Annals of Arid Zone 45(2): 1-31, 2006

The Sustainability of Arid Agriculture: Trends and Challenges

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Abstract: (Please supply)

Key words: (Please supply)

In efforts to provide food and fiber to a growing and developing world, agriculture is challenged to increase productivity. Moving water into arid regions and the introduction of irrigated agriculture constitute a key element in any strategy for increased global production. Arid regions offer large undeveloped land and a climate conducive to plant growth and can provide high yielding cultivation on condition that water is available. The sustainability of arid zone agriculture is questionable and faced with combined challenges of development and protection of water resources, managing salinity and creating long-term economically and environmentally sound operations. In this review we will address strategies to ensure the sustainability of arid agriculture via farm and regional management of water and salinity and the use of appropriate plant and crop sciences with an eye towards the agronomic feasibility of the technologies required to overcome the inherent challenges of agriculture in the drylands.

Defining Sustainable Arid-Agriculture

Since the term became fashionable, countless definitions for "sustainable agriculture" have been proposed (Gold, 1999). These can be quite detailed, for example; the US Congress which defined as sustainable agriculture that can: "satisfy human food and fiber needs, enhance environmental quality and the natural resource base upon which the agricultural economy depends, make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls, sustain the economic viability of farm operations and enhance the quality of life for farmers and society as a whole." (FACTA, 1990) Alternatively, sustainable agriculture has been characterized more simply, such as the definition put forward by farmer-philosopher Wendel Berry: "agriculture that does not deplete soils or people" (Jackson, 1984). Some argue that efforts to reach a precise definition are ill-advised (Pannell, 1999). As the etymology of "sustainable" can be traced to the Latin *sustinere* (sus-, from below and *tenere*, to hold) any definition will need to imply that the yields from such agricultural activities must be able to last. Frequently, sustainable development is described as having three components: ecological, economic and social. Given the limited scope of this article, only the first two elements will be reviewed, even as there are certain to be critical "social" aspects to a given local or national strategy for sustainable desert agriculture.

Discussions about the sustainability of *arid* agriculture could of course consider dynamics common to all agricultural ventures. Pest control methods that do not pollute or poison farm workers, fertilizers that will not contribute to water contamination and non-erosive tilling practices, to name a few, are important components of sustainable agriculture wherever humans work the land. Yet, a thorough review of all aspects associated with agricultural sustainability is beyond the scope of a single article. Hence, this review of sustainability in arid agriculture should offer a particular focus on those challenges that are unique to this class of drylands. This should begin by clearly indicating what constitutes "arid lands".

For over fifty years, arid zones have generally been defined by versions of "the Aridity Index" introduced by Thornthwaite (1948): a ratio relating annual precipitation (P) to annual potential evapotranspiration (ETp), the amount of water lost from non water limited soil by plant transpiration and direct evaporation from the ground. According to the UNEP index of aridity, defined as AI = P/Etp^{-1}, arid regions have a P:ETp ration of less than 0.2 and hyperarid regions less than 0.05 (UNEP, 1992). By this estimate, the United Nations estimates that some 10 million km^2 or 7.5% of the planet are "hyper-arid" lands while some 16.2 million or 12.1% of the earth can be classified as "arid". This generally refers to lands where precipitation does not exceed 300 mm $year^{-1}$. It is important to emphasize that the present survey will not include agriculture in the semi-arid zones, where rainfall can reach 500 mm $year^{-1}$, and the AI is between 0.20 and 0.50.

The harsh climate in the arid zones gives rise to conditions that are fundamentally different for agriculture than in other temperate regions, including semi-arid areas; 1) Typically, commercial agriculture must rely on irrigation; 2) Soil salinity is high and organic content is low; and 3) Because biotic activity is not particularly high, these lands are not robust and are considered to be especially vulnerable ecologically. While archaeological evidence indicates that domestication of crops, human agricultural organization and irrigation-based civilizations originated in the then "Fertile Crescent" of Mesopotamia between six and eleven thousand years ago, for the most part, the agriculture of ancient peoples was not particularly productive in arid regions. Indeed, numerous examples exist of ancient agriculturally based civilizations in the drylands whose lack of attention to the ecological implications of their practices eventually led to massive damage to the soils and water resources that supported them and their ultimate demise (Diamond, 2005).

Pulitzer prize winner Jared Diamond describes the fundamentally unsustainable agriculture of old which essentially sewed the seeds of its own destruction: "Because of low rainfall and hence low primary productivity, (proportional to rainfall), regrowth of vegetation could not keep pace with its destruction, especially in the presence of overgrazing by abundant goats. With the tree and grass cover removed, erosion proceeded and valleys silted up, while irrigation agriculture in the low-rainfall environment led to salt accumulation . . . . They committed ecological suicide by destroying their own resource base" (Diamond, 1999).

Key Challenges to Arid Agriculture

During the second half of the twentieth century, the demand for arid agricultural production grew as population densities in deserts across the planet rose. Practices emerged which allowed for dramatically expanded cultivation of these driest of lands. Moreover, the long-growing seasons and the increased feasibility of long-distance export of agricultural produce offered certain commercial advantages to farmers in arid lands. The Food and Agricultural Organization estimates that while 17% of the world's farmland is irrigated, because of the longer growing seasons, its contribution to overall production may be twice that. (Clemings, 1996) While U.S. irrigated lands only amount to 17% -- they produce roughly half the total value of crops nationally (Howell, 2001). So while the short-term economic feasibility of agriculture in the drylands is beyond question, its sustainability remains unclear. To be agronomically successful and economically competitive in the long-run, modern arid agriculture will need to rely on relatively intensive utilization of new technologies.

In general the agriculture that emerged during the past fifty years can largely be categorized as part of the modern "conventional" or "industrial" farming. The World Bank attributes the dramatic 70-90% increase in overall food production to mechanized approaches and techniques (Gold, 1999). As such, agriculture on arid lands in developed regions also frequently involved increasingly large farm units and expensive capital investment, farm equipment that efficiently replaces laborers, sophisticated irrigation systems, monocultures and extensive utilization of pesticides and fertilizers.

But despite their remarkable productivity, there were environmental side effects which raised questions about the sustainability of modern agriculture in arid regions. These included loss of soil fertility due to erosion, compaction, and loss of organic matter. Perhaps of greatest concern was the potential of irrigation to lead to waterlogging and to the salinization of the soil and surrounding water resources, or worse yet, their combined impact (Kahlown, 2002). Agricultural runoff became a leading source of water contamination in many Western countries. And of course the "mining" of aquifers is by definition unsustainable. From the state of Gujarat in India to the Ogalala aquifer in the American Middle West, water resources became depleted in order to meet the growing demands of agriculture. Pesticides left a toll on human health and in fact led to development of resistance in more than 400 insect species (Gold, 1999).These obstacles must be overcome if agriculture in arid and semi-arid lands is to truly be "sustainable".

There have been many calls by public interest groups for a retreat from modern agricultural technologies and their associated ecological ills, among them a return to organic, chemical free, diverse, low impact agriculture (NRDC, 1999). Yet, other perspectives advocated a middle path (Union of Concerned Scientists, 1999).

Recognizing the imminence of a food crisis (Brown, 2004) considerable investment has gone into reducing the impacts of the new technologies to create a modern agriculture in the drylands, which both offers the huge production benefits of industrial agriculture, but that also reduces its negative consequences. Of particular significance are the technologies designed to increase efficient water management and irrigation as well as the introduction of new plant breeds that are both salt and drought tolerant. Solutions to most of the traditional obstacles to arid agriculture exist and can be readily adopted. It also projects those areas where future research can both minimize environmental impacts and contribute to greater agricultural productivity in arid drylands.

- This paper reviews progress in the field, focusing on recent developments in desert farming in this context. It is divided into three sections:
- Challenges associated with providing efficient irrigation while maintaining the integrity of water sources in the drylands;
- Challenges associated with plant breeding and introduction of appropriate crops given land and water conditions in arid lands;
- The economic dynamics associated with modern arid-land agriculture.

The resulting picture is a cautiously encouraging one, where recent scientific and technological innovations have improved the profitability of arid agriculture and ongoing research promises to increase the yields and standard of living for agrarian communities in the drylands.

Water Management and Irrigation in Arid Lands

Long term water supply

Given the inherent dynamics of scarcity, the most fundamental question regarding water management to support agriculture in arid regions involves the sustainability of water sources. Traditionally, desert agriculture relied on the harvesting of runoff from the infrequent storms. Later, ground water was tapped by wells. More recently wastewater reuse and desalination offer supplementary sources of water. Each of these sources poses its own challenges and question marks.

Water harvesting in the drylands can in fact provide substantial quantities of water. Israel, for example, has expanded its water supply by some 7% by capturing rainwater and utilizing it for irrigation in arid and semi-arid regions (Tal, 2005). Yet, this supply is inherently given to periodic droughts and the quality of water may suffer from the salinization caused by evaporation. As the mining of ground water is a relatively recent phenomenon, its intrinsic un-sustainability is only now being appreciated. Some 15,000 wells have already gone dry in the Indian state of Gujarat, with enormous social turbulence and human desperation (Pearce, 2006). The steady disappearance of the Ogallala aquifer, by far the United States' largest freshwater resource, is only now beginning to leave its mark on the farmers across the drylands of the western section of the country (de Villiers, 2000). A variety of strategies are being explored to reduce water usage, including integration of crop and livestock systems on rangelands (Allen, 2005) as well as water conservation and phaseout of conventional irrigation systems (Postel, 1997). Ultimately, it is clear that agriculture that relies solely on groundwater, must adjust extraction rates to meet recharge rates, or inevitably face extinction.

The reliability of treated effluents and desalinated waters is ostensibly greater; however, they pose other problems – both environmental and economic. Water scarcity has promoted development of wastewater reuse programs in dry climate regions of the world. In Israel, effluents (treated wastewater) today contribute roughly a fifth of Israel's total water supply, and a far higher percentage of the irrigation supply for agriculture (Shelef, 2001). There are three major concerns involved with wastewater reuse: human health, detrimental effects to plant growth, and soil and groundwater degradation. Health concerns can be rectified by treatment levels high enough to insure safe use of the effluent (Carr *et al*., 2004). Contaminants in effluent include relatively high concentrations of mineral ions including nutrients, salts and specific ions toxic to plants including sodium, chloride and boron. Effluent is therefore regarded as both potentially beneficial when nutrients can be utilized for crop production instead of fertilizers and detrimental due to negative effects of salts on plant growth and yields (Pettygrove and Asano, 1985).

Management of effluent for irrigation, first and foremost, means salinity management and increased leaching requirements. Soil degradation and groundwater pollution can occur when the recycled wastewater contains chemical or biological contaminants not otherwise present in the agricultural ecosystem (Salem, 1996). In order for effluent to be the dominant water source for irrigation, water must be treated to a level allowing unlimited use on all crops and on all soils according to health, agronomic and environmental standards together.

Desalination of brackish groundwater and seawater potentially could provide limitless water for irrigation. The high energy costs involved and the cost and ecological issues surrounding disposal of concentrated brines challenge desalination projects. Although desalination is today still regarded as cost-ineffective (Beltrán and Koo-Oshima, 2006), desalination, first for drinking water and subsequently for irrigation is becoming more and more common, starting in water-poor-currency-rich, countries including Kuwait (Hamoda, 2001) and Israel (Tal, 2006).

Providing water for plants in an arid environment: Climate-driven demand plus salinity management

The water requirement of plants is mainly a function of the local climate. Most of the water consumed by a plant moves through it passively and evaporates into the atmosphere via the transpiration process. The same crop in a hot, dry, arid region can require 3 to 4 times the quantity of water compared to a cooler, more humid region (Rana and Katerji, 2000). A cultivated crop in an arid-region may well demonstrate increased growth and productivity compared to the same crop grown in a more temperate zone due to advantageous temperature and radiation, and the arid zone may allow production in seasons when cultivation is not possible in the other regions. For example, favorable climate has contributed to bell pepper yields reaching 160 t h^{-1} in the Negev Desert of Israel, far higher than normal in cooler climates where such production would depend on expensive climate control. The long seasons and winter harvest of the peppers make cultivation of high quality produce and export to European markets profitable for the Israeli farmers. Such production necessarily requires large production related inputs; specifically of water and fertilizers.

Irrigation water necessary to arid zone agriculture imports and transports dissolved mineral salts. These salts present a major obstacle to sustainability. Mineral ions in irrigation water include nutrients, often added by growers as fertilizers in advanced irrigation systems, as well as undesirable salts. In arid zones, large amounts of otherwise innocuous minerals located naturally in the soil can be mobilized as intensive water application is practiced (Smedema and Shiati, 2002). Plants take up water and mineral ions selectively. Most of the undesired soluble salts are left in the soil as water uptake occurs (Bernstein, 1975). Accumulation of these salts in the soil creates a negative environment for plant growth. Root zone salinity is often described as behaving in an identical manner to drought. Both the decrease in water and the increase in solute concentration in the soil cause a decrease in the soil solution's potential energy. Water flows from high to low potential along a gradient within the soil-plant-atmosphere continuum. Decreased potential in the root zone causes a reduction in this potential gradient and hampers flow from the soil to the plant (Gardner, 1991).

Of course, the greater the water requirement of the crop, the greater the absolute amount of salts left in the soil following uptake. In arid regions this amount can be compounded by naturally saline soils and by available irrigation water with high concentrations of salts. Since salt build up in the root zone is harmful and can become detrimental to agriculture, leaching is critical in irrigation management. Salts leached from the root zone do not disappear however. Leached salts make their way into both subsurface and surface water resources; often those utilized for agriculture themselves.

Overcoming obstacles to irrigation in the drylands

Irrigation has been "invented" and "reinvented" over thousands of years of human history in order to allow delivery of water and nutrients to plants where and when nature failed to provide agriculturally efficient rainfall. Desert agriculture depended historically on proximity to rivers and later on engineering schemes to bring water to the fields. Irrigation development in the mid-19th century, in the Punjab, the flat and fertile corner in north-west India by the British (Clemings, 1996), and the later during the 20th century in the Western USA (Rao, 2000; Reisner, 1993), relied on large-scale water movement and storage in order to open huge areas of land to agriculture. More recently, water from deep aquifers (up to more than a kilometer deep) is pumped locally to feed arid agriculture. (Glennon, 2002) Development of desert agriculture was, for a long time, concerned solely with the supply of necessary inputs and completely neglected emissions.

A major problem related to salt leaching in arid zones where large quantities of water are introduced involves the accumulation of salts in the groundwater below the root zone. Eventually (sometimes very quickly) the saline water tables rise up and intrudes into the agricultural soil (Beltran, 1999). Even when aquifers are deep or rivers distant, the salts in arid zones eventually make their way to water resources and become problematic. Salty water tables inhibiting leaching from the root zone were the scourge of ancients in Mesopotamia (Jacobson and Adams, 1958; Gelburd, 1985). The Babylonians built civilizations whose food supply depended upon irrigation of vast arid fields with readily available river water only to, over time, witness rising saline water tables, declines in productivity and yields, and eventual inability to supply the needs of the cities. Stories similar to this follow us through human history in arid regions and similar results continue to cause losses in modern agricultural productivity worldwide. (Christensen, 1998).

The Murray-Darling river basin in Australia is a noteworthy modern example where leached salts from agricultural lands return to the river and create a problem for downstream users (Herczeg *et al.*, 1993). Average salinity of River Murray water is 500% higher at the end of the river in South Australia compared to river sources in Victoria/New South Wales. Due to a combination of continued reductions of river flow, dryland recharge and leachate from irrigated agriculture along the river basin, downstream water is predicted to continue its rate of increase of salinity and double over the next 100 years (Murray-Darling Basin Ministerial Council, 1999). This salinity increase will lead to agricultural productivity decline and infrastructure losses estimated at over $1 billion.

The FAO (2002) estimated that the productivity of approximately 20-30 Mha irrigated land has been significantly decreased by salinity and that salinization results in the loss of an additional 0.25-0.5 Mha each year globally. Salinization is far from being a problem of “developing countries”. In 1990, 1.4 Mha of irrigated California land were assessed as having a water table within 1.5 m of the surface and 1.7 Mha were determined to be saline or sodic (Tanji, 1990). Recent work involving regional scale hydro-salinity modelling questions the sustainability of irrigated agriculture in the San Joaquin Valley, California due to inevitable salinization of soil and groundwater (Schoups *et al.*, 2005). Approximately 8.8 million hectares in Western Australia are threatened by rising water tables and may be lost to production by 2050 (NLWRA, 2001).

Often, irrigated agriculture in arid zones requires systems for drainage water collection in order to allow long-term leaching. Despite installation of extensive drainage systems and groundwater management in recent years, some 25% (more than 5 Mha) of the Indus River basin of Pakistan are still estimated to be effected by salinity and water logging (Tanji and Keilen, 2002). While drainage collection may facilitate field-scale salinity management, there remains an issue of disposal of the collected saline water. Leachate contains the unwanted salts, excess agricultural inputs including nutrients, herbicides and pesticides, as well as naturally occurring contaminants that, without irrigation would not have been mobilized. Proper design of drainage systems including shallow placement of laterals have been shown to cause lower drainage volumes and salt loading (Ayars, 2006). In spite of this, design criteria for drainage systems in arid lands are far from standardized.

California's experience with agricultural drainage water is particularly sobering. Strategies to dispose of the water via evaporation in wetlands failed miserably in the late 1970s and early 1980s due to high concentrations of selenium that caused fish mortality and bird deformities (Letey *et al.*, 1986; Presser and Ohlendorf, 1987). The selenium in California does not come from the irrigation water itself but is moved from the soil where it exists naturally. Demands of zero environmental release of contaminated agricultural water waste have been established to prevent environmental contamination from salts and nutrients. These demands, necessary for long term sustainability, create major challenges to irrigation management today in California and elsewhere.

Approaches to water and salinity management

A variety of strategies have emerged to address the negative phenomena associated with salinization due to irrigation.

Leachate collection and disposal: Even with low-salt-input irrigation, some excess water is eventually needed in order to maintain healthy root zone conditions for agricultural production. Sustainable management must take long term responsibility for the contaminants transported in this excess leachate. Drainage water collection systems and disposal schemes must become integral to desert agriculture to avoid environmental degradation. Examples today include regional interception of saline water before it enters the Murray River in Victoria and South Australia (Alexander, 1990), large scale off- and on-farm drainage collection in The Indus River Valley of Pakistan (Aslam and Prathapar, 2006) and in California where farm scale drainage systems and local containment and treatment of the leachate has become more prevalent (Tanji *et al*., 2002). Common to all of these cases is a problem of final disposal of the collected contaminants. Evaporation and water treatment can concentrate them into brines or solids and thus reduce the volume of the waste. Sea-ocean disposal is common where practical, but may not prove truly environmentally sound or sustainable, depending on specific chemical make-up of the contaminants.

Reduction of leaching: Agricultural root zone management most often incorporates a concept of "leaching fraction"; the quantity of excess irrigation water needed to maintain a predetermined salinity level in the soil. Leaching fractions are calculated based on: a) desired soil salinity; a function of presumed relative sensitivity of a given crop and; b) predicted water consumption of the crop based on cover and climate conditions. (Ayars and Westcot, 1985) The most common of these paradigms for decision making regarding the amount of water needed in order to leach salts do not sufficiently take into consideration soil type or feedback due to actual plant response to the saline conditions.

Current work suggests that salt balance calculations must take into consideration soil type and that there is substantial "self-regulation" by plants (Dudley *et al*., 2006; Shani *et al*., 2007). This suggests over-estimation of the amount of water needed to leach salts since plant water uptake will be reduced (and therefore leaching increased) for salty conditions, even without additional applications of water, as well as under-estimation of the yield-reduction cost from saline irrigation water. Application of soil-crop-climate integrated consideration of irrigation management (Dudley, 2006; Shani *et al*., 2007) could allow effective prediction of crop response to management variables, more efficient water use, and reduction in leachate.

Reduced inputs: Water use efficiency has increased in irrigated agriculture with the introduction of precision techniques including drip/trickle distribution systems. Adoption of low volume microirrigation systems (e.g., drip, micro-sprinklers) and automation increases the average efficiency to 90% as compared to 64% for furrow irrigation or 75% for sprinklers (Howell, 2001). Development of drip irrigation technology that allows low flow application of water uniformly throughout agricultural fields and the application of this technology in agricultural water management has been a cornerstone in Israel's progress in water use efficiency. The first regulated surface dripper was patented by Israeli water engineer Simha Blass in 1959. Modern drip systems were then developed in and for hyper-arid agriculture through work conducted in Israel's Arava Valley in the 1960s (Goldberg and Schmueli, 1970).

Drip irrigation promotes efficient water application by reducing losses in distribution systems, by distributing water directly to the root zone, and by promoting efficient water and nutrient uptake by locally maintaining conditions of relatively high water content. These advantages are supplemented by a number of other strategies also made possible by drip irrigation including distribution of fertilizers directly via the irrigation system (Bar Yosef, 1999), subsurface application with subsequent elimination of water loss from surface evaporation (Ben-Gal *et al*., 2004) and high frequency scheduling allowing matching of water application with plant transpiration demand (Segal *et al*., 2006). Today, microirrigation accounts for only some 1.5% of all irrigation systems worldwide, but is increasingly important in the more arid zones of developed countries. In the USA such systems increased from 0.6% of the total in 1979 to almost 4% in 1994 (Howell, 2001). The world area under microirrigation increased almost six- fold during the last 20 years from 1.1 Mha in 1986 to 6.1 Mha in 2006 (Reinders, 2006).

Both issues of water resource conservation and salinity management can be approached by reduction. Since water application in quantities greater than the plants' actual needs is a function of salinity, reduction of water application when conditions are saline is impractical for productive agriculture. Reduction therefore must concern the salts in the irrigation water. Use of lower salinity water allows more efficient use of water as a greater percentage of applied water direct plant consumption and less to leaching salts.

Today's policies of providing agriculture with marginal water contaminated with salts and nutrients are, in the end, highly non-sustainable. Better sustainability would be found by providing agriculture with the highest qualities of water; promoting highest productivity along with the lowest environmental consequences. It may well be a better strategy to desalinate water prior to distribution and thus have well contained, concentrated salt waste and allow greater irrigation efficiency, minimal field scale leaching, and minimal contamination with nutrients, soil contaminants (e.g., selenium, boron) and various agrochemicals than to irrigate copiously to leach salts and then find solutions for drainage water.

Plant Biodiversity and Crop Development

Introduction of sustainable crops in arid lands

Agriculture in arid zones does not depend only on water saving and the use of modern technologies. Competition in markets for conventional grains and produce generally favors production in less environmentally stressful areas where energy and input costs are lower. Thus, one option for dryland agriculture is to expand its traditional range of crops to new grains, fruits, vegetables and sources of fiber that offer specific advantages over agriculture in other zones.

Agricultural biodiversity based on utilization and development of germplasm resources is a prerequisite to achieving livelihood security – profitable and nutritional – for farmers in the drylands (Heslop-Harrison, 2002). A combination of selecting elite cultivars, reducing inputs (fertilizers, pesticides and the most important, water), cultivating extensive land area and domesticating under-exploited and wild plant species, can promote the development high value crops which are intrinsically adapted to arid conditions. These include crops for high value niche markets like dates and vine-cacti and as crops with pharmaceutical or cosmetic characteristics; like jojoba (Hodgson, 2002). But, how will plant breeders address the needs of arid lands? Can the existing crops meet these needs? What is the contribution of the introduction of new crops? Can we improve crops by selecting for drought resistance and hardiness in nutrient-poor soils?

Man's first experimentation with plant and animal domestication, initiated by Neolithic man (around 10,000 years ago) during their transition from nomadic hunter-gatherers to life in agrarian societies, signaled the beginning of modern civilization. Agriculture is believed to have multiple origins (Diamond, 2002) but largely took place in regions that at least today are considered drylands. Domestication, however, implies the cognizant selection of desired genetic traits and requires the availability of a variety of genotypes from which to select and suitable agro-technology to grow and manage crops. A subsequent conceptual revelation involved the recognition that seeds can be sown to produce plants when and where desired. The steady trial and error experimentation in plant domestication gave rise to agrarian economies that significantly increased man's capability to provide food, thus set the stage for unprecedented population growth. The process of plant domestication has evolved to a multidisciplinary science, involving selection of food plants with specific traits and development of agro-techniques for their cultivation. Modern agriculture everywhere in the drylands is strongly influenced by this ever-evolving process.

A negative outcome of plant domestication, regardless of climatic conditions, is the loss of genetic diversity through population bottleneck (crash of the size of a population), genetic drift (the random process by which the allelic frequency in the population changes over time), and inbreeding (mating between close relatives). Knowledge about the process of plant domestication remains very limited; however, it is possible that strong selection pressure exerted by humans on the wild diversity changed plant species (Vavilov, 1940). Darwin (1859) was the first to recognize the differences between domesticated plants created by artificial selection and breeding processes and their wild ancestors which evolved through natural selection.

Domestication, however, implies the cognizant selection of desired genetic traits and requires the availability of a variety of genotypes from which to select along with suitable agro-technologies to grow and manage crops. Crops in their present commercial form bear little resemblance to their original ancestors. Improved traits such as yield, shelf life, resistance to pests or diseases and fruit quality are used by plant breeders to select the best available cultivars. While plant breeders have made major achievements over the last 50 years in developing improved food crops, a progressive narrowing of the genetic base has occurred over the generations of selection, raising concerns about long-term sustainability.

Like our ancient predecessors practicing agriculture, farmers living in arid lands ask the same crucial question: which plant species are the most suitable and offer the most potential for cultivation and food production in any given locale? Of an estimated 250,000 species of flowering plants existing today, only twelve species are cultivated providing 75% of the world's edible crop production. Sugar cane, maize, wheat and rice comprise the four most important crops accounting for half of all food consumed (www.fao.org, 2002). A paramount challenge for agricultural researchers, therefore, is to introduce, domesticate and develop new crop candidates by breeding species with high water-use efficiency and greater resistance to adverse conditions, especially drought and salinity. Each crop needs to be evaluated for sustainability and profitability in each growing zone. The recently introduced new crops developed for arid lands will not replace the traditional crops needed for consumption and trade. The newly developed crops have great potential, however, as high-value and low-volume crops for specific niches where high input traditional agriculture is impractical or otherwise undesirable.

Plant breeding for technologies for drylands

Wild species reflect the rich natural variation and are highly heterozygous. In some cases crossing crops with wild ancestors — despite their traditional low yields and poor nutritional quality – may enhance crop performance (McCouch, 2004). Frequently, inbred progenies derived from these crosses have better performances than the better parent (Frey *et al*., 1975; Tanksley and McCouch, 1997), a phenomenon known as hybrid vigor. For example, rice yield was increase significantly up to 30%, following two introgressions from a wild relative (Deng *et al*., 2004). In tomato, introgressions of three segments from a wild relative resulted in 50% yield increase (Gur and Zamir, 2004). However, cross incompatibility between wild species and cultivated crops often generating sterile F_1 hybrid, low fertility of the resulting generations or low recombination between the genomes of the two species is the major factor that limits wild introgression breeding.

Complex traits, such as fruit size, yield and stress resistance are influenced by multiple genes, each segregating according to Mendel's laws, and their expression is modified by the environment (McCouch, 2004). These quantitative trait loci (QTL) are used in plant breeding and can be detected using molecular markers, or DNA-based markers. Genetic linkage maps based on molecular markers are being developed for a large number of species (http://probe.nalusda.gov). Studies in segregating populations are important for the localization of genomic regions derived from the wild parent that have the potential to improve yield, e.g. for wheat (Huang *et al*., 2003), soybean (Concibido *et al*., 2003) chickpea (Singh and Ocampo, 1997), and others. The use of introgression lines (ILs) — sets of lines each carrying a single defined chromosome segment from an exotic genome in an elite genetic background – simplified the analysis of complex traits. In tomato, crosses between the drought tolerant wild species *Solanum pennellii* and the elite inbred variety M82, ILs lines resulted in a population of segmental ILs (Eshed and Zamir, 1995). QTL mapping of these lines is based on the nearly isogenic nature of these lines and any phenotypic difference between M82 and an IL is associated with the *S. pennellii* genome (Gur and Zamir, 2004).

Marked-assisted selection (MAS) allows an efficient targeting of desired genes, such as disease and pest resistance, which allow for the improved yield of many crops. In the context of arid agriculture, identification of the loci (QTLs) that affect drought tolerance will strongly improve breeding efficiency. MAS is already helping plant breeders to improve valuable traits and an intensive effort is being made to generate the necessary resources for mapping drought tolerance (Tuberosa and Salvi, 2006), which will generate novel opportunities to drought tolerance breeding programs in a wide number of species. Moreover, the identification of these genes will facilitate better understanding concerning the nature of drought tolerance and its pathways, such as the genes involved in abscissic acid (ABA) production, or genes affected by ABA itself.

Grafting is the connection of two pieces of living plant tissue, the rootstock which provide the root system and the scion, which provide the reproductive part of the plant, so that they will grow as one plant. This technique permits the propagation of elite cultivars and the use of rootstocks, which are particularly able to withstand poor quality soils (compaction, poor drainage, low moisture, high salt levels) or to tolerate pathogens. Grafting is an ancient way of cloning plants, in particular fruit crops.

In *Citrus*, the salt-tolerant Cleopatra mandarin (*Citrus reshni* Hort. Ex Tan.) is widely used as a rootstock. Cleopatra's salinity tolerance is credited to exclusion of chloride ions by the roots as they take up water (Moya et *al* ., 2003). In vegetables, grafting is becoming popular as an alternative way to improve stress tolerances. In tomato (*Lycopersicon esculentum* Mill.), the grafting process itself did not affect fruit yield under non-saline conditions. However, under saline conditions fruit yield was found to be significantly higher in plants grafted onto resistant rootstocks (Estan et al., 2005). This strategy, combining desirable shoot characteristics with desirable root qualities, holds potential for improving performance of a wide number of cash crop vegetables growing under arid agricultural conditions.

Despite the complex technologies applied to obtain the hybridization between elite varieties and wild relatives (as embryo rescue, *in vitro* embryo culture, somatic hybridization) worldwide public opinion is often more accepting of these new varieties than genetically modified crops (GMC). For example, hybridization between cultivated chickpea (*Cicer arietinum*) and wild *Cicer* relatives result in abortion of the immature embryo due to post-zygotic barriers. The successful development of embryo rescue techniques is a first step to wide hybridization that will allow chickpea breeders to transfer desirable traits from wild relatives (Clarke *et al*., 2006). Unfortunately, despite decades of intensive research in this field, we are still a long way from understanding and applying technologies needed to successfully develop commercial forms of drought tolerant varieties and arid agriculture has not seen a meaningful quantum leap in productivity due to hybridization techniques.

Transgenic technology for the development of pest and salt-resistant crops

Transgenic technology today allows crop improvement in ways that traditional breeding techniques could not. While a variety of ethical and ecological objections to transgenic plants have been widely advocated (Lacey, 2002), these protestations have not stopped the steady expansion of transgenic plant cultivation. Currently 22 countries (11 developing countries) grow genetically modified crops (GMCs), with 103 Mha planted (53% in USA). The major transgenic crops are soybean (57%), maize (25%), cotton (13%) and canola (5%) (http://www.isaaa.org).

The majority of modifications have not involved the key characteristics required for successful cultivation in arid lands: salt and drought resistance. Rather, herbicide tolerance has been incorporated in major transgenic crops such as soybean, maize, canola, cotton and alfalfa accounting for some 68% of the global GMCs. Insect resistant transgenic crops account for ca. 19% of the global GMC's.

This may have important long-term implications for the sustainability of agriculture in the drylands. Despite the growth of regulation and the general commitment to reducing biocides in agriculture, since the 1960s after the publication of Silent Spring, sales continued apace, doubling roughly every ten years. During the past fifty years the number of "active ingredients" of pesticides climbed from a few dozen to close to one thousand (NRDC, 1999). Global sales of biocides by 2000 had reached 30 billion dollars a year. Although the rate of growth dropped precipitously during the 1990s, one recent study projected expanded demand as an unexpected result of global warming.

As would be expected, developing dryland nations are relatively modest consumers of pesticides for obvious economic reasons. African consumers comprise less than 6% of the global agricultural chemical market. But often less expensive, more persistent chemicals are sold in these countries where regulation may be non-existent. It can be expected that as countries move up the economic ladder, pesticide usage will increase. For example, China in 2004 ranked fifty in global pesticide usage, but showed a growth rate of 7 to 9% a year – higher even than its explosive increase in GNP (NRDC, 2005) Hence, pest resistant crops may be able to reverse these trends and keep pesticides of all forms to a minimum in arid agricultural regions.

Beyond the potential contribution to biocide reduction, what is the expected impact of GMC research for agriculture in arid lands? The progress that has been made in understanding the mechanisms involved in drought and salinity tolerance are significant (Huang *et al*., 2006; Naranjo *et al*., 2006; Leshem *et al*., 2006). However, the fact that the challenge involves complex-polygene traits makes the future of GMC resistance to salinity obscure and uncertain. It is surely conceivable that salt tolerant transgenic crops that increase yields in the drylands will be developed. But the new breeds, like traditional crops discussed previously, can only be sustainable if they are irrigated with better quality water, since water with high salinity irrigation will ultimately lead to excessive soil salinization and lands that will not support even the most robust strains. Assuming an ongoing investment in research and development in the field, many obstacles that presently exist can be overcome, but it is estimated that meaningful commercial progress will take many years.

Introduction of improved new cultivars and plant species as new crops in arid agriculture: Successful examples

To better understand the potential and the limitations of crop breeding's contribution to a sustainable agriculture in arid lands, it is well to consider several examples of new crop introductions from recent years. In particular we will consider the experience associated with *Cicer arietinum* L. (chickpea), *Cacti species*, *Simmondsia chinensis* (jojoba); and *Ziziphus* species.

Cicer arietinum L. (chickpea): The genus *Cicer* L. comprises of 43 annual and perennial species, 42 wild and one cultivated, the chickpea (*Cicer arietinum* L.). Chickpea has a deep and wide root system, giving it good drought tolerance. It's a self-pollinated and annual cool season grain legume crop grown under rainfall conditions in arid and semi-arid zones of India and Middle Eastern countries, with very high nutritive value and growing consumer demands. India produces 66% of the world chickpea production and consumes all its production domestically. Australia (22%) and Turkey (20%) are the most important exporters to international markets (FAOStat 5/2006).

Chickpea is affected by a large number of diseases, the most destructive of which are fusarium wilt (*Fusarium oxysporum*) and aschochyta blight (*Aschochyta rabiei*) (Kameswara Rao *et al*., 2003). The utilization of the wild genepool for breeding and improved resistance to diseases is challenging and difficult (Kameswara Rao *et al*., 2003). To date, eight annual species that share the same chromosomal number as the chickpea have been used in introgression program (Croser *et al*., 2003). Due to its long-day requirements, most Mediterranean chickpea stocks are relatively late to flower (Kumar and Abbo, 2001). Incorporation of early flowering alleles into Mediterranean cultivars might assist in reduced crop duration and avoid damage by biotic and abiotic stresses. The relatively simple inheritance of flowering time opens up new possibilities for breeding high yielding and stable chickpea cultivars for the semi-arid and arid regions globally (Kumar and Abbo, 2001). Moreover, the leaves typical of most wild *Cicer* and chickpea cultivars are compound. Leaf shape mutations to a simple leaf could possibly reduce transpiration demand. Genetic solutions that promise improved cultivation through new breeding lines combine early flowering, changing plant architecture (by leaf shape mutations), and Ascochyta tolerance suitable for short rainy seasons in semi-arid regions (up to 400 mm rainfall) (Bonfil et al., 2006). Traditional breeding in chickpea is a good example of crop improvement aimed to assist sustainable agriculture under extreme environmental conditions.

Cacti species: Cacti are native to North and South America and the West Indies (Gibson and Noble, 1986). Cacti species were introduced to Spain at the end of the 15th century and from there spread throughout the entire world. They appear in extreme habitats, hot deserts (up to 55ºC), as well as in cool areas with freezing temperatures and in tropical rain forests. Cacti can grow in poor and marginal soils (Nobel, 1988). These species have a range of specific adaptations that make them promising crops for introduction in arid lands: i.e., spines instead of leaves, succulent shoots, and the crassulacean acid metabolism (CAM) pathway for CO_2 fixation. Transpiration and photosynthesis take place during the night while during the day the stomata are closed. These mechanisms result in higher water use efficiency (Nobel, 1988; 1994). Today, cacti are cultivated as industrial, ornamental, vegetable and fruit crops (Mizrahi *et al.*, 1997).

The best-known cactus fruit crop is the shrub *Opuntia ficus-indica*, known as cactus pear or prickly pear, also called tuna in Latin America, ficodindia (fig of India) in Italy, tzabbar in Israel and sabar in Arab countries. The problems that historically have limited the cultivation of this species are its spiny peel, big and hard seeds, and the short annual period of production (Mizrahi *et al.*, 1997). Out-of-season fruiting can be induced in sandy soils by nitrogen fertilization (120 kg ha^{-1}) and by removal of flower buds and young cladodes (stems) (Nerd *et al.*, 1991 (B); Nerd and Mizrahi, 1994). In Israel's Arava Valley with 30 mm annual rainfall, extreme high temperatures (up to 47º) and 3500 mm annual pan evaporation, mango is irrigated with 2400 mm water per year while prickly pear is irrigated just 400 mm (Mizrahi *et al.*, 1997). The absolute minimum water requirement for prickly pear cultivation is 200 mm, also an important factor since all the cacti are very sensitive to prolonged lack of oxygen in the root zone (Le Houerou, 1996). Laboratory and field observations demonstrated that *O. ficus-indica* is sensitive to salinity as well (Nerd *et al.*, 1991 (A)).

People familiar with this crop consume and pay high prices for its fruits (Mizrahi *et al.*, 1997). However, a major challenge lies in introducing seedless and saline resistant cultivars using breeding efforts relying on only a few genotypes that exhibit such traits. Appropriate research leading to such modifications should facilitate greater acceptance by new consumers and potential for farmers in arid zones not yet familiar with this crop.

Vine cacti (*Hylocereus* and *Selenicereus* genera) are an interesting group of plants bearing attractive and exotic fruits. These epiphytic species are native to tropical regions of northern South America, Central America and Mexico. Flowers are nocturnal and remain open only for a few hours each day (Nerd *et al.*, 1997). The fruits are known in Latin America as pitahaya or pitayas, and are juicy, sweet and have black small crispy seeds with either a spineless peel (*Hylocereus* species) or a spiny one (*Selenicereus*). In the latter case, the spines are large and easily removed upon ripening.

Currently, worldwide interest in vine cacti species is increasing. Some twenty countries, including the United States, cultivate various vine cacti species (Nobel and de la Barrera 2004). In Israel, since the 1980s, an intensive program has been undertaken with the objective of introducing these species as new exotic fruit crops (Nerd *et al.*, 2002). At first, information about these species was extremely limited and therefore the initial introduction program was designed to ensure the development of agricultural techniques for profitable cultivation and a breeding program accompanied by cytological and molecular studies (Mizrahi and Nerd, 1999).

Early commercial cacti development studies revealed that the species are sensitive to high irradiation and low temperatures (less than 3°C). Consequently, in Israel the vine cacti are cultivated under shade-nets or in greenhouses and protected against cold (Raveh *et al.*, 1993). Due to the lack of natural pollinators (nocturnal animals) and the self-incompatibility of several genotypes, manual pollination is routinely performed (Weiss *et al.*, 1994; Nerd and Mizrahi, 1997). In addition, a long-term pollen storage protocol was developed in order to insure a constant supply of compatible pollen and to guarantee high yields (Metz *et al*., 2000). Fruit growth, ripening process and optimum harvesting time were studied for each species (Nerd *et al*., 1999).

The vine-cacti genotypes introduced to Israel came from the wild and the Israeli breeding program performed at Ben Gurion University has focused on improving fruit traits. Successful reciprocal interploidy crosses were performed between diploid *Hylocereus* species and the tetraploid *S. megalanthus* (Lichtenzveig *et al*., 2000; Tel-Zur *et al*., 2004). The fruits of the triploid hybrids combine the taste quality of *S. megalanthus* and the attractive appearance of *H. polyrhizus* (Tel-Zur *et al*., 2004). Moreover, some of the new vine-cacti hybrids show classical "hybrid vigor", i.e. heterosis. This is evident from their growth and development under extreme desert conditions, including high temperatures, low relative humidity and long drought periods. The successful introduction reflects a combination of hybridity (i.e., the fusion of parental genomes and such resulting phenomena as enzyme multiplicity) and genome doubling, which itself can result in epigenetic or epistatic effects. The triploid hybrids are fertile, with a relative high per cent of viable seeds. The number of seeds per fruit is strongly dependent on the pollen donor (Tel-Zur *et al*., 2005). Currently, the breeding program is comprised of F_2 and first backcrosses (BC_1) hybrids, which have started to flower and show promising preliminary results (Tel-Zur, unpublished data).

Simmondsia chinensis (jojoba): *Simmondsia chinensis* (jojoba) is a perennial dioeciously evergreen shrub endemic to the Sonora desert (California, Arizona and Mexico). The jojoba is naturally adapted to extreme high and low temperatures and dry climates. The annual water requirement for an adult jojoba plantation was found to be between 500 and 600 mm (Benzioni and Nerd, 1985). Jojoba seeds contain 40-60% liquid wax with a high melting point, similar in nature to sperm-whale oil (Yermanos and Ducan, 1976). In the past, Native Americans used jojoba wax for cooking, hair care, and for many therapeutic treatments. Today the wax and its derivatives have a wide range of potential uses in polish, cosmetics, pharmaceuticals, lubricants, gear additives, and anti-foaming industries (US National Research Council, 1985; Wisniak, 1987). Attempts to cultivate jojoba began in the late 1960s (Benzioni, 1995). Large plantations of jojoba have since been planted in USA, Mexico, Brazil, Australia, Sudan and Israel (Nimir and Ali-Dinar, 1991). In Israel, the introduction of jojoba as a new crop was made possible through field trials designed to optimize horticultural practices, and via a breeding program to maximize yield and other desirable traits, such as seed wax content (Benzioni, 1995). The majority of female jojoba plants bear only one flower bud on every second node. However, superior clones with high female density (whose inflorescences consist of about 3-10 flower instead the usual single female flower) having high yield potential, have been identified and selected for development (Benzioni *et al*., 1999).

Jojoba clones also differ in their chilling demands (Ferriere *et al*., 1989; Benzioni *et al*., 1992). They have a wide variation in their resistance to environmental conditions at the time of pollination, affecting fruit set as well as diversity in their flowering patterns, wax content and composition and seed dry weight (Benzioni *et al*., 1999). Yields collected in selected genotypes ranged between 1.53 to 3.35 kg dw plant^{-1} in 6-year-old plants (Benzioni *et al*., 1999), illustrating the range of genetic variability among genotypes. Jojoba grown in the southern, arid regions of Israel is mechanically harvested and watered by drip irrigation. The jojoba wax produced in Israel is exported, mainly for the cosmetic industry. In 2000, 130.3 tons were exported at US $10 per kg (http://ienica.csl.gov.uk/reports/israel.pdf). Due to the optimized horticultural technologies and the elite clones selected, jojoba cultivation in Israel is largely considered successful and profitable.

Ziziphus species: *Z. mauritiana* is an important fruit crop in India, *Z. jujube* is also indigenous in China, and *Z. spina-christi* is endemic to the Middle East. Similar to vine cacti, *Ziziphus* species can serve as a model for development, exemplifying the approach required for producing new arid zone crops, based on high market value with intrinsic adaptation to high stress conditions. *Ziziphus* fruits are consumed fresh or dried, and the trees are also used for soil conservation, livestock fodder, hardwood, fuel, high quality charcoal, and hedges. Leaves are employed in many traditional medicines. Furthermore, the fruits have a higher content of calcium, phosphorus, iron, Vitamin A and C than apples and citrus, and they are rich in phenols, compounds with high antioxidant activity (Jawanda and Bal, 1978; Machuweti *et al*., 2005).

Z. *mauritiana* (Ber) represents an unexploited fruit crop in the Middle East, especially in Israel, with long-term high commercial potential due to a very low input, and a high output. Ber was shown to be well adapted to drought conditions (150-200 mm annual rainfall), saline water (3.5 dS m^{-1}) and soil, and extreme temperatures (-6 to 45ºC in the arid regions of The Negev Highlands and The Southern Dead Sea in Israel). Chovatia *et al*. (1993) reported that under arid conditions in India, Ber cultivars yielded an average of 4-18 t ha^{-1} annually and exhibited significant differences in fruit weights, ranging from 4.6-30.9 g. In Israel, productivity at an experimental orchard at Neot Hakikar, just south of the Dead Sea for a mixture of six cultivars averaged 35-40 t ha^{-1} annually. Fruit weights ranged from 30-50 g (E. Zeiri, personal communication). This orchard was irrigated with 7,000 m^3 ha^{-1} annually with saline water. By way of comparison, dates, the most important fruit crop in the arid regions of the Middle East, require annually 25,000 m^3 ha^{-1} annually and yield 15-20 t ha^{-1}. Indeed, under the prevailing extreme climatic and edaphic conditions, the trees planted and grown at Neot Hakikar for 12 years did not show any phenotypic symptoms of stress, which emphasizes their incredible tolerance of extreme growth conditions. Ber has great potential as a new fruit crop in arid regions, however, more research is needed to improve the knowledge and technology for its production. In Israel, research and selection of improved genotypes is still in its early stages (N. Tel-Zur, unpublished data), while the traits for selection are fruit size, low aroma (unpleasant for unfamiliar consumers) and yield. Additional research should accelerate the rate of introduction and commercialization of this species to regional and international marketplace.

Economic Sustainability

Towards cost-effectiveness for arid agriculture

Just as sustainability requires that farming practices not be ecologically and hydrologically destructive, agriculture will not be sustainable if it loses money. From the perspective of economic strategy, farmers in arid lands can take advantage of the warm, protracted, growing seasons and new salt-resistant strains to attain a competitive advantage over other regions' agriculture. Several exotic fruit species that thrive in the drylands are bringing excellent prices in world markets. Recent prices throughout Europe for the vine-cacti fruit, for example often exceed seven euros kg^{-1}, a particularly high return for farmers in Israel who are now producing upward of 25 t ha^{-1} of the fruit with minimal water demands (25 to 80 m^{3} t^{-1}) (Mizrahi, 2007).

But, for the most part, arid agriculture is in an economically disadvantaged position. In addition to the problem of water scarcity, water quality is a factor in undermining the competitiveness of arid agriculture. Salinity and other minerals in the water and soil limit the range of crop options and reduce yields. International markets ultimately drive the economic viability of crops, and they often push farmers to make decisions that make economic sense in the short-term, but are unsustainable in the long-run, due to degradation of water and soil resources.

It is not just myopia, but lack of capital that can contribute to inappropriate crop selection and irrigation systems. For example, the massive cotton plantations, with their long-growing seasons and prodigious water needs established around the Aral Sea region combined with conventional irrigation practices and inappropriate drainage to emerge as a major factor in exacerbating salinization and contributing to the newly-created arid wasteland. It has been argued that reasonably simple changes, such as a shift to wheat and maize along with improved irrigation and drainage systems would both be able to reverse present trends and ultimately prove to be cost-effective (Cai, 2001). This sort of transformation towards sustainability is not, however, without costs. To cover the annualized investment of 299 million dollars, the authors recommended a salt tax to be paid by farmers.

The economic capability of farmers to invest in appropriate technologies is a critical factor to consider in crafting a strategy for sustainable agriculture. One of the key arguments raised by advocates against the dissemination of genetically modified crops in developing countries has nothing to do with ecology, but rather involves economic and social concerns. Subsistence and even modestly successful small farmers may not be able to afford the new generation of seeds developed at some expense by multinational corporations. As the new seeds increasingly become an essential economic commodity, indigent farmers are squeezed out of the market, and replaced by agri-business operations (Shiva, 2001).

In some circumstances, the problem is not lack of capital but excessive, recklessly rendered capital invested in water infrastructure that can exacerbate problems associated with arid agriculture. Given agriculture's role in national cultures and concerns for food security, promotion of agriculture in the desert frequently defies economic logic. Since it began construction in 1991 Libya has spent roughly 30 billion dollars to transport 600,000 acre feet of million-year old fossil water 1000 km across the desert to irrigate fields on arid lands near the Mediterranean coast (Pearce, 2006). Colonial Kadaffi's "man-made river" is only the most extreme of numerous examples of water transport projects that will never past muster with any cost-benefit analysis. During the 1950s, some 80% of all Israeli budgeting for infrastructure went for a National Water Carrier that today brings relatively saline water from the Sea of Galilee to the drylands in the south (Galnoor, 1980).

With such prodigious subsidies, it is little wonder that farmers in some arid lands can be prosperous despite their own economically dubious practices. Yet, in the long run, if agriculture is to remain sustainable and to compete in international and domestic markets, arid farming will require pragmatic "cost-effective" decision rules. This is especially true in developing countries where the local economies do not have the ability to subsidize an agriculture sector. A full accounting of the costs, including both negative and positive externalities, is important when considering a sustainable agricultural strategy for a given region.

The economics of irrigation

While many types of crops can flourish unassisted in rainy climates, agriculture in the drylands typically requires extensive investment in irrigation infrastructure as well as ongoing outlays for maintenance and energy. For example, in the arid regions of Syria, the relative portion of irrigation in overall production costs reached 52-60% for cotton, 34-51% for wheat, 35% for fava beans, and 20% for vegetables (Gül *et al.*, 2005). These involved inefficient furrow systems, so that the predominant component of irrigation costs only involved the fuels for water pumps, rather than pipes or drip systems. The high percentage of irrigation expenses are to some extent a function of the low-value crops. In dry regions of Spain, however, Garrido *et al.* (2006) reported that water extraction costs constitute only a tiny fraction of local produce.

Frequently, domestic irrigation policies follow their own, arcane, logic. Saudi Arabian wheat production, literally fueled by the government's energy glut, is an extreme case in point. The 141,732 tons produced there in 1980 grew ten-fold to 1,800,000 tons by the year 2000, due to an increase of 600,000 to 1,620,000 ha of irrigated lands (FAO, 2007). But it is the most expensive wheat in the world. Most dryland nations lack the oil reserves and capital to subsidize field crops. The aforementioned analysis in Syria, for example also showed that as fuel prices rose (or as the 80% subsidies on fuels were removed) cotton and wheat quickly became losing propositions for local farmers.

Rainwater harvesting in the drylands, offers a relatively ancient and low-capital water management technique in deserts. Harvesting has been proven to be a cost-effective source of agricultural water in a variety of contexts. A recent study in Turkmenistan, evaluated the costs and benefits of " takyrs" -- the traditional slightly sloping dense clay surfaces which act as natural catchment areas. Some 250-350 million m^3 of water are collected each year in a variety of traditional reservoirs, even as today much of the water is unutilized. In assessing their feasibility, researchers monetized the reservoirs' construction, maintenance and operational expenses (Fleskens *et al*., 2007). Benefits were primarily based on increased fodder production. With an average life expectancy of the facilities set at 30 years, the beneficial values of the system far exceeded the costs of producing alternative water sources for these drylands. This cost-benefit ratio increased dramatically when wheat cultivation replaced reserve fodder crops in the irrigated zone (Gintzburger *et al*., 2005).

In Israel, a rain-harvesting and effluent distribution reservoir system has been established during the past decade involving a system of over 190 reservoirs, almost all for arid and semi-arid agricultural irrigation. The initiative has increased the national supply of water, but the costs of reservoirs are relatively high, with construction of a typical reservoir (producing 0.5 to 2 million m^3 of water every year) costing from one to five million dollars. No economic evaluation of the initiative has yet been undertaken, but clearly the cost-benefit ratio will be dependent on the life expectancy of the reservoirs which is unknown and of course on the discount rate selected (Tal *et al*., 2005).

Drip irrigation offers the most environmentally sustainable irrigation strategy. When considering the agronomic advantages of drip irrigation systems, it is initially difficult to understand why less than 2% of irrigated lands world-wide have adopted them. The answer, of course is economic. The initial outlays for a drip irrigation system have not increased meaningfully during the past decade, ranging from $2,000 to $3,000 ha^{-1} for orchards in arid and semi-arid regions. This price includes the entire irrigation system, including pumps and computer systems. With a ten-year life expectancy, the investment is easily returned, especially for high value-added fruit and vegetable crops (Netafim, 2007; Postel, 1997). Yet, farmers, particularly in developing drylands, frequently do not have the resources to make such a substantial capital investment, even if it will improve their long-term competitiveness. This is also true in wealthier nations. For example, when drip and furrow irrigation were compared in arid areas of Wyoming for the raising of sugarbeets, the returns were $2310 versus $2080, respectively. The larger the area converted to drip irrigation, the shorter the " payback time" but at best, drip system costs were covered after a period of seven years (Sharmasarkar, 2001).

If an analysis is only based on a modest time-horizon, economic assessment will not necessarily produce the environmentally optimal solution. As interest rates rise, sustainable irrigation practices may not always beat conventional irrigation methods when the sole criterion for comparison involves short-term increased yields. But when the environmental advantages produced by efficient irrigation, and the associated savings incurred by preventing production losses are integrated into the calculations, it makes for a far more compelling equation. One recent analysis of water logging in the India Tungabhadra project, for example revealed that the lost production value caused by soil degradation from inappropriate irrigation was at least 14.5% of the system's productive potential, and that the sub-optimal distribution losses were almost three times more (Janmaat, 2004).

Water logging is among the environmental woes that economists are quick to attribute to inappropriate water pricing, or what is deemed as an economically irrational policy (Wichelns, 1999). Ironically, it is often water subsidies which push farmers to retain inefficient and environmentally destructive irrigation practices (Hellegers, 2006). Investor Richard Sandor's often quoted adage characterizes the dynamic well: "When nature is free, it becomes an 'all you can eat buffet.' And I don't know anyone who doesn't overeat at an all you can eat buffet" (Daily, 2002). When farmers in arid lands face the real costs of water, the economic common sense of efficient irrigation systems becomes irresistible. Israeli farmers, after being confronted with higher and less subsidized water prices, expeditiously converted their operations to drip irrigation systems without any command and control prescriptions (Tal, 2006).

The costs of alternative sources of water for desert agriculture

Kuwait was among the pioneers in desalination technology, with much of the steady growth in demand for water by local municipal and agricultural needs met by five major desalination plants that utilize a multi-stage flash distillation process (Hamoda, 2001). The extremely high energy requirements made the cost of water production for agriculture in most other nations prohibitively expensive. Two decades after the Kuwaiti venture into desalination, the precipitous drop in price for desalinized water already has begun to change the economic calculus for arid agriculture in Israel. Israel's new reverse osmosis desalinization facilities, opened in January 2006 can produce a cubic meter of water (1000 liters) for 52 cents (Tal, 2006). During its first year of operation, much of its waters were actually consumed (at subsidized rates) by Israeli agricultural operations. While the very low salinity of the water was welcomed by local farmers, the very low levels of calcium and complete absence of magnesium in this ideal drinking water can actually cause damage to many crops (Yermiyahu, 2007). A recent survey among Israeli farmers reports that only a third believed that water at the new desalinized price was reasonable for a profit-making farm and relatively few reported a willingness to cultivate additional high value-added crops if they could be guaranteed high quality desalinized water at that price (Rassas, 2007). But desalinized brackish water can now be produced at 30 cents per m^3 which is very close to market rates.

Wastewater reuse offers another promising source of water for desert agriculture. Like the rest of the world, urbanization in the drylands continues apace and the reuse of effluents by farmers contributes to solving a potentially problematic environmental problem. In Kuwait, economic analysis suggests that the additional treatment required to bring effluents to a level acceptable for reuse by agriculture would only increase the overall costs of existing sewage treatment by 30% (Hamoda, 2001). If, however, wastewater reuse is part of a water supply policy for arid agriculture, there is always the risk that the treated sewage will be used regardless of whether it meets adequate treatment standards. This has often been the case in India (Prinz, 2000) with predictable implications for public health and long-term hydrological contamination.

Israel presently recycles 72% of its sewage, the vast majority of which provides irrigation for arid farms (Tal, 2006). Yet, present treatment level standards, based on non-arid European treatment criteria have been ruled inadequate. In arid regions, for most of the year, there is inadequate flow in streams to dilute effluents (Inbar, 2002). Accordingly, the government recently approved the phase-in of a much tougher set of treatment standards that essentially require tertiary treatment. A cost-benefit analysis conducted by consultants for the government showed that while the upgrade in sewage treatment levels would cost 230 million dollars, it was an investment with a high benefit/cost ratio, producing an average benefit at least three times the cost per cubic meter of upgraded treated wastewater. The additional expense associated with the upgrade per cubic meter was estimated at 10-15¢/m, while the average benefit ranged from 40-55¢/m (Lavee, 2003). Benefits were calculated based on the ability of farmers to expand the range of profitable crops beyond those which are approved for irrigation with secondarily-treated wastewater. Additional benefits to farmers included those associated with the reduction in wear and tear on irrigation equipment and the reduced nitrogen in the water.

A review by Lawhon and Schwartz (2006), as well as an economic analysis done on behalf of the farm lobby (Rosenthal, 2005) found that the benefits expected from wastewater recycling following tertiary treatment were highly overstated due to the assumption that farmers currently using wastewater would be able to upgrade to high-value crops. This assumption was argued to be flawed due to the additional investments and knowledge necessary to substitute crops. Additionally, neither economic analysis attempted to quantify the benefit to the environment as a result of cleaner wastewater, the main motivation for the higher standard in the first place. Despite the debate over the economic consequences of the upgrade, the Israeli government eventually approved the new standard, which will be implemented gradually in order to give farmers and local authorities' time to adjust to the costs of improved sewage treatment.

The economic equation justifying sustainable agriculture ultimately should be informed by the truism that it is invariably more cost-effective to prevent the agricultural damage associated with unsustainable farming then to try to remedy contamination after the fact. There are exceptions. For example, the drainage associated with remediating water logging in India produced an intensification of land use on formerly fallow lands, a shift to remunerative crops and increased crop yields that made restoration efforts cost-effective (Datta *et al.*, 2000). But other cases show a far less sanguine economic picture. While the vast majority of Australian farmers have begun to adapt their practices to the pervasive salinization of their soils, less than half believe that the investment has produced any benefit at all (Kington and Pannel, 2001).

Given market conditions, preventative practices may not be perceived as profitable without government intervention to ensure that externalities of salinizing practices are internalized by local farmers. Pannel (2001) reported that such a measure, the conversion of annual crops to perennial trees in Australia, is typically not sufficiently profitable, especially when interest rates are high. The off-site benefits, to the non-agricultural sector of such conversions, of course change the equation completely. This is one of the critical areas that decision makers should consider when formulating public policy about dryland agriculture. It has long been recognized that the full benefit of agricultural production involving "positive externalities" to the non-farming sectors (the tourism dividend from scenic country sides, the water quality benefits, etc.) are often higher than the market value of the crops themselves (Fleisher and Tsur, 2000). Yet, rarely do decision makers include these benefits in their agricultural calculations. In any event, the Australian experience suggests that along with prevention efforts, adaptation of salt resistant plants by farmers will ultimately be ineluctable -- if farmers can afford them (Pannel, 2001).

Towards the Future

The most important challenge for a farmer in the drylands involves selecting the crop that is most appropriate and profitable for specific local conditions and an irrigation system that can maintain productivity in the long-run. Economic considerations are unavoidable. Farmers must choose crops that are able to return the costs of the associated inputs: water, irrigation infrastructure, energy and labor. These expenses can be especially high in arid lands.

These decisions are increasingly complex, not only because of the advances in agricultural technologies, but due to the rapidly evolving environmental reality. There is little doubt that global warming poses a new challenge for agricultural researchers focusing on the desert. Recently, the US Department of Agriculture estimated a 32-ton drop in global wheat harvests – roughly half of the entire US wheat harvest. The precipitous decline is attributed to high temperatures (Brown, 2005). Scientists will have to scramble to produce crops for arid lands that can adapt to such changing climatic conditions.

The associated energy situation and rise in fossil fuels prices has already begun to affect the dynamics of arid agriculture. Among the crops that may be considered by dryland nations in their agricultural production scheme are those grains from which fuels can be produced. Given the inherent limitations on production in the deserts, this appears to be a less than optimal impulse. Put more specifically, the production of ethanol from corn should not be part of a long-term agricultural strategy for the drylands. As agricultural pundit Lester Brown points out, the grain required to fill a 25-gallon SUV gas tank with ethanol, for instance, could feed one person for a year (Brown, 2006). Recent demonstrations over the four-fold rise in the price of tortillas in Mexico are among the first symptoms of these changing dynamics.

Agriculture in arid lands will succeed when it best exploits the desert's natural advantages. These include long hours of sunshine, long and multiple growing seasons and in some case the low number of pests and diseases. Innovation in agronomic treatments such as drip irrigation, fertigation, and high level of mechanization are likely to build on these relative advantages or at least even the playing field, creating competitive conditions for farmers in arid lands. Because of the constant need for innovation, one of the keys to sustainable and successful agriculture in arid lands lies in a close and constant cooperation between researchers and farmers. High yields and excellent crop quality can be achieved in arid areas but they require ongoing monitoring and scientific research.

For example, the role of new crops in increasing farmers profit has frequently been demonstrated. Totally new products, such as exotic fruits and vegetables, create a new niche for farmers in the drylands. Though technical and scientific difficulties have limited the introduction and domestication of many "underexploited" species, detailed studies that bring comprehensive research and analysis about each species in a variety of climatic and geographical locations should be undertaken. This will require expanded research funding in these substantive areas.

Ultimately, the history of agriculture in desert lands has not been a happy one. Many of the seemingly prosperous agricultural civilizations disappeared unceremoniously due to unsustainable practices. During the twentieth century, agricultural communities in arid regions collapsed due to environmental blunders. Today's improved technology and scientific understanding about the ecological and hydrological conditions in arid lands offer the hope of lasting prosperity for agricultural operations in the drylands. Yet, to be sustainable, farmers will need to be able to invest in appropriate water management technologies and remain nimble and clever in their introduction of optimal crop types onto lands that are not naturally hospitable. While there is a strong basis for optimism in a review of the developments of agriculture in arid lands, this must be balanced with an equally powerful measure of humility and caution.

References

Alexander, D.J .1990. Managing resources of the Murray-Darling Basin of Australia. *Water Resources Journal* 164: 87-99.

Allen, V.G. et. al., 2005. Integrating Cotton and Beef Production to Reduce Water Withdrawal from the Ogallala Aquifer in the Southern High Plains. *Agronomy Journal* 97: 556-567**. (Full authors name please).**

Aslam, M. and Prathapar, S.A. 2006. *Strategies to Mitigate Secondary Salinization in the Indus Basin of Pakistan: A Selective Review*. Research

Report 97. International Water Management Institute. Colombo, Sri Lanka. 31 pp.

Ayars, R.S. and Westcot, D.W. 1985. Water quality for agriculture. *FAO Irrigation Drainage Paper 29*. FAO, Rome.

Ayars, J.E., Christen, E.W. and Hornbuckle, J.W. 2006. Controlled drainage for improved water management in arid regions irrigated agriculture. *Agricultural Water Management* 86: 128-139.

Bar-Yosef, B. 1999. Advances in fertigation. *Advances in Agronomy* 65: 1-77.

Beltrán, J.M. 1999. Irrigation with saline water: Benefits and environmental impact. *Agricultural Water Management* 40: 183-194.

Beltrán, J.M. and Koo-Oshima, S. 2006. Water desalination for agricultural applications. *FAO Land and Water Discussion Paper 5*. FAO Rome.

Ben-Gal, A., Lazorovitch, N. and Shani, U. 2004. Subsurface drip irrigation in gravel filled cavities. *The Vadose Zone Journal* 3: 1407-1413.

Benzioni, A. 1995. Jojoba domestication and commercialization in Israel. In *Horticulture Review* (Ed. J. Janick), Vol. 17, pp. 231-264. Wiley, New York,

Benzioni, A. and Nerd, A. 1985. Effect of irrigation and fertilization on vegetative growth and yield of jojoba in relation to water status of the plants. In *Jojoba. Proceedings of 6th International Conference on Jojoba and its Uses* (Eds. J. Wisniak and J. Zabiscky), pp. 201-212.

Benzioni, A., Palzkill, D.A. and Nelson, J.M. 1992. Flower bud dormancy, ABA concentration, and survival during frost of jojoba genotypes under water stress. *Journal of American Society of Horticulture Science* 117: 976-980.

Benzioni, A., Shiloh, E. and Ventura, M. 1999. Yield parameters in young jojoba plants and their relation to actual yield in later years. *Industrial Crop Production* 10: 85-95.

Bernstein, L. 1975. Effects of salinity and sodicity on plant growth. *Annual Review of Phytopathology* 13: 295-312.

Bonfil, D.J., Goren, O., Mufradi, I., Lichtenzveig, J. and Abbo, S. 2006/2007. Development of early-flowering Kabuli chickpea with compound and simple leaves. Plant breed (in press).

Brown, L. 2004. *World food Security Deteriorating: Food Crunch in 2005. Now Likely.* Earth Policy Institute, Washington.

Brown, Lester 2006. Ethanol could leave the world hungry. *Fortune,* August 16 2006.

Cai, X, McKinney, D.C. and Rosegrant, M.W. 2001. *Sustainability Analysis for Irrigation Water Management in the Aral Sea Region.* International Food Policy Research Institute, Washington, DC. Discussion Paper, 48 p.

Carr, R.M., Blumenthal, U.J. and Duncan Mara, D. 2004. Guidelines for the safe use of wastewater in agriculture: Revisiting WHO guidelines. *Water Science and Technology* 50: 31-38.

Chen, Chi-Chung, McCarol, Bruce, " Pesticide Usage as Influenced by Climate: A Statistical Investigation". (not in text)

Chovatia, R.S., Patel, D.S. and Patel, G.V. 1993. Performance of Ber (*Ziziphus mauritiana* Lamk) cultivars under arid conditions. *Annals of Arid Zone* 32: 215-217.

Christensen, P. 1998. Middle eastern irrigation: Legacies and lessons. In *Transformations of the Middle Eastern Environments: Legacies and Lessons* (Eds. J. Coppock and Juoiseph Miller Editors) New Haven, Yale School of Forestry and Environmental Studies vol. 103, pp. ......

Clemings, R. 1996. *Mirage: The False Promise of Desert Agriculture*. San Francisco, Sierra Club Books. 247 pp.

Concibido, V.C., et al. 2003. Introgression of a quantitative trait locus for yield from Glycine soja into commercial soybean cultivars. *Theoretical and Applied Genetic* 106: 575-582. (**Please provide full editors name**).

Croser, J.S., Ahmad, F., Clarke, H.J., Siddique, K.H.M. 2003. Utilization of wild Cicer in chickpea improvement-progress, constraints, and prospect. *Australian Journal of Agriculture Research* 54: 429-444.

Daily, G. and Ellison, K. 2002. *The New Economy of Nature, the Questo to Make Conservation Profitiable*. Washington, Island 13.

Darwin, C. 1859. *The Origin of Species by Means of Natural Selection (Reprint).* New York: Collier, 1962.

Datta, K.K., Jong, C. and de Singh, O.P. 2000. Reclaiming salt-Affected land through drainage in Haryana, India: A financial analysis. *Agricultural Water Management* 46: 55-71.

Deng, Q.Y. et al., 2004. Studies on yield-enhancing genes from wild rice and their marked-assisted selection in hybrid rice. *Hybrid Rice* 19: 6-10.

de Villiers, M. 2000. *Shrinking Aquifers Water*. Stoddart, Toronto.

Diamond, J. 1997. *Guns, Germs and Steel: The Fate of Human Societies*. New York, Norton.

Diamond J. ...... Evolution, consequences and future of plant and animal domestication. *Nature* 418: 700-707.

Diamond, J. 2005. *Collapse, How Societies Choose to Succeed or Fail*. Viking Press, New York.

Dudley, L., Ben-Gal, A. and Shani, U. 2006. Influence of plant, soil and water properties on the leaching fraction. *Agronomy Abstracts* P25711.HTM.

Eshed, Y. and Zamir, D. 1995. An introgression line population of *Lycopersicon pennellii* in the cultivated tomato enables the identification and fine mapping of yield associated QTL. *Genetics* 141: 1147-1162.

FACTA (Food, Agriculture, Conservation, and Trade Act of 1990), Public Law 101-624, Title XVI, Subtitle A, Section 1603 (Government Printing Office, Washington, DC, 1990) NAL Call # KF1692.A31 1990].

FACTA (Food, Agriculture, Conservation, and Trade Act of 1990), Public Law 101-624, Title XVI, Subtitle A, Section 1603 (Government Printing Office,Washington, DC, 1990) NAL Call # KF1692.A31 1990].

FAO 2002. Statistical databases – agriculture. www.fao.org.

FAO (Food and Agriculture Organization) 2002. Crops and drops: Making the best use of water for agriculture. FAO Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO (Food and Agriculture Organization) 2005. Water Desalination for Agricultural Applications. http://www.fao.org/docrep/meeting/009/j4238e.htm

FAO 2006. FAOStat (online). http://faostat.fao.org

FAO (Food and Agriculture Organization) 2007. Asian Wheat Producing Countries – Saudi Arabia, (last visited, January 28, 2007). http://www.fao.org/ag/AGp/agpc/doc/field/Wheat/asia/saudiarabia.htm

Ferriere, J., Milthorpe, P.L. and Dunstone, R.L .1989. Variability in chilling requirements for the breaking of flower bud dormancy in jojoba. ***Australian Journal of Plant Physiology*** 12: 355-362.

Fleischer, Al. and Tsur, A.Y. 2000. Measuring the recreational value of agricultural landscape. European Review of Agricultural Economics 27: 3.

Fleskens, K., Ataev, A., Mamedov, B. and Spaan, W.P. 2007. Desert water harvesting from takyr surfaces: Assessing the potential of traditional and experimental technologies in the Karakum. *Land Degradation and Development* 18: 17-39.

Frey K.J., Hammond, E.G. and Lawrence, P.K. 1975. Inheritance of oil percentage in interspecific crosses of hexaploid oats. *Crop Science* 15: 94-95.

Galnoor, I. 1980. *Water Policy Making in Israel, Water Quality Management Under Conditions of Scarcity, Israel as a Case Study* (Ed. Hillel Shuval) New York, Academic Press, 296 p.

Gardner, W.R. 1991. Modeling water uptake by roots. *Irrigation Science* 12: 109-114.

Garrido, A., Martínez-Santos, P. and Llama, R. 2006. Groundwater Irrigation And Its Implications For Water Policy In Semiarid Countries: The Spanish Experience. *Hydrogeology Journal* 14: 1431-1435.

Gelburd, D.E. 1985. Managing salinity. Lessons from the past. *Journal of Soil and Water Conservation* 40: 329-331.

Gibson, C.G. and Noble, P.S. 1986. *The Cactus Primer*. Harvard Univ. Press, Cambridge, MA.

Gintzburger, G, Le Houerou, H. and Toderich, K. 2005. The Steppes of Middle Asia: Post–1991 Agricultural and Rangeland Adjustment. Arid Land Research and Management 19, 215–239.

Glennon, R. 2002. *Water Follies, Groundwater Pumpnig and the Fate of America's Fresh Waters*. Island Press, Washington.

Gold, M. 1999. *Sustainable Agriculture: Definitions and Terms*. Special Reference Briefs Series No. SRB 99-02, US Department of Agriculture.

Goldberg, D. and Schmueli, M. 1970. Drip Irrigation: A method used under arid and desert conditions of high water and soil salinity. *Transaction of the ASAE* 13: 38-41.

Gül, A., Fadil Aw-Hassan, R. and Aden Büyükalaca, O. 2005. Economic Analysis of Energy Use In Groundwater Irrigation of Dry Areas: A Case Study In Syria. *Applied Energy* 82: 285-299.

Gur, A. and Zamir, D. 2004. Unused natural variation can lift yield barriers in plant breeding. P*LoS Biology* 2:e245.

Hamoda, M.F. 2001. Desalination and water resource management in Kuwait. *Desalination* 138: 385-393.

Herczeg, A.L., Simpson, J.H. and Mazor, E. 1993. Transport of soluble salts in a large semiarid basin: River Murray, Australia. *Journal of Hydrology* 144: 59-84.

Hellegers, P. 2006. The role of economics in irrigation water management. *Irrigation and Drainage* 55: 157-163.

Hodgson, J. 2002. Nutraceuticals tread business tightrope in Europe. ***Nature Biotechnology*** 20: 322-323.

Howell, T. 2001. Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal* 93: 281-289.

Huang, S., et al. 2006. A sodium transporter (HKT7) is a candidate for Nax1, a gene for salt tolerance in Durum wheat. *Plant Physiology* 142: 1719-1727. (**Please provide full editors name).**

Huang, X.Q., Coster, H., Ganal, M.W. and M.S. Roder. 2003. Advanced backcross QTL analysis for the identification of quantitative trait loci alleles from wild relatives of wheat (*Triticum aestivum* L.) ***Theoretical and Applied Genetics*** 106: 1379-1389.

Jawanda, J.S. and Bal, J.S. 1978. The ber, highly paying and rich in food value. *Indian Horticulture* 23(3): 19-2.

Kameswara Rao, N., Reddy, L.J. and Bramel, P.J. 2003. Potential of wild species for genetic enhancement of some semi-arid food crops. ***Genetics Research Crop Evolution*** 50: 707-721.

Kington, E.A. and Pannel, D.J. 2001. *Dryland Salinity in the Upper Kent River Catchment of Western Australia, Farmer Perceptions and Practices*. SEA Working Paper, University of Western Australia.

Kumar, J. and Abbo, A. 2001. Genetics of flowering time in chickpea and its bearing on productivity in semiarid environments. *Advance Agronomy* 72: 107-138.

Lawhon, P. and Schwartz, M. 2006. Linking environmental and economic sustainability in establishing standards for wastewater reuse in Israel. *Water Science and Technology* 53: 203-212.

Le Houerou, H.N. 1996. The role of cacti (*Opuntia* spp.) in erosion control, land reclamation, rehabilitation and agricultural development in the Mediterranean Basin. *Journal of Arid Environment* 33: 135-159.

Leshem, Y., et al. 2006. Suppression of Arabidopsis vesicle-SNARE expression inhibited fusion of H_2O_2 containing vesicles with tonoplast and increased salt tolerance. *Proceedings of National Academy Science* 103, 18008-18013. (**Please provide full editors name**)

Letey, J., Roberts, C., Penberth, M., and Vasek, C. 1986. An Agricultural Dilemma: Drainage Water and Toxics Disposal in the San Joaquin Valley. UC Agricultural Experimental Station Special Publication 3319. 56 p.

Lichtenzveig J., Abbo, S., Nerd, A., Tel-Zur, N. and Mizrahi, Y. 2000. Cytology and mating systems in the climbing cacti *Hylocereus* and *Selenicereus*. *America Journal of Botany* 87: 1058-1065.

Machuweti, M., Zenda, G., Ndhlala, A.R. and Kasiyamhuru, A. 2005. Sugars, organic acid and phenolic compounds of *Ziziphus mauritiana* fruits. ***European Food Research Technology*** 221: 570-574.

McCouch, S. 2004. Diversifying selection in plant breeding. *PloS Biology* 2: 983-989.

Metz, C., Nerd, A. and Mizrahi, Y. 2000. Viability of pollen of two fruit crop cacti of the genus *Hylocereus* is affected by temperature and duration of storage. *HortScience* 35: 22-24.

Mizrahi, Y. and Nerd, A. 1999. Climbing and columnar cacti: New arid land fruit crops. In *Perspectives on New Crops and New Uses* (Ed. J. Janick), pp. 358-366. ASHS Press, Alexandria, VA.

Mizrahi, Y., Nerd, A. and Nobel, P.S. 1997. Cacti as crops. *Horticulture Review* 18: 291-320.a

Mizahi, Y. 2007. Profitable, Water-Saving Crops, Proceedings of the Negev Conference for

Agricultural Development, February 27, 2007, (Hebrew) 17

Murray-Darling Basin Ministerial Council, 1999. The salinity audit of the Murray-Darling Basin: a 100-year perspective. Murray-Darling Basin Commission, Canberra, 39 pp.

Naranjo, M.A., Forment, J., Roldan, M., Serrano, R. and Vicente, O. 2006. Overexpression of *Arabidopsis thaliana* LTL1, a salt-induced gene encoding a GDSL-motif lipase, increases salt tolerance in yeast and transgenic plants. *Plant Cell Environment* 29: 1890-1900.

Nerd, A., Gutman, F. and Mizrahi, Y. 1999. Ripening and postharvest behaviour of fruits of two *Hylocereus* species (Cactaceae). ***Postharvest Bio Technology*** 17: 39-45.

Nerd, A., Karadi, A. and Mizrahi (A), Y. 1991. Salt tolerance of prickly pear cacti (*Opuntia ficus-indica*). *Plant Soil* 137: 201-201.

Nerd, A., Karadi, A. and Mizrahi (B), Y. 1991. Out-of-season prickly pear: fruit characteristics and effect of fertilization and short drought periods on productivity. *HortScience* 26: 527-529.

Nerd, A. and Mizrahi, Y. 1994. Effect of nitrogen-fertilization and organ removal on rebudding in *Opuntia ficus-indica* (L) Miller. ***Sci Hortic.*** 59: 115-122.

Nerd, A. and Mizrahi, Y. 1997. Reproductive biology of cactus fruit crops. *Horticulture Review* 18: 321-350.

Nerd, A., Tel-Zur, N. and Mizrahi, Y. 2002. Fruit of vine and columnar cacti. In *Cacti: Biology and Uses* (Ed. P.S. Nobel), pp. 195-197. University of California Press.

Netafim 2007. personal communication from Marketing Department.

Nimir, M.N. and Ali-Dinar, H.M. 1991. Jojoba, anew cash crop in marginal lands. *Acta Horticulture* (ISHS) 270: 369-372.

NLWRA (National Land and Water Resources Audit) 2001. Australian Dryland Salinity Assessment 2000: Extent, Impacts, Processes, Monitoring and Management Options. Commonwealth of Australia, Canberra, Australia.

Hamoda, M.F. 2001. Desalination and Water Resource Management in Kuwait. *Desalination* 138: 385-393.

Nobel, P.S. 1988. *Environmental Biology of Agaves and Cacti*. Cambridge. Univ. Press, New York.

Nobel, P.S. 1994. *Remarkable Agaves and Cacti*. Oxford University Press, New York.

Nobel, P.S. and de la Barrera, E. 2004. CO2 uptake by the cultivated hemiepiphitic cactus Hylocereus undatus. *Annals of Application Biology* 144: 1-8.

NRDC (Natural Resources Defense Council) 1999. Fields of Change A New Crop of American Farmers Finds Alternatives to Pesticides, New York.

Pannell, D.J. and Schilizzi, S. 1999. Sustainable agriculture: A matter of ecology, equity, economic efficiency or experience? *Journal of Sustainable Agriculture* 13: 65.

Pannel, D.J. 2001. Dryland salinity, economic, scientific, social and policy dimensions. *The Australian Journal of Agricultural and Resource Economics* 45: 517-546.

Pearce, F. 2006. *When Rivers Run Dry, Water The Defining Crisis of the Twentieth Century*. Bsoton, Beacon Press, 37.

Pettygrove, G.S. and Asano, T. 1985. *Irrigation with Reclaimed Municipal Wastewater*. Lewis Publishers, Chelsea, Mi. 518 pp.

Postel, S. 1997. *Last Oasis, Facing Water Scarcity*. Washington, World Watch, 102-103.

Presser, T.S. and Ohlendorf, H.M. 1987. Biogeochemical cycling of selenium in the San Joaquin Valley, California, USA. *Journal Environmental Management* 11: 1432-1009.

Prinz, D. and Singh, K. Anupam. 2000. Water Resources in Arid Regions and their Sustainable Management. *Annals of Arid Lands* (Special Issue on Research) vol. page no. requred..

Rana, G. and Katerji, N. 2000. Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: A review. *European Journal of Agronomy* 13: 125-153.

Rao, P.K. 2000 A tale of two developments of irrigation: India and USA. *International Journal of Water* 1: 41-60.

Rassas, D. 2007. Stakeholders' perspective on the feasibility of seawater desalination as a solution to water scarcity in Israel: Economic and Environmental ratification of using desalinated water in Agriculture in Israel, (unpublished

Master Thesis) Sede Boqer, Ben Gurion University.

Raveh, E., Weiss, J., Nerd, A. and Mizrahi, Y. 1993. Pitayas (genus *Hylocereus*): A new fruit crop for the Negev desert of Israel. In *New Crops* (Eds. J. Janick and J. Simon), pp. 491-495. Wiley, New York.

Reinders, F.B. 2006õ Micro-irrigation: world overview on technology and utilization. 7th International Micro-Irrigation Congress, 13-15 September 2006, ICID, Kuala Lumpur, Malaysia.

Reisner, M. 1993. Cadillac Desert, The American West and Its Disappearing Water, Penguin, New York.

Rosenthal, G. 2005. Critical Analysis of the Inbar Committee Recommendations for Division of Burden of Upgrade of Treated Wastewater. Kivun Strategy, Economics, and Business Development (Hebrew).

Salem, S.S. 1996. Environmental considerations for wastewater reuse in agriculture. *Water Science and Technology* 33: 345-353.

Schoups, G., Hopmans, J.W., Young, C.A., Vrugt, J.A., Wallender, W.W. and Tanji, K.K. 2005. Sustainability of irrigated agriculture in the San Joaquin Valley, California. *Proceedings of Nattional Academy Science* 102: 15352-15356.

Singh, K.B. and Ocampo, B. 1997. Exploitation of wild Cicer species for yield improvement in chickpea. *Theoretical and Applied Genetics* 95: 418-423.

Segal, E., Ben-Gal, A. and Shani, U. 2006. Root water uptake efficiency under ultra-high irrigation frequency. *Plant and Soil* 282: 333-341.

Sharmasarkar, F.C. et. al., 2001. Agroeconomic Analyses of Drip Irrigation for Sugarbeet Production. *Agronomy Journal* 93: 517-523. (**Please provide full editors name)**

Shelef, G. 2001. Wastewater Treatment, Reclamation and Reuse in Israel, Efficient Use of Limited Water Resources (Ramat Gan: BESA Center for Strategic Studies, Bar-Ilan University).

Shani, U., Ben-Gal, A., Tripler, E. and Dudley, L.M. 2007. Plant response to the soil environment: An analytical model integrating yield, water, soil type and salinity. Water Resources Research (In press).

Shiva, V. 2001. Monsanto's Expanding Monopolies. http://www.vshiva.net July 1.

Smedema, L.K. and Shiati, K. 2002. Irrigation and salinity: a perspective review of the salinity hazards of irrigation development in the arid zone. *Irrigation and Drainage Systems* 16: 161-174.

Tal, A., Ben-Gal, A., Lawhon, P. and Rassass, D. 2005 Sustainable Water Management in the Drylands: Recent Israeli Experience. Israel Ministry of Foreign Affairs.

Tal, A. 2006. Seeking sustainability: Israel's evolving water management strategy. *Science* (August 25): 1081-1084.

Tanji, K.K. 1990. Nature and extent of agricultural salinity problems. In: Agricultural Salinity Assessment and Management No. 71, 1–17. ASCE Manuals and Reports on Engineering Practice (Ed. K.K. Tanji), ASCE, New York.

Tanji, K. and Kielen, N. 2002. *Agricultural Drainage Water Management in Arid and Semi-arid Areas*. FAO Irrigation and Drainage Paper 61. FAO, Rome, Italy.

Tanji, K., Davis, D., Hanson, C., Toto, A., Higashi, R. and Amrhein, C. 2002. Evaporation ponds as a drainwater disposal management option. *Journal Irrigation and Drainage Systems* 16: 279-295.

Tanksley, S.D. and McCouch, S.R. 1997. Seed banks and molecular maps: unlocking genetic potential from the wild. *Science* 277: 1063-1066.

Tel-Zur, N., Abbo, S. and Mizrahi, Y. 2005. Cytogenetics of semi-fertile triploid and aneuploid intergeneric vine cacti hybrids. ***J Hered.*** 96: 124-131.

Tel-Zur, N., Abbo, S., Bar-Zvi, D. and Mizrahi, Y. 2004. Genetic relationships among *Hylocereus* and *Selenicereus* vine cacti (Cactaceae): Evidence from hybridization and cytological studies. *Annals of Botany* 94: 527-534.

Thornthwaite, C.W. 1948. An approach toward a rational classification of climate. *Geographical Review* 38: 55-94.

UNEP (United Nations Environmental Program) 1992. World Atlas of Desertification. Edward Arnold, Seven Oaks, Nairobi, Kenya.

NEP, (United Nations Environmental Program). 2006. Global Deserts Outlook, Nairobi, Kenya (Ed Exequ el Ezcurra).

Union of Concerned Scientists 1999. Frequently Asked Questions About Sustainable Agriculture. in Sustainable Agriculture--A New Vision (Union of Concerned Scientists). Available at UCS Website (7/99): http://www.ucsusa.org/agriculture/sus.ag.faqs.html.

US National Research Council. 1985. Jojoba: new crop for arid lands, new material for industry. National Academy Press, Washington DC.

Vavilov, N.I. 1940. The New Systematics (Ed. J. Huxley. Clarendon), pp. 549-566. Oxford, UK. (**Pl. provide titile of chapter).**

Wichelns, D. 1999. An economic model of waterlogging and salinization in arid regions. *Ecological Economics* 30: 475-491.

Wisniak, J. 1987. Jojoba Oil. The chemistry and Technology of Jojoba Oil. A Oil Chem Soc, Champaign, IL, p. 173.

Weiss, J., Nerd, A. and Mizrahi, Y. 1994. Flowering behavior and pollination requirements in climbing cacti with fruit crop potential. HortScience 29: 1487-1492.?????

Yermanos, D.M. and Ducan, C.C. 1976. Quantitative and qualitative characteristics on jojoba seed. *Journal of America Oil Chemistry Society* 53: 80.

Yermiyahu, U. 2007. Irrigation with Desalinized Water: Advantage or Disadvantage, Proceedings of the Negev Conference for Agricultural Development, February 27, (Hebrew) 13.