Arid Soil Research and Rehabilitation, Volume 4, pp. 1–17
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0890-3069/90 $3.00 + .00

The Role of Algae and Cyanobacteria in Arid Lands. A Review

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Abstract *Algae, cyanobacteria, and lichens occur in surface cryptogamic crusts, as free-living organisms in water bodies and within or on rocks in arid lands. The possible roles algae, cyanobacteria, and lichens could play in arid environments include physical improvement and protection of the soil, contribution of nitrogen to the arid ecosystem by nitrogen-fixing cyanobacteria and lichens, and primary biomass production for use as food and other secondary production. Physical improvement and protection of arid soils has potential in controlling desertification and rehabilitating arid lands. Culturing algae and cyanobacteria for biomass production, already being utilized in nonarid environments in agriculture, aquaculture, and now in the biochemical industry, has bright prospects in arid areas with their abundant sunshine. Primary production by the organisms can also be used for direct human and livestock consumption and in urban waste treatment. Biomass production can thus act as a means of resource diversification and therefore relieve pressure on fragile arid lands.*

Keywords algae, cyanobacteria, arid lands, soil rehabilitation, biomass production

Arid Lands as Habitats for Algae and Cyanobacteria

If, in a given location, the potential evapotranspiration is much higher than the annual precipitation then one can say the place is arid. There are several criteria for the delineation of arid lands and even the characterization of a region as a desert is always relative although some attempts to define arid areas have been made (Bailey 1979). For example, according to Shreve (1934), the Sonoran area of southwestern United States receives an average of over 290 mm annual rainfall while the Nubian desert of Egypt receives less than 100 mm and some parts of the Sahara, the Atacama of South America, and Tarim Basin of China still less with an annual average of 50 mm. All these areas are classified as deserts. Even within deserts the microreliefs, such as the presence of sand dunes, rugged terrain, and bushes and burrows, all tend to minimize the physical factors of temperature, light, and wind, somehow ameliorating the climate and thereby making generalizations about zonal aridity imperfect.

Le Houerou (1970), however, considers a zone that receives less than 100 mm as desert, while zones with an annual rainfall of more than 400 mm could be humid, subhumid, or arid. The Thornwaite index, which is based on water balance, that is, the amount of precipitation received in relation to potential evapotranspiration (PET), is also still used. The index ranges from + 100 when precipitation exceeds PET throughout the year, to − 100 when precipitation is zero throughout the year. When precipitation equals PET, the index is zero. Areas with index values between 0 and − 20 are considered subhumid, between − 20 and − 40 semiarid, and below − 40 arid (Goudie and Wilkinson 1977). Whittaker (1970) further distinguishes deserts on the basis of temperature, namely, tropical and subtropical, warm temperate, cool temperate, and arctic-alpine deserts. All arid lands connote one thing: acute water shortage.

Climate and physical realities of arid lands are very well described by Grenot (1974) McGinnies (1979) and in reports of International Biological Programme, Desert Biome. Maps of arid zones of the world are presented by Meigs (1953) and McGinnies (1979).

Organisms

Cyanobacteria are prokaryotes, a group of organisms that characteristically lack membrane-bound subcellular organelles, such as mitochondria, and that do not have their genetic material located on more than one chromosome in a membrane bound nucleus (Delaney *et al.* 1977). Besides *Prochloron*, a prochlorophyte, cyanobacteria are the only prokaryotes that possess chlorophyll *a* and are able to fix their own carbon effectively. This distinguishes them from the two true bacteria groups, Chlorobiineae and Rhodospirillineae, which while being photosynthetic do not possess chlorophyll *a*. Another group claimed to be photosynthetic but extremely difficult to cultivate in pure culture, the Prochlorophyta, consists of a single genus, *Prochloron*. The algae, while not being prokaryotic, are very similar to the cyanobacteria in morphology and are the smallest organisms that carry out photosynthesis. It was this similarity in morphology and the possession of chlorophyll, which cyanobacteria share with algae, that was responsible for their being called blue-green algae until about ten years ago. Recent trends in cyanobacterial taxonomy found this basis of defining affinity unjustifiable, hence the change in the name of the group and the basis of their nomenclature. Stanier *et al.* (1978) proposed that they assume the name, cyanobacteria, with an effective date of 1 January 1979, and also proposed that their taxonomy from then onward should be in accordance with the International Code of Nomenclature of Bacteria. Rippka *et al.* (1979) have recognized 22 genera and 3 groups that they place in 5 sections. The five sections, their major characteristics, and those of their representative genera are presented by Stewart (1980). Stewart states that the nomenclature and systematics of Cyanobacteria based on the International Code of Botanical Nomenclature were practical but were found to contain errors due primarily to the procaryotic nature of the group and their phenotypic plasticity. The new nomenclature involves some name changes (Gallon 1980).

The simplicity of cyanobacterial and algal structure imparts some robustness in environmental adaptation, such that the cyanobacteria assume the dominant role in the colonizing of arid rock surfaces including those that are smooth and more or less vertical. In some arid soils cyanobacteria have been reported as the dominant species and sometimes as the only species (Barbey and Coute 1976). They have been known to be the primary colonizers after volcanic eruptions (Rayburn *et al.* 1982). More revealing was the report by Shields and Drouet (1962) on the distribution of terrestrial algae and cyanobacteria within the Nevada nuclear test site in the USA which had survived acute gamma-irradiation exposure up to 2560 krads. These two organisms are present everywhere because their viable cells are present in the atmosphere and are probably carried throughout the world by the wind (Schlichting 1969).

The often stated major limitation to the survival of these two groups in the terrestrial environment is the low environmental pH, but tropical species have been known to grow at low pH values. They also require nutrients and sunlight for survival but cyanobacteria, the more primitive of the two, are nutritionally versatile. Until recently considered obligate phototrophs, they are capable of chemotrophic growth in dim or blue light insufficient to allow growth on mineral media or in the presence of DCMU, which inhibits photosystem II (Fogg *et al.* 1973). In carbon dioxide depleted media and with different sugars chemoautotrophic growth in the dark has been obtained with a number of strains (Shilo 1975). Stanier (1973) also notes that in some cases carbon dioxide is never the sole carbon source but that in such auxotrophs the requirement for vitamin B_{12} is absolute. He further contends that cyanobacteria can perform a light-dependent assimilation of organic substrates, such as acetate and amino acids, which enter a limited number of biosynthetic pathways with CO_2 still as the major source of carbon. Stewart (1973) summarizes: "The more extreme the physical conditions are, the more likely one is to find cyanobacteria, provided light, water and carbon dioxide are available." Peveling (1987) has also noted that lichens and free-living microalgae are remarkably tolerant of long periods of dryness.

In general, the factors that determine which organisms are found in an arid surface include parent rock material, texture of the soil, topography, land use history, water availability and its source, and light and temperature regime. Anderson *et al.* (1982) have shown that the extent of biological crust development in Utah, USA, was related to soil texture, conductivity, pH, and soil phosphorus level.

Cyanobacterial and Algal Habitats in Arid Lands

Friedman *et al.* (1967) classified cyanobacterial and algal desert habitats as follows:

(1) Edaphic—when they occur on or near the surface of the soil.
  (a) Endedaphic—when they are just beneath the soil surface.
  (b) Ededaphic—when they occur on the surface, usually as crusts.
  (c) Hypolithic—when they occur underneath surface rocks and stones.
(2) Lithophytic—Cyanobacteria and algae in rocks proper.
  (a) Chasmolithic—those occurring in rock cracks and fissures.
  (b) Endolithic—those embedded in rock fabric.

The scheme does not include algae and cyanobacteria that occur in water bodies. The various arid areas of the world have different sizes of water bodies, most of them often saline and of very high pH. There are also rivers, temporary streams, lakes, and puddles that are formed after rainstorms. In these water bodies floating masses of unicellular and filamentous algae and cyanobacteria may be present, and their biomass is determined by the depth of the water body and attenuation of incoming radiation by the mass, and also by nutrient availability.

The above scheme is self-explanatory except for algae and cyanobacteria that occur in epedaphic habitats in the form of crusts. Crusts, of various compositions as seen by desert pedologists, are of various compositions and are compactions believed to be relics of hydromorphic soils formed under wetter conditions in the past. The crusts of arid soils are usually sandy and Skujiņš (1975) described three types in North Africa based on origin:

(1) Crusts of physicochemical origin which are formed by cementing of wind sorted fine particles
(2) Crusts of mechanical origin formed in cultivated areas. The process of forming these crusts is a reversal of what happens in the first case; here the heavier sand particles loosened by ploughing are carried away leaving the compacted finer ones for cementing.
(3) Crusts of biological origin which are formed by microorganisms, such as fungi,

> and photosynthetic microorganisms, such as algae, cyanobacteria, and lichens. This type of crust is often found on top of the first two and are variously referred to as crusts, cryptogamic crusts, or algal mats (Isichei 1980; Stewart *et al.* 1978). Biological crusts are often found in the topmost layer of bare soils except in sandy deserts. This top layer is what Kovda *et al.* (1979) referred to as the horizon of maximal biological activity.

These crusts have been well studied in the Americas and Central Asia. Reynaud and Lumpkin (1988) have reported on the crusts of China while Ali and Sandhu (1972) reported on those from arid India. Reynaud (1987) discusses the floristics and the factors affecting the occurrence of nitrogen-fixing cyanobacteria found in dry crusts from Senegal in the Sahel zone of West Africa (see also Faurel *et al.* 1953) while accounts of surface microorganisms of the Kalahari desert in Southern Africa are given by Skarpe and Henriksson (1987, see also Welsh 1965).

Related to pedological crusts are takyrs. Kovda *et al.* (1979) describe takyrs as desert soils with a bare, parquet-like surface, broken up by a network of splits into numerous polygonal aggregates. They are typical of the deserts of Central Asia (Bolyshev 1955). Rain crusts, claypans, playa, etc., are similar to takyrs and these, like takyrs, have biological crusts. It is difficult to distinguish the pedological cementations from biological crusts except that algal crusts are usually darker in color and usually have lichens and mosses associated with them.

Cameron (1966) is of the opinion that algal and cyanobacterial floras of hot deserts and Antarctic xeric, mesophilic, and perhaps hydrophilic habitats are composed of the same species. This was expressed again by Ocampo (1973). Shreve (1934) had earlier pointed out that all the desert regions of the world have similarities in biological manifestations. Plants are similar in structure, function, and behavior in deserts. Shreve, however, does not believe that the species are the same but that structural parallels are common, such as the *Euphorbia* and *Aloe* of Africa resembling the *Cactus* and *Agave* of America, respectively. This feature is observed in tropical rain forests (Richards 1973) where the physiognomy is similar in Central America, Africa, and Asia but the species are markedly different.

Algae and cyanobacteria may also share this characteristic even more than higher plants. A casual look at the various arid habitats for algae and cyanobacteria schematized above shows that the habitats are likely refuges from the desert environment such that a chasmolithic habitat in the Sahara is not different from that in the Atacama of Chile. It is to be noted, however, that algae and cyanobacteria are characterized by phenotypic plasticity that may enable the species to survive in different environments.

Forms of Occurrence of Cyanobacteria and Algae

Algae and cyanobacteria occur as free-living forms and in various associations with other organisms either as cryptogamic crusts on the surface of soil, on or in rocks, or in water bodies.

The cyanobacteria further show their close relationship to the bacteria by the way they live freely and form symbiotic associations with other organisms. They form symbiotic association with algae, fungi, bryophytes, pteridophytes, cycads, and angiosperms. Stewart (1980) has listed these eukaryotic genera and their cyanobionts. The symbiosis between *Anabaena azollae* and *Azolla,* a water fern, is famous because of the contribution to the nitrogen requirement of rice in paddies [See Reynaud and Roger (1978) for a report of work based in semiarid Senegal].

According to Stewart (1980), 9 genera and about 90 species of cycads have nitrogen fixing root nodules inhabited by heterocystous cyanobacteria. Grobbelaar *et al.* (1984) reported that all 28 species of *Encephalartos,* a cycad native to South Africa, have been found to produce cyanobacteria-infected coralloid roots which reduce acetylene (i.e., fix nitrogen). The cyanobionts in cycads are mostly *Nostoc* spp.

The symbiotic association of great importance in arid lands is that of cyanobacteria, and also algae, with fungi, the association that results in lichens. Cyanobacteria occur in symbiosis in about 8% of the 1700 species of lichens (Stewart 1980). Faurel *et al.* (1953) reported that there were 114 lichen species in the Algerian and Tibesti regions of the Sahara. They further reported that most of these were crustose lichens and 28% of them had cyanobacteria as the sole symbionts while the rest were either heteroisomerous or homoisomerous with algae. Follam (1965) reported 153 species for the Atacama desert while a rather rich flora of 44 species exists in the Negev desert, an area of 9000 km^2 (Galun 1966). Friedmann and Galun (1974) provide lists of lichens found in various deserts of the world. The southern central arid zone of Australia has 40 species of lichens and the crust formed by these and free-living cyanobacteria and other cryptograms occupy 30% of the arid areas of Australia (Rogers *et al.* 1966). Kappen *et al.* (1975) reported that lichens were more apparent in deserts than cyanobacteria, algae, and fungi. They stated that in the Namibian desert lichens locally dominated the vegetation while in the lomas of the Chilean deserts the lichens even served as food for the Guanacos.

There are many reports on the algae and cyanobacteria of arid lands but the most extensive is that of Friedmann and Galun (1974). Russian workers have been active in the Central Asian deserts while most of the work in the Sahara to date has been by French scientists. The most extensively explored arid areas in the world for algal and cyanobacterial activity are the arid lands of North America.

The number of algal and cyanobacterial species in Central Asian deserts is more than 40 (Novichkova-Ivanova 1972). There are 147 algal taxa known for the takyrs and only 30 for the sandy desert where the number is often correlated with moisture content.

Vogel (1955) describes the forms in which cyanobacteria occur in the Namibian desert. Welsh (1965) further gives an exhaustive list of the cyanobacteria in this region. But (1967) reports on the algal-cyanobacterial associations from the deserts of Western Pamier. The Atacama desert is extremely dry and therefore has very few species. Killan and Feher (1939) and Hethener (1967) give lists of those species found in the Sahara while Gauthier-Lievre (1941) reported on those occurring in fresh water and salt marshes of the same area.

While most of the algae and cyanobacteria occur as cryptogamic crusts on arid land surfaces or freely in water bodies, there are those that exist as hypolithic or endolithic organisms. Hypolithic microalgae occur in diaphanous substrates—fine layers of rock minerals that allow some light through. Endolithic microbial communities could be found in desert varnish, which are dark-colored oxides of iron and manganese, on hard rocks whose deposition are attributed to precipitation by cyanobacteria, chemoheterotrophic bacteria, and filamentous fungi (Krumbein and Jens 1981). Cyanobacteria, bacteria, lichens, eukaryotic microalgae, and filamentous fungi are the usual organisms of chasmolithic communities. For these and endolithic photosynthetic organisms light is important so that light colored and translucent rocks are favored (Friedman and Ocampo-Friedman 1984). Endolithic communities in hot and cold deserts worldwide bear superficial resemblance while chasmolithic communities are floristically more diverse among regions (Friedman and Ocampo-Friedman 1984).

Possible Roles of Algae and Cyanobacteria in Arid Environments

Algae and cyanobacteria can play three major roles in the arid lands:

(1) physical improvement and protection of the soil,
(2) contribution of nitrogen to the ecosystem, and
(3) primary biomass production for use in food and secondary production.

Physical Improvement and Protection of Soil

Cryptogamic crusts could be useful in consolidation and stabilization of surfaces through prevention of soil erosion, improvement of water infiltration, and retention and enhancement or seedling establishment (see Metting *et al.* 1988).

Early studies of algae and cyanobacteria in deserts were concerned with their protection and improvement of the soil. Booth (1941) found that the ratio of soil loss in soil with cyanobacterial crust compared to the same without crust was 1:22. He also found that water infiltration was not slowed by crusts and that protected soil contained more moisture. Cornet [(1981), as cited by Metting *et al.* (1988)] showed that *Scytonema* crust in the Sahel of Senegal reduced loss of moisture to the air almost 18 times and that relative humidity under the top lcm of a dry soil was between 8 and 9% with a *Scytonema* crust and 1.3% without a crust. Burns and Davies (1986) have observed that mucilaginous green microalgae are used as soil conditioning agents in some parts of the USA. Soil aggregate stabilization is achieved by adsorption and binding of particulates by microbial polysaccharides as well as enmeshments by living microbial filaments. Species of *Chlamydomonas* and *Asterococcus* have been reported to significantly improve integrity of soil aggregates subjected to disruption by wind (Metting *et al.* 1988).

Shields and Durrell (1964) observed that algal mats provided a substrate for the germination of seeds of higher plants. This is not surprising since cyanobacteria act as pioneers in plant succession. They also add organic matter to soil after death and exert a solvent action on certain soil minerals, maintaining a reserve supply of elements for higher plants.

Fletcher and Martin (1948) made the interesting observation that where cyanobacteria infested rain crust in the Nevada deserts existed, silt and clay contents of such soils increased and sand content decreased. Increases as high as 300% in organic carbon and 40% in nitrogen were observed. Kovda *et al.* (1979) observed that algae and cyanobacteria played an important role in takyr formation. Green algae and diatoms form a pellicle 2 to 5 mm in thickness on the surface of the takyr and appear capable of considerably increasing alkalinity. Microorganisms are also very active in breaking down aluminosilicates in the soil by their biological secretions. Algae and cyanobacteria probably account for the high nitrogen content of the takyr humus.

Nowhere can the protection that algal-cyanobacterial crusts give the soil be more appreciated than in northern Sahel where vegetation cover is less than 30% (Gillet 1975). The soils, mainly Aridisols with a general trend southward of arid brown soils, and a mosaic of ferruginous tropical soils (Alfisols) with a scattering of Vertisol clays and clay loams, developed on alluvial material, are better assessed on their vulnerability to erosion (Berry 1975). The highest rates of soil loss potential are found on ferruginous soils (Alfisols) where coefficients of runoff as high as 40–60% for rainstorms of 40–50 mm have been recorded (UNESCO 1979). In this subdesert zone the high coefficient could be achieved with a rainstorm of just 20–40 mm. An analysis of an exceptionally heavy rainstorm of an average total of 700 mm over the Samaru (11°11′N, 7°38′E) catchment basin in northern Nigeria showed that 400 mm was lost as runoff (Kowal 1972). In West Africa the general trend is an increase in the proportion of total precipitation that comes in storms as one moves from the wetter south to the drier north.

This is a worldwide phenomenon and Bell (1979) has showed that in areas of extreme aridity, two or three consecutive storm bursts may sometimes account for the entire seasonal rainfall. He further states that these areas may experience daily rainfalls that exceed the mean annual value.

Production is limited in the Sahelian rangelands if precipitation is less than 150–200 mm per year (Penning de Vries *et al.* 1980). If the runoff rate is high then the effective rainfall for production has to be much higher. In the Sahel, Penning de Vries and Djiteye (1982) observe that runoff is 20–50% of the annual precipitation when the slope exceeds 1%. Algal-cyanobacterial crusts have the potential for increasing infiltration and stabilizing surface soil.

St. Clair *et al.* (1986) showed that slurries prepared from mature soil cryptogamic crusts could be used effectively as inocula on dry soils in a semiarid rangeland in Utah, USA.

Contribution of Nitrogen to the Arid Ecosystem by Cyanobacteria

Algalization, the practice of inoculating flooded paddies with mixtures of cyanobacteria has been used for biofertilization in paddy rice cultivation. Inoculation with cyanobacteria has often been associated with improved crop performances (Roger and Kulasooriya 1980) even if agronomically significant levels of biologically fixed nitrogen have not been observed (Metting *et al.* 1988).

All heterocystous species of cyanobacteria have been shown to fix dinitrogen (reduce acetylene). Stewart (1980) provides a list of heterocystous, nonheterocystous, and unicellular dinitrogen-fixing species. The list could be much longer and Bothe *et al.* (1984) states that more than 50% of the filamentous, nonheterocystous species fix dinitrogen. Nowhere could nitrogen fixation by cyanobacteria be better appreciated than in arid lands because it has been shown that nitrogen is probably the most deficient vital element in the world's arid regions (Dregne 1968; Cowling 1969; Charley 1972; Cline and Rickard 1973; Penning de Vries *et al.* 1980). Total N concentrations range from 0.008 to 0.064% in some Saharan soils and are less than 0.05% in dry regions of California (Binet 1981).

Of all the arid lands, those in southwestern North America have been the most studied for dinitrogen fixation. Shields (1957) found that amino nitrogen content of algal surface crusts was four times and lichen seven times higher than in samples with neither cyanobacterial or lichen crust in an evaluation of 13 volcanic areas in the western and southwestern USA (Paul 1978). Rychert *et al.* (1978) further report that fixation in clay deserts could reach 10–100 kg N $ha^{-1}yr^{-1}$ in extreme cases, while 2–3 kg N $ha^{-1}yr^{-1}$ could be fixed in other types of deserts. Skujiņš and Klubek (1978) state that in clay containing arid soils the major nitrogen input is by dinitrogen fixing cyanobacteria. The fixed nitrogen is, however, ultimately released in the soil as ammonium, nitrified and then reduced to N_2 and lost from the system.

Reports have also been made from other areas. Reynaud and Roger (1978) report that fixation in the paddies of arid Senegal could range from 10 to 30 kg N ha^{-1} per cultivation cycle. They considered the upper figure of 30 kg N ha^{-1} as exceptional but in a later report (Reynaud and Roger 1981) they observed that a fixation rate of 57 kg N ha^{-1} could be attained, this time, in a flooded coastal dune base, also in Senegal. I estimated (Isichei 1980) that in the Sahel zone of Nigeria 2–5 kg N ha^{-1} could be fixed by *Scytonema* mats every year. Skarpe and Henriksson (1987) observed nitrogenase activity corresponding to 6.8 mmole and 0.6 mmole N_2 fixed $m^{-2}hr^{-1}$ for dark-colored and light-colored crusts respectively from western Kalahari. Species of *Nostoc* and *Scytonema* were associated with both kinds of crusts.

Lichens that have cyanobacterial symbionts also fix dinitrogen. Millbank and Kershaw (1973) reported that between 19 and 28% of fixed nitrogen in the lichen, *Collema tenax,* was released into the growth medium. Release of nitrogen compounds is a normal feature of cyanobacterial metabolism (Taha and Refai 1962, Binet 1981) and this is true of the lichen thallus. Apart from nitrogen, cyanobacteria also contribute growth substances such as vitamins to plants (Roger and Reynaud 1982).

It might be argued that dinitrogen fixation in arid areas may be minimal given the prevailing low humidity. Moreover, I found (Isichei 1980) with *Scytonema,* growing in Sahel and savanna areas, that fixation did not take place at relative humidities less than 50% and relative humidities in the Sahara rarely had exceeded 50% (Grenot 1974). One important factor, however, is the behavior of cyanobacteria and lichens in relation to moisture. Cyanobacterial crusts absorb water very fast but lose the same very slowly. Lange *et al.* (1968) found that in the Negev the normal frequency of dewfall allows for a 2–3% carbohydrate production daily in lichens. This may be true also of cyanobacteria. West (1981) noted that microorganisms involved in desert nitrogen cycles have been found to be adapted to function under much drier conditions that those in more mesic environments. Ammonification and nitrification by bacteria have been found to occur at water potentials as low as -4.5 MPa. It is also most certainly expected that the widely spaced storms revive cyanobacterial and lichen crusts into activity. Dry crusts of cyanobacteria start acetylene reduction activity 24 h after rewetting (Isichei 1980) and nitrogenase activity comes after respiration and photosynthesis (Scherer *et al.* 1984). Duration of fixation may be short but in arid lands where N limits production this may be significant, and Stewart (1978) has cautioned that fixation rate need not be high. Another factor that affects dinitrogen fixation, the high soil pH values, is favorably met in arid areas. It might be possible that high light intensities and high temperature may negatively affect fixation and general growth of cyanobacteria (Reynaud and Roger 1978, Rychert *et al.* 1978) but it is also possible that they adapt to prevailing light intensities (Fogg *et al.* 1973).

Primary Biomass Production for Use as Food and Other Secondary Production

It has often been stated that some of today's arid lands were moister places in the past. The present state of the arid areas resulted from several stresses of which moisture deficiency, accentuated by overgrazing, particularly in tropical and subtropical deserts, is the most important. It would seem as if a way to reverse the trend would be remoistening. Provision of water may not necessarily solve the problem because of attendant problems, such as salt accumulation and low agricultural yields from nutrient deficiency, but also an initial upsurge in production may in turn lead to overstocking in grazing systems (Novikoff 1976). Water availability is essential for ecosystem restoration but it is also desirable to give the arid ecosystem some respite by a change in resource utilization and agriculture. The method of range use, proposed by McKell and Norton (1981), looks attractive but needs rigorous enforcement to work. My proposal here is a supplement to, or change, of the fodder available in the arid environments. This necessary change could be provided by the production capacities of microorganisms.

The ascendancy of biotechnology and genetic engineering in the last decade has made the cultivation of algae and cyanobacteria for various end products a reality such that the question now is: how economically feasible is a mass production of an organism? Algal and cyanobacterial mass culturing and related issues have been extensively discussed in two recent publications (Borowitzka and Borowitzka 1988a, Lembi and Waaland 1988) and several species of algae and cyanobacteria are now produced commercially (see Bold and Wynne 1985, Cohen 1986, DePauw and Persoone 1988, and Regan 1988 for lists of species). Apart from the well known use of nitrogen-fixing cyanobacteria for biofertilization in rice paddies, marine algae are also cultured as direct feed for fish and other aquatic organisms in the aquaculture industry (Lembi and Waaland 1988).

Roger and Watanabe (1986) have observed that on moist soils with adequate sunlight algal and cyanobacterial standing crop can be as large as 1000 kg ha^{-1}. They reported a case of 24 tons (fresh weight) ha^{-1} of cyanobacterial biomass from a flooded rice soil. In cultures the potential productivity of algae is higher than that of tropical forests, marshlands, or intensive agriculture systems (Richmond 1986).

The high production potential of algae and cyanobacteria could be put to more extensive use in the making of protein-rich foodstuffs in the form of single cell protein in the arid areas of developing countries (see Jassby 1988). For example, *Spirulina platensis* abounds in Lake Chad in the Sahel zone of Africa and in other soda lakes of arid Africa. Melack (1979) found that this species in Lake Simbi in Kenya reached a photosynthetic rate of 12.90 mg O_2 $m^{-3}h^{-1}$, a very high rate that was achieved because of the high chlorophyll *a* content of 200–650 mg m^{-2}. Turnover times were 9–19 h. Reynaud and Roger (1981) reported that a flooded dune soil in Senegal attained an average algal and cyanobacterial biomass of 400 g m^{-2}.

Microbial production could be used for both human consumption and animal feed and will go a long way in reducing the pressure posed by overgrazing on tropical arid lands.

Cultivation of algae and cyanobacteria is not new. The Kanem people of Chad Republic have for ages been using *Spirulina platensis* for food. It is harvested with fine nets, sundried, and eaten. *Nostoc* species which occur as small balls growing in river beds are reported to have been eaten in South America and southeast Asia. The arid lands have more than enough light for photosynthesis [see Fitzpatrick (1979) and Table 1] and natural waters have the right pH for algal growth. The major limitations may be water and nutrient availability but artificial water supplies can be used in pond systems.

According to Benemann *et al.* (1979) the mass cultivation of algae and cyanobacteria has many of the general attributes of agriculture, namely, extensive land use, dependence on sunlight and climate, invasion by pests, weeds and herbivores, *and* large requirements for water and fertilizers. Such mass cultivation is particularly favored by the climate of the arid areas.

Commercial cultivation of *Chlorella* for food coloring was first carried out in Japan in the late 1950s (Tamiya 1957). Kawaguchi (1980) puts the number of *Chlorella* factories operating in China and southeast Asia at 46 as of 1979. *Scenedesmus* is being produced in commercial quantities in Germany. *Dunaliella*, a green alga, tolerates hypersaline environments and is now a good source of beta-carotene and glycerol (Borowitzka and Borowitzka 1988b). *Porphyridium* is a source of mucilages (Vonshak 1988). Feasi-

Table 1

Mean Annual Total and Relative Duration of Sunshine, and Degree of Aridity for 18 Stations Selected to Represent 8 Major Arid Areas

Arid Area and Station	Latitude	Longitude	Elevation m	Degree of Aridity[a]	Total Sunshine, h	Total Sunshine of Maximum Possible %
Saharan						
Giza, Egypt	30°02′N	31°13′E	21	E	3500	80
Dakar, Senegal	14°44′N	17°28′W	20	S	2800	64
Wad Medani, Sudan	14°24′N	33°29′E	405	A	3800	87
Central Asia						
Omsk, USSR	54°56′N	73°24′E	94	S	1900	43
Aral Sea, USSR	46°47′N	61°40′E	56	A	2450	56
Thar						
Quetta, Pakistan	30°11′N	66°57′E	1799	A	3450	79
Karachi, Pakistan	24°54′N	67°08′E	4	A	3100	71

North American						
Salt Lake City, USA	40°46′N	111°55′W	1329	A	3100	71
El Paso, USA	31°48′N	106°24′W	1194	A	3600	82
Atacama						
Atacama Desert, Chile	(23°S)	(69°W)	(800)	E	4000	91
Parinacotta, Chile	18°12′S	69°16′W	4392	A	2500	57
Monte-Patagonian						
Trelew, Argentina	43°14′S	63°18′W	39	A	2400	55
San Juan, Argentina	31°36′S	68°33′W	827	A	3000	68
Namib-Kalahari						
Alexander Bay, S. Africa	28°34′S	16°32′E	21	A	2300	52
Uppington, S. Africa	28°26′S	21°16′E	814	A	3550	81
Mocemedes, Angola	15°02′S	12°02′E	44	A	2200	50
Australian						
Deniliquin	35°32′S	144°58′E	102	S	2400	55
Alice Springs	23°48′S	133°53′E	546	A	3200	73

[a] E = Extremely arid, A = arid, S = semiarid.
From Fitzpatrick 1979.

bility studies are conducted in several places on producing waste-grown algae and cyanobacteria, and production has been reported from Israel. In Mexico, the Sosa Texacoco Corporation produces several tons of the cyanobacterium, *Spirulina maxima,* per day from basins for soda extraction of Lake Texacoco. Texacoco uses a production process designed by the Instut Français du Petrol which utilizes bicarbonate rich media and carbon dioxide enrichment using gas siphons (Durand-Chastel 1980). The product from the Mexican venture, Tecuitlati, has found a direct use as a protein supplement in bread and gruel. *Spirulina* is one of the richest sources of plant proteins—up to 70% by weight (Jassby 1988). It is also converted to animal protein when used as fodder for poultry and hog breeding. Studies have been initiated to exploit *Spirulina,* abundant in Lake Chad, for commercial use (Bertil Ostrom, Sweden, personal communication). In addition to protein production, algal biomass technology could be used for oxygen production in waste-water treatment in tropical urban and rural situations. Oswald (1988a) reported that such biomass-based systems are operational in California, USA.

The mechanics of carrying out the cultivation of algae and cyanobacteria in arid lands has to be further studied but a considerable amount of information can be gained from areas where cultivation is already in progress [see Venkataraman (1969) and Hamdi (1982, p. 59 ff)]. Oswald (1988b), for example, reports that yields have risen to short-term levels of up to 25 g $m^{-2}day^{-1}$ (dry weight) in outdoor cultures in the past three decades. Richmond (1986) estimates sustained commercial yields of between 12 and 15 g $m^{-2}day^{-1}$. The major limitation will be the technology for obtaining water and fertilizers. Available water may determine the organism to be cultivated-alkaline water for *Spirulina* and hypersaline water for *Dunaliella,* for example. Most water in tropical arid areas, especially from underground sources are most likely to be alkaline. Mineral media employed in algal mass cultural are given by Borowitzka (1988). Studies must also be carried out on acceptability in areas where algae and cyanobacteria are not yet in use. The processing of cultivated organisms has been discussed in several places, for example, by Means *et al.* (1962) and Oswald and Golueke (1968) while Mohn (1988) discusses harvesting alternatives. There are other problems that may arise once production has started, amongst which are the usually dilute standing crops and the invasion by nonselected species and pathogens, such as those of cyanobacteria discussed by Hamdi (1982, p. 56 ff).

Acknowledgments

I wish to thank Prof. W.W. Sanford without whose encouragement this article would not have been written. I am grateful to Dr. F. Adeniyi for information on *Spirulina.*

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