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Sustainable Land Use Systems for Arid Lands: Research Needs for the Next Twenty-Five Years

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Abstracts: The world's drylands continue to deteriorate and degrade under heavy pressure and poor management. The limited historic success in treating these problems suggests new approaches are needed. These most focus more on causes, which are often economic or power related, than on symptoms, such as erosion. New methods of funding research, education and improved management are needed. Improved understanding of the dryland science is a necessary step, but equal attention must be paid to understanding what, why and how people make land use decisions. A better understanding of the value of Nature's Services and Natural Capital will help revise economic policies to favor sustainability.

Key words: Drylands, sustainability, research, management, education, economics, reform.

The Challenge

'A thing is right when it tends to preserve the integrity, stability and beauty of the biotic community. It is wrong when it does otherwise'. Aldo Leopold (1949).

The drylands and deserts of the world have been, and are being, damaged and made less productive by overgrazing, over-cutting for firewood and timber inappropriate farming, poor irrigation management leading to problems with water-logging and salinization, mining, construction of highways and utility corridors, wars and military training, air pollution, the deliberate or accidental introduction of invasive species, recreational activities, particularly off-road vehicle recreation, industrial projects, climate change, housing, and urbanization (Lovich and Bainbridge, 1999; Bainbridge, 2007a). The underlying causes of dryland degradation are more often economic and cultural rather than ecological (Hallsworth, 1987; Carney and Farrington, 1998; Chambers *et al*., 1991). The limited historic success in slowing the rate of desertification and limited efforts for restoration are linked to the consistent pattern of treating the symptoms rather than the causes.

The semi-arid and arid areas of the world make up about 35% of the global land area and affect the daily lives of almost a billion people. Globally more than 60% of the rangeland, 60% of rain-fed croplands, and 30% of the irrigated croplands are at risk for further degradation, and as many as a million hectares are assessed to be completely lost to production each year (Middleton and Thomas, 1997; UNEP, 2005). Water supplies are declining and increasingly polluted (Pearce, 2006). The annual cost of these environmental declines is estimated at about $ 65 billion and rising (Adeel *et al*., 2006). This unsustainable use has limited the ability of dryland residents to make a living, reduced their quality of life, destroyed communities, created environmental refugees, led to conflicts over land and water, reduced health and life expectancy, and severely degraded natural systems and biodiversity (Lean and Hinrichsen, 1992; Myers, 2001; Solh *et al*., 2003; Bainbridge, 2007a; Sengupta, 2007).

There will be no simple technical fix, but by addressing the underlying causes of dryland deterioration, understanding the history of abuse, and applying the best restoration and management practices we can slow and reverse the damaging changes; however, it will not be easy. Restoration and improved management of arid resources are essential for reversing the process of desertification and improving the quality of life for desert communities. This work is hampered by our limited understanding of these complex systems and by the very high environmental variability of most arid ecosystems.

Despite growing awareness and understanding of the need for action, there has been very little funding for long-term, complex research projects or for large-scale restoration that include both ecological and cultural considerations (Naveh, 2005; Bainbridge, 2007a). There has also been relatively little work to expand and support existing opportunities for economic development of arid lands. Most of the desert restoration work that has been done has been required by environmental laws in developed countries, while more serious cases of ecosystem decline in developing countries have received less attention until recently (Aronson *et al*., 1993; Lee and Schaaf, 2002; Lee, 2004).

However, there are many signs of hope. Changes in the type of research and efforts to improve management have been very encouraging to someone who has been hoping and advocating change for almost 30 years. Recent efforts in China, the Middle East, and the Mediterranean are using more integrative research and implementation (Zhang *et al*., 2007; Xu *et al*., 2006; Thomas *et al*., 2005; ISC, 2006). However, national and international efforts still neglect desert research and restoration because they have little political value, are not glamorous, and will not in most cases yield immediate economic returns. When restoration has been implemented, the costs and benefits have rarely been tracked, leaving lessons unlearned (Heady and Bartolome, 1980).

While improved techniques for desert restoration and management are needed, the fundamental challenge remains to understand the desert environment better, and then to change the economic and cultural pressures and incentives that lead to desertification (Bainbridge, 2007a; Adeel *et al*., 2006; ISC, 2006; IISD, 2006; Reynolds *et al*., 2007). This will require a wide-ranging and rigorous program of applied and basic research, demonstration, and education, which must all be addressed in a global climate with unknown and difficult to predict changes that may make these tasks much more difficult.

Research for the Next Twenty-Five Years

A number of reviews on the frameworks for reversing desertification by interdisciplinary international groups are now available (Adeel *et al*., 2006; AHTEG, 2006; ISC, 2006). This article, on the other hand, provides a personals view of the author, developed so as reach across the traditional boundaries of science, economics, politics, sociology, gender, age, and culture, and improved by suggestions from researchers from around the world.

A new paradigm for desert research needs to be created, one that recognizes the inherent dignity and worth of all people and ecosystems and that restores environmental health to improve the quality of life as well as the stability and joy found in community and cooperation. Funding and incentives to promote and support long-term inter- and multi-disciplinary research for sustainability must be developed and must include support for effective education, demonstration, and implementation programs that promote and reinforce sustainable management practices.

The growing awareness of very serious problems with global and local ecosystem stability, resource availability and environmental decline is encouraging new consideration of the sustainability of our current management of land, water and community. It was just twenty years ago that the World Commission on Environment and Development, chaired by Gro Harlem Brundtland, highlighted the importance of sustainability (WCED, 1987). This ground breaking book defined sustainability as, "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs." The book also highlights the importance of addressing the problems of poverty and inequity as necessary steps for preventing continued environmental deterioration.

The concept of an ecological footprint was developed to help answer the question of how much productive land, water and resources we need to support our lifestyles (Wackernagel and Reese, 1996) (For a quick, personal ecological footprint quiz, see http://ecofoot.org). Developing an ecological footprint for a nation and the world is challenging, but several attempts have been made (Wackernagel *et al*., 1999; EEA, 2005a; Global Footprint Network, 2006). Trends are not encouraging, with the ecological footprint of the world expected to increase 50% by 2015 (Wackernagel *et al*., 2002; Dietz *et al*., 2007).

A comparison between ecological footprint and resource availability is recommended. It has exposed problems even with countries that appear to be prosperous, but has not been done for countries with extensive areas of drylands or deserts, where the picture would generally be appalling and would highlight the importance of improving water-use efficiency and restoration as well as land and human capital. Ecofooprints can also be applied to historic and prehistoric land management (Nelson and Schollmeyer, 2004).

Ecological footprint analysis can also be applied to regions, cities, towns, watersheds, or farms. A first attempt at a sustainability diagram for a desert city in a developed country illustrates the challenges of arid lands (see **Fig. 1**) (Bainbridge, 2007b). Local communities can help develop their own sustainability indicators (Reed *et al*., 2006).

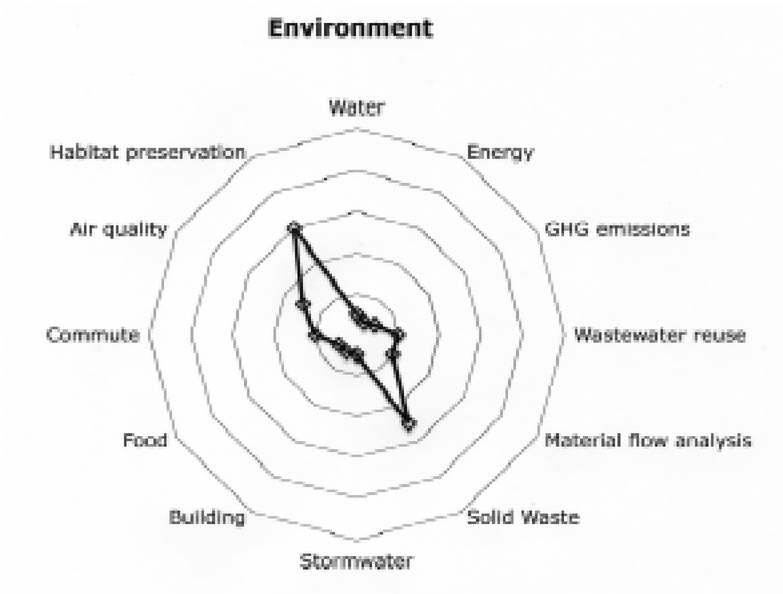

Fig. 1. A sustainability plot for San Diego, a desert city that does not think it is a desert city.

Ecological footprints for materials and products can also be calculated (Schmidt-Bleek, 1999), and these calculations should be included in development planning and export-import schemes. The virtual water included in products produced in arid lands is a special concern (Pearce, 2006). Energy calculations often show surprising results as well (McWilliams, 2007).

Sustainability is not simply about the environment. To be sustainable a community must be working within environmental constraints, but must also have a healthy economy and programs as well as policies and traditions that provide support for community, safety, cohesion, cooperation, education, health, and equity (van Dresser, 1976; Meadows, 1991; Moffatt, 1994; Vemuri and Costanza, 2006; Costanza *et al*., 2006). This social, economic, and environmental approach to sustainability is sometimes referred to as the "triple bottom line" (Elkington,1997; Kim *et al*., 2006). The approach is particularly important in arid lands where resource constraints are most severe, but has rarely been applied to these fragile and degraded ecosystems.

Researchers and policymakers in many nations are making an effort to develop alternative measures for defining progress that incorporate a broader range of social, economic, and environmental considerations. This includes such metrics as the Genuine Progress Indicator (26 factors), the Index of Sustainable Economic Welfare, Gross National Happiness, and Sustainable National Income. Instead of simply looking at money flow with Gross National Product or Gross Domestic Product, these indexes consider the quality of life and of the environment

(Venetoulis and Cobb, 2004; IISD, 2005; EEA, 2005b; Bainbridge, 2006a). These measures can also be applied at the sub-national level (Costanza *et al*., 2004).

Ekins (2001) suggests that defining the "sustainability gap" may be more practical and useful in measuring the health of drylands and deserts. The sustainability gap can be evaluated by using carefully selected indicators that look at demand and supply (Bell and Morse, 2000). An understanding of the sustainability gap for a city, watershed, or farm is also a useful tool for policy and research development. Indicators can also be used to assess the degree of desertification and recovery (Hambly and Angura, 1996).

Although there is a growing awareness of the problem, interdisciplinary research on arid land sustainability is still rare. In many desert and dryland areas we do not understand the basic ecosystem structure and function, the economic system, the legal system (formal or informal), land ownership and rights (tenure), and the cultural factors that influence decision-making. These gaps in knowledge should be addressed with an extensive and intensive research program on adaptive management that involves the full range of stakeholders (Fraser *et al*., 2006; Bainbridge, 2007a; Prell *et al*., 2007). I suggest that the research priorities include climate change, cultural issues, economics, ecosystem science, and engineering.

Climate Change

Human activities and actions have precipitated environmental decline since the earliest days of humanity. Early grazing and wood harvesting forever altered the lands of the Middle East, the Mediterranean, and China (Thirgood, 1981; Elvin, 2004). These adverse impacts have followed us around the world as we have brought our animals, plants, and incessant demands for more resources to new lands. With the rise of global industrial civilization, the rate and magnitude of environmental change have dramatically increased, along with the risk of unexpected and adverse repercussions. Global climate change is the latest example. The basic facts are no longer in question, but the repercussions are less perfectly understood (Christianson, 1999; IGPCC, 2007). In addition, disruption of global and regional nutrient and hydrologic cycles has had unexpected and undesired effects on ecosystem stability (Ayers *et al*., 1997; Bainbridge, 1997a).

Global climate change is already being blamed for serious problems in the world's drylands and the issue is expected to worsen. The problem is where, when, and by how much? These questions are not yet answerable. Although temperature predictions are becoming more accurate, rainfall predictions remain uncertain and are more important for arid land management (McKeon, 2006). Research to improve forecasting is critical.

Many scientists and ecological economists argue that we should be careful when we do not understand what will happen, that a precautionary principle should be adopted. Conventional economists and politicians argue that if we do not understand things, we can ignore them because a technological fix can always be found. Even in the absence of good predictions for climate change, progress can be made toward more sustainable management of drylands. To do this we need to better understand how and why people make the decisions they do about land and water use. This will require an enhanced knowledge of micro- and macroeconomics as well as of culture. Improved on-the-ground practices will require a better understanding of ecosystem structure and function. To develop better water management systems, more comfortable and **healthful** buildings and cities, and more efficient industrial operations and farms funding for engineering research must be increased.

Management: The Human Dimension

The degradation of drylands adversely affects local and global ecosystems, biodiversity, Natural Capital, and Nature's Services (Daily, 1997; Costanza *et al*., 1998; Zeidler and Mulongoy, 2003). Many residents of and travelers to desert lands value their beauty and mystery. Tourists offer a potential revenue stream from ecotourism operations to protect and enhance the quality of a desert (Weaver, 2001). Developing sustainable economies for arid lands will require a range of ecologically sustainable resource management systems that fit the culture and the environment of a desert region as well as the global economy. In many cases the cultural practices and management systems may need to be revamped to recognize an ecological reality.

Environmental and economic problems in the world's drylands and deserts are linked to socio-political problems that are little studied, poorly understood, and often involve opinions that are very different if not irreconcilable. Funding and political constraints limit the range of available options. Few landscape-scale systems studies have been done, but perhaps no area of research offers such a good potential for improvement. Support for broader systems consideration and capacity building for this type of study is increasingly recognized (Zeidler and Mulongoy, 2003), and the development of the Ecosystems Approach Sourcebook is a step in the right direction (CBD, 2007). The LADA project will provide new insight into the complex factors that lead to land degradation (Koohafkan *et al*., 2003). As Forrester (1969) correctly observed, failure to consider systems aspects of problems often leads to treating symptoms rather than underlying causes, which often exacerbates the problem as a result of the "counter-intuitive behavior of social systems." Efforts to develop these systems considerations in computer models may also be very rewarding (van Delden *et al*., 2007). The use of the Complex Adaptive Systems framework in research can also help. Integrative studies that create links across disciplines and that use geographic information systems and satellite data to work with local communities could be very instructive and productive.

Short-versus long-term funding

Environmental change may have been underway for decades or centuries, and understanding these changes may be important in developing improved management plans (Richter and Markewitz, 2001; Bainbridge, 2007a). Funding cycles of one, two, or perhaps five years are inadequate to support the research that is needed to assess and promote sustainability. The importance of long-term funding has been recognized in only a few programs, most notably the Long-Term Ecological Research Program of the National Science Foundation, which provides long-term funding and facilitates cooperative interdisciplinary research (Callahan, 1984; LTER, 2007).

The balance between current investments and increasing productivity and value in the future is at the root of many desertification problems. If the discount rate is set high, then investment in restoration and sustainable management will not be seen as desirable. Yet continued environmental decline is not viable. The gap between paying now and benefiting later is perhaps the biggest challenge confronting improved management of private and public lands.

Asset-based economics can help improve consideration of long-term versus short-term considerations. An asset-based system would put a much higher value on the future, encouraging planning horizons of 20, 50, or 100 years or more, and would bring into the market the external costs of illness and death caused by farm pollution, environmental damage, clean up, and mitigation, and the potential productivity of the farmland.

Worldview and cultural ethos

The relationship between the worldview of the observer, the system model developed to explain what is seen, and the manner in which solutions are tested and refined as new observations are made must also be considered in developing improved management practices. What we see depends on who we are and how we look at a situation. As a **permittee** on a grazing allotment in Arizona commented after being forced to reduce grazing for riparian improvement, the riparian areas had always "looked bad" during his 50 years of use. Yet areas that had been sandy, were re-vegetated, verdant and had flowing water after only 6 years of improved management, and the allowable grazing level was raised (GAO, 1988). Asking a goat herder in the Atlas Mountains about climate change and its effect on desertification would be equally problematic; the hills have "always" been barren.

Funding limitations and hiring freezes, even in rich nations, have left many public management units with inadequate staff to undertake mandated programs (GAO, 1988). In less developed countries the crises are even worse, with operating budgets for agents as low as $ 1 a year for supplies (Chambers *et al*., 1991).

Without local participation, the research, extension, and assistance programs are unlikely to succeed. Involving local people is critical, to benefit from their knowledge, skill, and commitment. They will still be there long after the scientists, advisers, and experts are gone. A sophisticated computer model of land management will not work if it is not grounded in reality—and if the local stakeholders are not involved (Prell *et al*., 2007).

Why do we do what we do?

Gladwin (1979, 1983) laid the groundwork for a better appraisal of farmer decision-making, which can help us to develop policies and programs that will nurture sustainable development and environmental restoration. But much more research is needed on the cultural foundations and beliefs that guide decision-making. Research to make facilitating change while respecting traditional cultural practices and institutions easier could be very helpful. Network analysis can help to determine how many contacts are needed at the local level for change to take place (Lubell and Fulton, 2007). Multiple contacts and reinforcement are usually needed for change. Secure land tenure and an optimistic view of the future are needed for successful environmental management and restoration. A desperate farmer or rancher near the edge of bankruptcy will find it impossible to invest energy and resources to plant and see a tree grow to maturity or to build a fence and protect a critical watershed by working with his neighbors (Place *et al*., 2004).

Network analysis could also be usefully applied at the state, regional and national level to determine why desertification funding is approved or denied and why programs fail or succeed. More post- project analysis and follow-up would be very useful and would cost very little.

Stakeholder participation

Educational efforts must increase to make sure that those who will benefit most from an investment in sustainability are involved. These efforts should involve women, who as mothers and wives are most immediately affected by environmental decline. Many programs have failed because they have primarily been directed to men, when in much of the world women are the primary food producers, fuel gatherers, and water carriers (Curtis, 1986; Howe, 1993; Kuchli, 1997; Kabeer, 2003; Ramphele, 2005). Programs must be more carefully designed to include women at all stages of research, extension, and development (CGIAR, 1985; Fortmann and Rocheleau, 1985). Stakeholder engagement in adaptive, participative planning and decision-making can increase buy-in and lead to improved management.

Opportunities and strategies for the poorest, the landless

An emphasis on the poor is also needed, because the poorest are hardest hit by environmental decline (Chambers *et al*., 1991). The landless, or soon to be landless, are most vulnerable to deteriorating conditions. Government and international aid programs and policies often benefit only the richest farmers or ranchers who can use credit to consolidate land and power, to usurp water and other resources, and to manipulate the courts and enforcement organizations (Sinha, 1991). Research to help these families develop sustainable ways of life is critical, particularly when they are environmental refugees or immigrants who do not understand the ecosystem opportunities and constraints. This can be seen in the history of the settlement of the western United States, where settlers went hungry and broke in areas where native people lived well.

Traditional management systems

We are finally recognizing the importance and value of knowledge acquired over generations of experimentation and observation in arid lands. A growing body of research has begun to explore the richness of traditional knowledge (Nabhan *et al*., 1982; El Amami, 1984; Agarwal and Narain, 1997; Wilken, 1987; Rivera, 1998; AHWG, 2003; CST, 2005; Youlin, 2005). In 1999, the Convention of Parties to Combat Desertification first established an ad hoc committee on traditional knowledge and reports are starting to become available (Anon., 2005; UNCCD, 2005). The Society for Ecological Restoration International has created an Indigenous Peoples' Restoration Network (IPRN, 2000).

Understanding traditional practices should be the first step in any large-scale restoration or sustainable resource management program (Anderson and Moratto, 1996; Homburg *et al*., 2005; Barr, 2006). Often "expert" knowledge from advisors trained in the developed countries is unsound and can do considerable harm when traditional systems are displaced or disparaged (Nabhan *et al*., 1982; Shiva and Bandyopadhyay, 1986; Davis, 2005). By the same token, recognition of the value of traditional systems can lead to renewed interest in their operation and products, which can offer increased prices and market opportunities.

Understanding traditional management systems is an excellent cause for personal, foundation, and government support. Research is needed across the full range of management activities. What practices are sustainable? Why? How?

Management research

One of the areas that has been most neglected is management research. This could include research on a wide range of management issues and perspectives. A systematic and comprehensive review of management approaches and practices around the world would be very helpful. This might be presented in a relational data-base, so that possible solutions could be found by climate type, soil type, land ownership system, cultural system, or marketplace.

There are also many opportunities for studying land management from an ecosystem perspective, which can often provide new insights. The United Nation's SUMAMAT program is intended to address land management and sustainability issues and to support development of marginal drylands and arid lands. Better-funded regional sustainable resource management research and demonstration centers, based on the very successful program of Precodepa (Niederhauser, 1986), could be established with tasks prioritized and assigned across the range of institutions and countries. Private partnerships with NGOs should be sought out and supported.

Research could create a comprehensive census of useful plant species and resource management practices of the arid lands, their ecological, economic, and cultural relationships. The Sepasal Program and Economic Botany Bibliographic Database suggest what can be done, but much more needs to be invested (RBGK, 2007). The development of a free, on-line comprehensive database of traditionally used plants is a long way off for most regions and countries. Increased research to evaluate the traditional medicinal plants of the arid lands and to establish a detailed database for related species is also needed. Databases on herbs, fodder and craft, and construction plants for arid lands are also needed. These databases would facilitate benchmarking the best management practices for specific soil and climate conditions from around the world. A related database of invasive species, their impacts on ecosystems, and how best to control their growth should also be established. In cases where no good local species exists for certain needs, an introduction could be considered, but only after clearance by an invasive species unit to reduce the chances of introducing a pest species—with the best intentions—an all too common flaw of "expert" assistance. The invasive species unit would also monitor introductions to look for unintended consequences.

Economics, Regulations, and Perverse Incentives

People can rarely be encouraged to do something that is "right" if it is not also economically advantageous (Bainbridge, 1985). What is advantageous is usually the result of policies and programs that have not considered environmental or social costs or benefits. Research is urgently needed to rectify this omission. There are also opportunities for economic return on investment that are not being recognized in many areas.

Economic research

Economic considerations are usually the most critical factor in the success or failure of sustainable resource management (Hallsworth, 1987; Blaikie, 1985; Blaikie and Brookfield, 1987). Often the problems in a specific field can be traced back up the causal chain to actions far away that affect global trade, prices, and markets, **Fig. 2** (Bainbridge, 2007a). Economics is a political game, where the rules are generally set to protect powerful interests today, rather than quality of life, environmental sustainability, or way of life concerns. Redirecting investment to more sustainable activities may produce

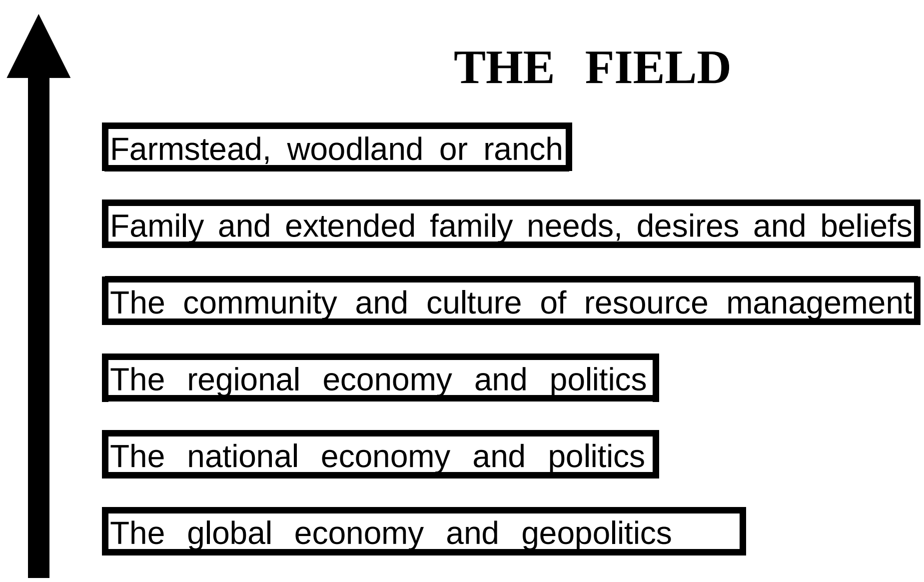

Fig. 2. The causal chain

significant gains, but is not easy (Lange, 1998). The predominant economic view that the environment does not matter is gradually eroding, but economic policy that reflects ecological functions and systems remains rare (Bainbridge, 2006a). The evaluation of the benefits from large-scale riparian restoration suggests that bigger is better (Holmes *et al*., 2004).

The Causal Chain of Land Use Decision-Making

Subsidies, regulations, and policies often also work against sustainable resource management. These impacts may reach around the world, as current subsides to grain farmers in the United States adversely impact small farmers on several continents. The identification and internalization of external costs, such as environmental degradation, is essential (Bainbridge, 2007c). The rules that currently encourage "mining" potential renewable resources must be restructured. Although national tax, regulatory, and trade policies are important, so, too, are local laws, regulations, and institutional (banks, courts) behavior. Development of sustainability gap data may help encourage needed restructuring of economic policies.

As Pigou (1920) noted early in the last century, the market will fail unless it includes all costs. If the market were complete, any attempt at separate environmental and social accounting would not be necessary; however, the flawed and incomplete market we have today, with enormous uncounted for and incorrectly attributed costs, performs very poorly. It considers only a small fraction of the total transaction cost, leaving many "externalities" out of the picture (Antheaume, 2004; Bainbridge, 2006a). If full costs were known, many current market transactions would not occur, and we would face a much more hopeful, secure, and sustainable future (Ròbert *et al*., 2002; Young, 2006).

To reduce consumption of non-renewable resources and to limit adverse impacts, we need to understand the input and output of companies and the life-cycle costs of products, from the cradle to the grave (made, used, disposed) or cradle to the cradle (made, used, recycled, reused, or returned to nature). This is the goal of most sustainability reporting, from the Eco Management and Audit Scheme to the Global Reporting Initiative (McDonough and Braungart, 2002; IFA, 2005; EMAS, 2006; GRI, 2007).

Detailed economic analyses of the potential of sustainable resource management systems in selected areas is needed, including establishment cost, risk and potential income under differing scenarios (see, for example, Scherr, 1991). These analyses should include farm-level, watershed, and regional implications. Sensitivity analysis may prove more useful than simple budgeting or cost/benefit analysis for these complex multi-year and multi-factor programs. Improved understanding of the full range of economic costs, and benefits of improved management and environmental restoration is needed for specific sites and applications, watersheds and regions.

Existing opportunities

Research on the best management practices will show that many opportunities for sustainable management, environmental restoration and profit exist (Amara and Abdemmebi, 2007). Not all communities are in desperate straits, and not all crops or products of the drylands are unsustainable. Intelligent and hard-working families may simply need access to capital as well as minor guidance in marketing and managing their business to increase income and to make more efficient use of limited resources (Thomas *et al*., 2005; Bainbridge, 2007a). This is particularly important for pastoralists, who have generally been little served by banks and financial institutions.

Economic research where there is no money

Very little economic analysis has been done in areas where little money changes hands. This makes improving land management very difficult. Much more research is needed to evaluate the accounts and import/export balance sheets of families, communities, regions, and states in arid lands. The evaluation must include non-cash transactions, such as labor cooperation, self-grown or shared food, firewood, and other resources (see for example Sheridan, 1980). One cannot create good policy when one only understands a small part of the economy that is cash-based.

Economic and ecological feedback

The economic and biological impacts of land degradation tend to have damaging positive feedbacks. As grazing reduces plant cover, it increases surface soil temperatures and decreases water infiltration into the soil. The higher surface temperatures reduce the accumulation of organic nitrogen, which is often a limiting factor in dryland ecosystems. The reduced soil moisture and soil nitrogen lead to a vegetation decline, which increases grazing pressure, which further reduces productivity until grazing must be abandoned. Large increases in desertified arid lands can lead to regional changes in ecosystem function. The degradation of arid lands may also increase denitrification, adding to the problems of ozone destruction and global warming (Schlesinger *et al*., 1990).

The economic effects of land degradation can also develop positive feedback, namely accelerating destruction. As grazing declines, the pressure becomes greater to get more benefit from the little browse that remains, and the increased grazing pressure on remaining plants eliminates the few remaining pockets of desirable browse. The first response is usually to switch grazing animals, from cattle to sheep, and as the situation worsens, only goats or camels can survive. If pressure remains high, a barren rock, gravel, or dusty plain will develop.

Material flow analysis

Improving our accounting of materials, water, and energy will not be easy, because we have not studied these issues very carefully, and the flow pathways and impacts can be complicated and long term. To understand social and ecosystem effects, we need to know much more about material flows, from firewood to agricultural chemicals (EEA, 2001; Brigenzu *et al*., 2003; Binder *et al*., 2004). We should be able to clearly describe the following: How much is there? Where does it come from? Where does it go? Does it move in air, water, food or dust? Is it local or global?

Concentrated or diffuse? Are materials bio-magnified? Are metabolites or breakdown products more hazardous?

Even when materials are non-toxic to humans, they can lead to ecosystem catastrophes (Günther, 1997; Vitousek *et al*., 1997). These materials may have very insidious effects on native species (Bainbridge, 1997a; Brooks, 2003). This is best recognized for nitrogen and phosphorus, but they are not the only concerns. Eco-toxicity is common from many materials that are used as in agriculture, for roofing, or in building materials or that are emitted as pollutants from transportation systems, manufacturing and power production. Nitrogen, phosphorus, and zinc are common examples (Karlen *et al*., 2001; Reck *et al*., 2006). Are these materials lethal, mutagenic, or teratogenic? Can we and/or ecosystems shed materials if exposures are infrequent, or do they build up over our lifetime? Do they break down in hours, days, years, millennia? Can they be collected and destroyed or recycled? In arid zones many materials persist for a very long time.

We also need to consider natural and human disasters. What happens to all of the hazardous and eco-toxic materials in a fire, flood, earthquake, hurricane, or tornado? These materials can be a major source of pollution. Large quantities of industrial, commercial, and agricultural chemicals are often released in natural disasters, adding to the magnitude of the catastrophe and making cleanup much more difficult.

Policy research

Policy analysis is rarely undertaken when efforts are made to improve arid land management, but the drivers of unsustainable practices are often policy-related. The institutional settings are inherently complex, but must be understood to develop policies that will work (Ascher, 1999; Briassoulis, 2004; IISD, 2006). Research on tax, credit and regulatory policies that provide economic disincentives for sustainable resource practices is urgently needed. Monitoring can help reveal when management is working (Margoluis and Salafsky, 1998). Failures to implement existing laws and regulations and to forward international aid to intended recipients as well as the corrosive effects of corruption and bribery would benefit from recognition and research. Research on responses to disasters, natural or man-made, would also be valuable. By better understanding failures in past efforts, we could improve response to future events. Research on how to better bring both science and traditional wisdom into policy discussions could be very productive. The disconnect between knowledge and policy is often striking in developed and developing countries.

Environmental accounting and sustainability reporting

Although much progress has been made in environmental accounting (Rikhardsson *et al*., 2005), the work has really just begun. Much more accurate and complete information is needed on a wide range of costs and benefits (Bainbridge, 2006a). Environmental accounting also has to be made much easier for a wide range of users. Quality assurance and auditing systems will also need to be improved.

Database developers, information source managers and accountants must be educated on the importance of this work and the need for readily accessible information (Bainbridge, 2006a). Considerable additional research and increased integration of information across disciplines is needed to make sustainability reporting faster, cheaper, more useful to all stakeholders, and more fun. It is perhaps the most important work in the world for the next decade as we rethink what society's goals might be (Daly and Cobb, 1989).

Access to capital: microcredit

Increasing access to capital for small landholders is critical and can perhaps be achieved by following the model of the Grameen Bank and other successful microcredit programs to create land restoration programs in the world's arid lands. The UN's Year of Microcredit in 2005 involved more than 40 partnering agencies and institutions (Year of Microcredit, 2005).

Infrastructure needs

One of the common problems in arid lands development is the difficulty of reaching distant markets. More research on infrastructure needs and innovative solutions for local and regional transportation are needed. This could start with a comprehensive review of traditional transport solutions from around the world.

Marketing sustainability

Improved market analysis and development are also needed. How can prices to growers and producers be raised? Can value-added products, such as dried foods and food mixes, that are easier to store and transport be created on a farm? Can regional or local cooperation lead to organic or fair-trade certifications that will add to returns? What legal or regulatory barriers need to be revised or removed?

Ecological Science

A better understanding of deserts and drylands is essential (Reynolds *et al.*, 2007) and will require research across the range of basic and applied science and engineering.

Basic science

Very little is known about many arid land ecosystems, even in rich counties. Funding for basic science research has been declining, and fieldwork has fallen out of favor. Fortunately, much of this research is not costly, requiring little more than time and expertise; however, more investment in basic science research will be essential. One good question is how to make this happen. In many countries the work can be done with help from locally trained para-botanists, para-ecologists, and scientists trained on full scholarships in developed countries.

Long-term interdisciplinary research projects are critically important, yet rare. The National Science Foundation's Long-Term Ecological Research sites are, unfortunately, almost unique (Havstad *et al*., 2006), and they are sadly under-funded, with about $ 20 million a year spread over twenty six sites. Each, site could easily use $ 5-10 million of base funding. A much better understanding of ecosystem structure and function in the world's drylands and deserts is needed to develop sustainable management systems (Reynolds *et al.*, 2007). This should include the full range of research, from soils to microclimate, plants to fungi, termites to cattle. The scale of research should extend from the microsite to the landscape scale.

Plant inventories and ethnobotanical studies are particularly important in degraded areas (Muenchrath *et al*., 2006). Candidate species for restoration and wider use must be identified. The value of these genetic resources must be recognized and mechanisms must be developed to identify the rights of collective action that led to their creation and protection (Eyzaguirre *et al*., 2004). Methods to return funding to the source of their protection and to reward their caretakers are also important. The periodicity of seed set, seed upgrading, and seed storage as well as planting information must be developed so that plants can be reintroduced into degraded areas with sufficient genetic base to survive and prosper.

Another area for research is the possible adverse impact of management practices on ecosystems and native species (Fleischner, 1994; Bainbridge, 2007a). As Hawlena and Bouskila (2006) report, widespread development of water catchments in the Negev has adversely impacted native lizard species.

Applied science

In addition to basic science, research is needed across the full range of applied science, from agroecology to agroforestry, dairy to pastoralist, soils to climatology, and basic revegetation to ecological restoration (see, for example, Bradshaw and Chadwick, 1980; Burke, 2001; Bainbridge, 2007a). Application of traditional science remains important as well, with demands for plants that are better adapted to drought and salt. Research on innovations in more efficient irrigation and analysis of traditional irrigation systems will also be of value. Water harvesting is an important area for research and demonstration at many scales. Ideally these would by multidisciplinary studies involving a range of scientists and students working on common problems. Additional research on the successes and failures of existing restoration work is also needed. Re-creation and analysis of traditional systems at the landscape scale should also be included (Evenari *et al*., 1982). The benefits of restoration on biodiversity and ecosystem structure and function should be evaluated carefully (Jordan *et al*., 1988; McNeely and Scherr, 2002). The importance of protecting cultural diversity to maintain biological diversity is finally being realized (ISC, 2006).

The goal of applied science research is to develop working landscapes that are managed for productive agriculture and rural livelihoods, while conserving and restoring critical ecosystem services and biodiversity at a landscape scale. Emphasis of this research must include improving ecosystem services (species habitat, watershed functions) and increasing natural capital.

Applied engineering

The most important first step is openly acknowledging that applied engineering has some very challenging sustainability problems that include improving sustainability in production, processing, and distribution. This should perhaps also include efforts to develop a workable set of sustainability indicators and to improve all external costs, including environmental and health costs in engineering development. What is not measured is not managed.

The most intriguing and exciting work for agricultural and biological engineers is the development and refinement of locally adapted sustainable resource management practices and agro-industrial ecosystems (Bainbridge 2007d). Two of the most important challenges are improving energy and water-use efficiency (Boers *et al.*, 1986; Droppelman *et al.*, 2000; Bainbridge, 2001, 2002, 2006b, c).

Basic engineering and building science

Research is also needed to improve the sustainability of buildings, facilities, transportation, refrigeration, manufacturing, and processing. More sustainable practices in building can help improve the quality of life and reduce energy demand (Steen *et al.*, 1994; Bainbridge, 2004; Haggard and Cooper, 2007).

Educational Change

These problems of sustainable management are not simple, and educational efforts must better address their complexity. As Ackoff (1986) noted, "We do not experience individual problems but complex systems of those that are strongly interacting. I call these messes. Because messes are systems of problems, they lose their essential properties when they are taken apart." In resource management these are sometimes called "wicked" problems (McNamee *et al.*, 1986). Most sustainable management problems are this type, and educational efforts to address them have been limited. More often the increasingly narrow focus of education and research in academic institutions contributes to management problem. The tunnel vision favored in most higher education institutions today is poorly suited for evaluating, understanding, and designing sustainable resource management systems (Bawden *et al.*, 1984; Bainbridge, 1985). Solutions developed for poorly and narrowly defined "problems" often lead to new, more serious problems.

"Expert" solutions are often less adapted to local situations than to traditional practices. These narrowly focused solutions are typical responses from students who have been channeled into increasingly narrow disciplines and who rarely receive systems training in the sciences, let alone in the more challenging connections and interactions between social and physical systems. With fewer scientists and advisors coming from farm backgrounds, many lack the well-rounded and practical knowledge learned "on the farm" as children. Efforts are also focused on the richest and most powerful resource managers, while those who need help the most are, with rare exceptions, ignored. But ecological solutions can be developed (Altieri and Anderson, 1986).

Rather than encouraging participation in solving these important problems that have been created by flaws in educational training, the current system is more likely to punish those who attempt to deal with them (Schneider, 1988). Publication of sustainable research is often punished by academic reward systems that favor single author, peer-reviewed articles in the "right journals" (Baumann, 2002).

A secondary effect of specialization is the difficulty of securing funding for innovative research. Narrowly trained researchers review research proposals and more often than not fund narrowly focused research. Federal, state, and private organizations are conservative and commonly fail to explore innovative approaches, especially integrative programs that step over traditional boundaries. As the National Research Council (1989) commented, "The hallmark of an alternative farming approach is not the conventional practices it rejects, but the innovative practices it includes." Encouraging innovation is essential and will require new methods of reviewing research proposals. Providing support for innovative demonstrations and field trials is particularly important.

The US research and educational system has further compounded the problem of research direction by separating basic, applied, and management research, and many of the world's scientists are still brought through this flawed system. The increasing attention on problem-based learning (Wilkerson and Felleti, 1989; Duch *et al*., 2001) may provide the opportunity to return to "hands-on" learning opportunities in resource management.

Applied long-term interdisciplinary studies must also be better rewarded. Current academic reward systems favor theoretical or lab studies, which can be quickly completed and published, rather than practical solutions to real problems. Recognizing or rewarding practical solutions to resource management issues is essential.

Working Towards Sustainability

We face a daunting challenge in protecting and restoring arid lands while improving their productivity. To succeed we will need to apply the best traditional practices and refine and develop new strategies for restoration. There are many obstacles and problems to improving resource management in drylands. The primary goals of improved environmental management are better economic opportunities, health, and living conditions for people as well as environmental protection and restoration. Some solutions are relatively well understood but are blocked by institutional and regulatory policies and problems; however, many other practices will require detailed economic and environmental research, as described earlier in this paper. In addition to research, the following steps must be taken for implementation.

Funding

The magnitude of the task of sustainability globally can be calculated by reviewing the area of land needing treatment and the per hectare cost of restoration. The worst affected countries are often those least able to pay, with many struggling to pay immense debt services on loans from developed countries. Debt relief will be a critical, but first step. The developed countries will have to participate in the restoration work even after debt relief, because these developing countries will still have few resources for research and restoration. Research on better funding mechanisms and programs to encourage volunteer participation are needed. Support for education, research, and demonstration will be essential, but costs would be modest. Creating more programs similar to Australia's Land Care would not be expensive (Campbell and Siepen 1994).

Education

The adoption of sustainability-based educational goals could help enrich and enliven programs and redress historic weaknesses in business curriculum

(Common, 1995; Thomas, 2004; Haigh, 2005). In addition, a new degree is needed–a Doctor of Lands (DL). This would reflect the applied nature of restoration and resource management, as different from a Ph.D. as a DBA (Doctor of Business Administration) (Bainbridge, 2007a). For examples of DL–type dissertations, see Kaus (1992) and Daka (2001). A new approach to these studies is also needed, one that would encourage a cluster of doctoral dissertations and master's theses on land management and restoration in a specific area, with participants from fields such as ecology, economics, anthropology, business, political science, and women's studies sharing insights and discoveries working on a common problem. Research capability must be nurtured in developed countries, where fieldwork is rarely undertaken these days (too slow and unpredictable for tenure), and even more in developing countries, where the problems are most acute. Field research of this kind is not expensive, but it requires a long-term commitment and security. Funding cycles of 10 to 20 years are desirable. A systems approach is essential, and funding should reflect this by supporting multiple investigators across a range of disciplines and institutions. Funding should also support work by local land managers as they are brought into the program. The new Australian initiative to develop a Desert Knowledge Cooperative Research Center is an excellent step that could be replicated in other dry lands. The focus on finding sustainable solutions and a new understanding of livelihood is very encouraging.

The 2001 inaugural meeting of Chinese restoration ecologists in Guangzhou was an encouraging first step in addressing the complex environmental problems that face China today (Xiaoying, 2001). But without the commitment of long-term funding, few results can be expected.

Information dissemination

On-line publication of all dissertations, technical reports, and publications related to restoration of arid lands (both M.S. and Ph.D.) should be supported to assist students from universities with limited library resources and to offer practitioners access to as much information as possible. The internet has made information distribution much easier and more effective, and, surprisingly, internet access is available in many remote areas as a result of rapidly expanding cell phone links. We should also consider creating an information program to release articles and information to radio and newspapers worldwide as well as providing expanded resources on the Web that are designed to interface with low-speed downloads and the new $ 100 computer.

Funding to develop and support better extension efforts for farmers, foresters, ranchers, homeowners, and businesses in arid lands is also needed. A key first step in many areas would be preparing a detailed guide to the information that already exists (see, for example, Mitchell and Bainbridge, 1991).

We should also develop an interdisciplinary curriculum adapted for the world's drylands. This would provide teachers and professors with well-developed course materials covering the full range of topics, from arid land agroforestry to sustainable marketing (see, for example, Zulberti, 1987; Oxley and Lemon, 2003).

The Coverdell Water Wise Schools (2007) program offers information and pictures for teachers worldwide. The growing body of material available on-line for desert restoration (www.desertrestore.org) is also a step in the right direction.

Foundation or corporate support might be found to prepare and disseminate a library package for schools that includes key books and resources, in paper format for areas without computers or power and on CD or memory sticks for areas with computers. Funding for distribution of key journals to schools, government agencies, and NGOs in arid lands would also be desirable.

We might also develop ecological, economic, and cultural sustainability literacy requirements for degree programs and provide incentives (good jobs) for those who complete these programs (Bainbridge, 1985: Haigh, 2005). We could also provide on-line training and short courses to upgrade the skills of current workers and land managers.

It would also be very helpful to support a comprehensive interdisciplinary review of the rewards and incentives system in academia around the world. Once the flaws in the educational system are better understood, changes could be made to foster the creation of long-term, interdisciplinary research alternatives, such as those involved in applied science and stakeholder participation.

Demonstration

Funding should be found to establish more regional programs with demonstration of sustainable resource management (Bainbridge, 1997b). Practices such as watershed-scale restoration, rainwater catchments, innovative irrigation systems, riparian restoration, filter strips, mixed grazing, intercrops, trees with grazing, and shelter for livestock could be developed on public (schools, universities, parks, farms, etc.) and private lands with a program of regular tours, short courses, and workshops. Demonstration projects will provide hands-on training for students as well as many research opportunities. Work is needed at the 10,000-hectare scale for abandoned lands and at the 1-hectare scale for the small landholder. Setting goals for demonstration and monitoring results should include stakeholders (Foerster *et al*., 2000; CFRP, 2004).

Summary

There is much to be done in the next twenty-five years. The management of drylands can be dramatically improved, but it will take a concerted effort by many people, companies, organizations, agencies, institutions, and governments. The quality of life for dryland dwellers can be improved, and biodiversity and ecosystems can be protected and restored. It simply takes the vision and will to begin.

New approaches for funding restoration projects must be found to increase active restoration of degraded drylands and complementary research on ecological and social systems. A better understanding of what works, and why, will help; however, the money or incentives still must be found to drive implementation. Even with effective low-cost approaches that can be used to treat thousands of acres of land, the costs add up.

Restoration funding must include international, national, state, local, and personal commitments. Toyota Motor Corporation's support for desertification control in China is a good example of corporate engagement. Few countries have committed more than token amounts toward rehabilitation, because it is not sexy, fast, exciting, or politically expedient. Perhaps what will help is publicizing each country's National Regeneration Effort (NRE), the amount of national expenditures for restoration in relation to gross national product and annual national budget (Le Houerou, 2000).

China has perhaps the best record for funding desertification research and control, and they have also made a big effort to bring in outside funding and volunteers (Anon., 2001; DPVA, 2005). But the work in the drylands of China and in the rest of the world has barely begun, and results have not been consistent.

It may also be possible to develop environmental offset programs, such as a dust control, market initiative similar to those being tested for carbon, or a land offset program that links urbanization or transformation of natural areas to restoration elsewhere in the region or the world. Carbon sequestration with agroforestry systems would offer another possible source of funding.

Improving our understanding of the costs and benefits of restoration and of current exploitation versus sustainable management of resources is also important. A full and detailed accounting of Natural Capital, Nature's Services, and Human Capital is essential for all resource management decisions and, in the end, may prove to be the most powerful consideration.

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