Is Sustainable Development of Deserts Feasible?

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Abstract

Hot deserts that presently cover about one-fifth of the land area of our planet are rapidly devouring more and more arable lands mostly due to anthropogenic causes. We propose an interdisciplinary approach to revitalizing and commercializing hot deserts, which is based on systems thinking and Russian and NASA space technology experience in designing life-support systems for long-duration flights. We formulate ten principles for the design of sustainable life support systems in deserts, which can make the development of the deserts feasible. It is discussed how the principles can be employed to design and operate desert's eco-industrial parks with greenhouses in which the transpired and evaporated moisture is collected and condensed. The potential benefits of setting up the eco-industrial parks in deserts include the slowdown and eventual reversal of the desertification trend, the migration of many industrial production facilities from mild-climate regions to deserts, the increased availability of potable water and food in deserts, the development of poor African countries, and the emergence of new investment markets.

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Introduction

Hot deserts cover about one-fifth of the Earth's land area (1). They are usually characterized by the lack of moisture and the abundance of sunlight. Both factors generally make hot deserts unsuitable for living. One of the key global environmental problems is the rapid expansion of deserts into arable lands. According to UN estimates, one-third of the Earth's land area is at risk of turning into desert wasteland (2). By 2025, two-thirds of the arable land in Africa is expected to disappear, along with about one-third in Asia and one-fifth in South America. Over 30% of the land in the United States is affected by desertification. Over 250 million people are threatened by desertification, and more than half of them are at risk of being displaced to other parts of the world. The major desertification causes are overcultivation, overgrazing, deforestation, poor irrigation practices, sloppy conservation, overtaxed water supplies, and soaring population. The continent most affected by desertification is Africa with its Sahara desert, which is the largest hot desert in the world. To fight desertification, provide food, water, and other humanitarian aid, and reduce poverty in Africa, UN yearly spends billions of dollars.

On the other hand, desert is now considered as a potential solution to energy crisis, another key global problem today. Every year, each square kilometer of hot desert receives a solar energy equivalent to 1.5 million barrels of oil, and about 57 million TWh of solar energy falls down on all hot deserts of our planet (1, 3). In contrast, the total world energy consumption in 2005 was as low as 135,000 TWh (4). The Sahara alone, with an area of 9.1 million km^2, receives about 20 million TWh of heat per year, which, even with the today's 10-15 % solar energy/electricity conversion efficiency, is ten times more than the overall energy consumption in the world (3). This gave a rise to a lot of projects aiming at utilizing solar energy, ranging from photovoltaic batteries to power plants with sunlight concentrators. However, the direct implementation of these sun-powered technologies as separate processes is strongly hindered by the high expenses caused by the transportation of produced power, negative environmental impact on desert wildlife, and the absence of highly efficient power storage technologies, which are needed to supply power when the Sun is not shining. It should be noted that the implementation of these technologies alone is nearsighted because this solution cannot slow down desertification, bring deserts back to the stock of arable lands, and contribute to solving the problems of the increasing water and food deficit.

At the same time, desert is a system similar to the extreme habitats studied by space life support science since the mid 1950s, which are characterized by the availability of a powerful source of thermal energy and nearly complete absence of organic life and water (5, 6). This suggests that this 50-year experience, which is based on systems approach to solving the problems of food, water, air, and energy supply, should be analyzed and the results can be used in formulating the recommendations for sustainable development of deserts.

Results and Discussion

We will focus our attention on life support systems for long-duration space missions, such as a flight to Mars and settlements on the red planet. There are two types of life-support systems, aboard a spacecraft and on the surface of a planet with no atmosphere. The first type is characterized by stringent constraints on the mass, volume, area, and power, and complete absence of resupply sources. For the second type, the constraints are much less stringent, depending on the resources of the planet and the stocks of materials and technologies brought from the Earth. Obviously, the problem of deserts has much in common with the second type. As we are going to apply the results of space technology research to Earth’s deserts, the problem of air revitalization will not be discussed here and the focus will be placed on the problem of water reclamation, which is crucial for deserts.

Life support science in space technology was developed on the basis of two regenerative systems: physicochemical and biological. Let us consider each of them in detail.

Physicochemical regenerative life support systems in space technology. Design of a space life support system begins with specifying the values of power, mass, and volume (5-14). The existing physicochemical methods for water recovery from human wastes can be conditionally classified into three groups. In the first one, the contaminants are caught, adsorbed, or absorbed by adsorbents, ion exchange resins, packed-filter surface and volume, or other types of collectors. Although these devices do not consume much power and can provide high water recoveries, their service life is a strongly decreasing function of the concentration of contaminants in wastewaters, they are not universal in treating wastewaters of different nature, and their capacity per unit of treated water is very low for concentrated solutions, which results in more frequent replacements. The treatment mechanism for the second group is based on the withdrawal of water through semipermeable partitions, such as membranes, under the action of pressure, electric field, etc. Although their power consumption is not high, they cannot efficiently treat highly concentrated solutions such as urine, and their water recoveries are not high (as a rule, 50 to 80%) because their driving force is much affected by the concentration polarization near the semipermeable surface and the resistance of the cake deposited on the membrane surface. The third group employs different types of evaporation. Although these devices can provide high water recoveries, their power consumption is rather high and the formation of solid deposits of contaminants, such as scale, on the heating surfaces can considerably reduce their efficiency.

It should be noted that all physicochemical devices are based on the principle that the recovery of water from a wastewater opposes the driving force of the treatment process, which negatively affects their capacity and power consumption. In addition, the presence of organics in human wastes imminently causes the growth of bacteria inside the devices, which strongly deteriorates their performance. It should also be noted that the contaminants in human wastes often include a mixture of salts, mineral substances, and organics, which, as a rule, cannot be effectively recycled by physicochemical methods and returned to the system's matter turnover. Their disposal implies that the same amount of these substances should be resupplied as stocks. For example, urine, a rather concentrated solution (more salty than seawater), contains a lot of useful components, which can be used for the mineralization of recovered water and as nutrients in a space greenhouse. Its treatment by physicochemical systems requires high expenditures of power and other material resources, including the addition of strong bactericides (5), with all these useful components being disposed. The above disadvantages of physicochemical treatment systems together with the power and mass constraints imposed on the design of spacecrafts and orbital stations makes it practically impossible to build a truly regenerative physicochemical life support system (5, 6, 9). As a result, the water in the Russian and international space stations has been reclaimed mostly from the humidity condensate using a simple filtration-ion-exchange-adsorption-mineralization-disinfection system, with the recovery being as low as 80%. The deficit of water is compensated by water stocks and the water produced by hydrogen-oxygen fuel cells, which generate electricity in addition to solar-powered photovoltaic batteries. A part of this water is used to produce oxygen for breathing. The latter illustrates one of the main principles of life-support system design: preference is given to devices and methods the byproduct or wastes of which can be beneficially utilized aboard the station. Numerous experiments, including long-duration manned experiments in ground-based, closed-loop testing facilities, imitating the conditions of Moon and Martian missions – 3-month to one-year Russian experiments at the Institutes of Biomedical Problems (Moscow) and Biophysics (Krasnoyarsk), 3-month experiment at Johnson Space Center, "amateur" Biosphere 2 in Oracle, AZ (15), and orbital operation of a Russian SRV-SG (system for recovering water from wash and shower wastewater) in the 1980-90s, confirmed that physicochemical systems alone cannot provide a high water recovery even in ground-based experiments (5, 6, 12-14). It should be noted that the basic design principles for physicochemical systems, which include the highest productivity, least footprint, and production of desired components at the expense of waste generation, contradict the nature's principles.

Bioregenerative life support systems in space technology. It was found in the studies of bioregenerative systems (5-9), which are considered as the alternative to physicochemical systems, that their performance aboard space stations will be characterized by a rather high power consumption, which is needed to produce artificial light (use of free sunlight energy as the photosynthesis driving force for the biodegradation of organic contaminants aboard space stations is impossible because of their tightly insulated walls), and large initial masses and volumes. Although five tests of a human-algae-mineralization life support model conducted in the ground-based experimental facility built in the late 1960s at the Institute of Biomedical Problems, Moscow, Russia showed a high efficiency of unicellular algae for oxygen and water regeneration, the volume of this system per one crew member was 15 cubic meters and contained 45 liters of algal suspension with a dry algae density of 10 to 12 g/l, which considerably exceeds the payload, power, mass, and volume specifications for the life support system in space stations (9). Their possible advantage for food supply does not work either: to grow the daily portion of fresh greens for one crew member requires several square meters of greenhouse area, which cannot be afforded from design considerations. In addition, the biological processes run quite slowly and the plants and bacteria are much sensitive to the nature of contaminants in the wastewater and the absence of gravity. Potentially, a truly regenerative biological system can be built only on the sunlit sides of the Moon and Mars, where there is plenty of free surface area and minerals (6, 8). It should be noted that the absence of air atmosphere on these planets is a serious additional threat to the viability of bioregenerative systems: any emergency dealing with the composition of air in the greenhouse (excessively high concentrations of methane, carbon oxides, dinitrogen oxide, etc), growth of pathogens, or breaks in power supply can cause the death of plants, algae, and bacteria (7-10). Also, the important factor for bioregenerative systems is the use of biologically active water in their water turnover. The experiments conducted at the Institute of Biomedical Problems in the end-1970s and early-1980s showed that almost all physicomechanical water-treatment systems, except for pressure-driven membrane processes (reverse osmosis, ultrafiltration, and the like), produced a "biologically dead" water, which, at least, noticeably slowed down the growth of greenhouse plants. The use of electromagnetic treatment and saturation of recovered water with salts and other minerals by slow percolation through soil beds made the water biologically active and accelerated the growth of the plants.

Summarizing the above, it should be noted that the efficiency of a life support system is in direct proportion to its water recovery and can be substantially increased due to its production of food, oxygen, and other useful substances, as well as due to the processing of wastes other than human (5, 6). The losses of power during its transmission and production, especially low conversion degrees and low ratios of produced power to power-generator volume, can considerably reduce the efficiency of the life support system as a whole. That is why the use of direct sunlight to drive the biological process in bioregenerative system is strongly recommended (6-12).

Principles for the design of sustainable life support systems in extreme habitats. The above implies that the design of sustainable life support systems for extreme habitats characterized by the availability of a powerful source of solar energy and nearly complete absence of organic life and water should be based on systems approach and closely mimic the basic nature’s principles. The main design principles for such a system are summarized in Table 1.

Some of these principles have been successfully implemented in ecological design, the approach that applies nature’s principles to food production, generation of fuels, conversion of wastes, and repairing environments (16, 17). Eco-parks (floating wind turbines with specially cultivated microorganisms) were successfully used to revitalize the dead waters polluted by toxic waste from a local landfill and septage water dump in Cape Cod and decompose high-strength industrial food wastes in Brazil, Australia, China, Central Europe, and United States.

Table 1. Design principles for sustainable life support systems in extreme habitats characterized by the abundance of sunlight and deficit of water

DESIGN PRINCIPLE	DESCRIPTION/EXAMPLES
Large footprint	System's footprint area should be as large as necessary for consuming all wastes in due time (system should be wasteless) and generating enough electric and thermal power by solar-powered generators
Efficiency enhancement by consuming wastes	The efficiency of the system can be increased by consuming the wastes (carbon dioxide, nitrogen compounds, and other nutrients and catalytic substances) produced by the units not involved in the regenerative processes.
Diversification of solar energy consumption	The consumption of solar energy should be diversified: electric power by photovoltaics and power plants with sunlight concentrators, thermal power for photosynthesis, heat accumulators for dark periods, accompanied by the use of different power sources, such as hydrogen-oxygen fuel cells and the like.
Diversification of biofuel production	Feedstocks and processes for biofuel production should be diversified: starch, cellulose, lignocellulosic biomass, fermentation, biorefinery, etc.
Waste of one process is an input to another	The processes to be integrated into the system should be able to use its wastes and/or products as feedstocks, with all the wastes, including the wastes of these processes, being completely processed by the system.
Waste formation = waste consumption	The rate of waste formation should not exceed the system's capacity of processing the waste.
Complete water recycling	The system should provide complete water recycling by collecting all the evaporated plant transpiration and soil moisture and the water contained in the gathered crop. The water vapors and collected water should be treated by methods as close to the natural treatment processes (electrostatic ionization, soil infiltration and percolation) as possible to provide its biological activity.
No foreign materials	Foreign substances that can poison or slow down the regenerative processes are strictly prohibited.
Localization	All subsystems and units should be as close to each other as possible to reduce the transportation expenses and losses.
Monitoring	The system should be carefully monitored and controlled to achieve the highest efficiency.

Life support systems approach to the development of deserts. Let us examine how the proposed recommendations can be applied to deserts. The major problem with desert environment is water deficit. This problem can be solved if we remember that up to 90% (depending on the interplay between temperature, humidity, and carbon dioxide concentration) of the water that entered the soil is given off by plant transpiration and soil evaporation back to the atmosphere. Greenhouses in which the transpired and evaporated moisture is collected and condensed, much like it is done in Russian and American ground-based biomodules for future space stations (for example, by using special moisture-absorbing sponges) instead of letting it go to the atmosphere, can be used to grow vegetables and fruits for food and crops and biomass for biofuel.

One of the critical wastes in many industrial processes is carbon dioxide. But at the same time, the increased concentration of carbon dioxide enhances the growth of plants. For example, a group of scientists at Weizmann Institute's Environmental Sciences and Energy Department found that the increased concentration of carbon dioxide led to the expansion of the Yatir forest, planted at the edge of the Negev Desert 40 years ago, into arid lands (18). This is attributed to the fact that higher concentrations of carbon dioxide make it easier for plants to consume carbon dioxide without giving off a considerable amount of water vapor through their pores.

In order to develop deserts and slow down desertification, we can build wasteless eco-industrial parks integrated with solar- and wind-powered generators of electrical power and greenhouses with closed water loop producing biomass and food. In these parks, the capacity of industrial plants should be limited by the capacity of greenhouses to consume their wastes as nutrients and/or catalysts (phosphorus, nitrogen, carbon dioxide, etc.) and the total capacity of power-storage facilities for the operation in dark periods. Carbon dioxide can be used for enhancing the growth of plants and the production of additional amounts of water needed for operating needs (Sabatier reactors, Bosch reaction). Consequently, the parks can reduce the emission of harmful gases into atmosphere. In addition to nature-like water treatment operations such as electrostatic ionization and percolation, the water can be treated in solar stills, which are powered by free solar energy. The industrial plants involved in the parks should be located as close as possible to the sources of electric power and the consumers of their wastes, such as greenhouses, Sabatier reactors, etc., and should not produce any substances that can poison the living organisms and plants in the greenhouses. Biofuel can be one of the products of these parks, which can be used to produce power for their operation in dark periods. A part of the absorbed sunlight should be used for the metabolic processes in the plants and the rest for the production of electric power and heating thermal accumulators. The high efficiency of such parks can be provided by their wasteless operation, the efficient allocation of their subsystems and units, the use of natural nutrients available in the desert and those contained in industrial wastes and produced in the greenhouses, the use of free solar and wind energy and the natural mechanisms of photosynthesis and respiration in plants.

As compared to space stations, deserts impose much less constraints on the design of their life support systems. The presence of gravity and direct sunlight, the availability of minerals, air, and nearly unbounded surface area makes this problem much easier. Using the fact that 90% of the water involved in plant growth is transpired by plants and evaporated from the soil, with as low as 10% contained in the plant tissue, the problem of water recycling can be solved by the collection of these water vapors and their condensation. Technically, this can be accomplished using dehumidifiers or any other water-absorbing device. In contrast to regular greenhouses, in which the moisture is disposed outside to avoid the formation of dew on the surface of plants and, hence, the intense growth of pathogens, the collected moisture can be returned to the production cycle to considerably reduce, or even eliminate, the resupply of water to the greenhouse. The results of the Biosphere 2 project (7) suggest that the evaporated water to be collected should be specially treated to make it biologically active, which is achieved in nature by the electrostatic treatment of water vapors in clouds and the percolation of rain water through soils and rocks. Both treatment processes can be set up in the greenhouse facility. For example, the electrostatic treatment of water vapors can be accomplished by Chizhevsky air ionizers. The results of space technology studies demonstrating that a reduced concentration of deuterium in water can enhance the biological activity of water, which implies a higher rate of biomass growth and faster consumption of wastes, can also be utilized (19). If necessary, the collected water can be treated to a higher purity degree by the solar still integrated with the greenhouse (20). The optimal concentration of gases in the greenhouse can be adjusted by adding portions of fresh air from the surroundings and/or other gaseous mixtures. In hot deserts, the sunlight intensity is much higher than 4000 foot candles consumed by plant photosynthesis (11), which allows one to use a part of the roof area for the installation of photovoltaics and/or solar stills.

The electric power needed to operate the greenhouses in deserts can be generated by nearby solar-powered photovoltaic batteries, steam turbines with sunlight concentrators, and/or wind turbines and stored in electrical, mechanical, thermal, or chemical storage devices, the efficiency of which today is getting closer and closer to the level acceptable for the industry (21, 22).

The growth of biomass and/or crops in such greenhouses for the production of biofuel can significantly contribute to the mitigation of global climate changes and provide additional amounts of fuel (23-25).

Specific interdisciplinary scientific and engineering studies have to be performed to determine the feasibility and cost benefits of this approach to the development of hot deserts for different parts of the world. In particular, computer scientists should develop efficient monitoring systems to watch and control material balances and flows throughout the park; operations research specialists should develop the procedures for optimal allocation of facilities and efficient use of resources; biologists and ecologists should study and catalog various biological processes to determine inputs, outputs, and process rates; space technology specialists should apply their experience in life-support systems design to build closed-loop systems; engineers should apply structural thinking and their experience in chemical technology, alternative energy, and agricultural fields. The studies can be started with the Mojave Desert in California, the Great Basin Desert in Nevada and Utah, the Chihuahuan and Sonoran deserts in the US Southwest and Mexican North, the Arabian desert, and the Negev desert in Israel. Then, the results of these studies can be extended to the Sahara and other African deserts.

Some of the potential benefits brought about by the proposed approach are the slowdown and eventual reversal of the desertification trend; the migration of many industrial production facilities from mild-climate regions, where most people live, to deserts; the generation of biofuel for both industrial facilities and transportation devices in deserts; the increased availability of potable water and food in deserts. From the humanitarian viewpoint, billions of dollars spent by UN on desertification consequences and poverty in Africa may be used to develop infrastructures that will make poor African countries self-sustainable. The economic benefits may be the potential boom of investments in desert lands, which would help minimize the risks of economic crises such as the recent collapse of the housing market that contributed to the turmoil on Wall Street.

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