7. Conclusions

The arid zones of the world have an unexpected diversity of agroecologies and production systems. The agrometeorological needs for these areas have been insufficiently addressed. There is a need for a better agroecological characterization, which should include assessment of agroclimatic conditions at macro-, meso- and micro-scale. There is a need for better meteorological networks, relying mainly on automatic weather stations with remote data transfer. Meteorological services need to work with the private sector to exchange data obtained from privately-operated weather stations with technical advisory services to ensure the quality of the data collection.

Given the relative sparsity of meteorological stations in the arid zones, there is a continuing need for research on ‘data substitution’, in particular on data spatialization methods, using various combinations of state-of-the-art statistical techniques and satellite information.

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