Integrated Irrigated Crop–Livestock Systems in Dry Climates

V. G. Allen,* M. T. Baker, E. Segarra, and C. P. Brown

ABSTRACT

Arid and semiarid landscapes are often fragile and, thus, vulnerable to both natural weather extremes and human activities. Climate change and increasing demands for food to meet needs of a growing global population will place greater stress on these environments. Cropping and livestock systems have generally succeeded in these regions to the extent that the environment could be altered through water development and irrigation. Water sources for irrigation, including surface and groundwater, are declining in quality and quantity. Improvements in irrigation use efficiency now exceed 95% but often have led to increased water use, instead of water savings, as more systems have been installed. Also, as groundwater becomes scarce, more energy is required to extract water from greater depths. Increasing demands for alternative water uses and depletion of historic water sources make many irrigated systems in dry climates nonsustainable. The Texas High Plains exemplifies these challenges, where agriculture depends heavily on irrigation at nonsustainable rates of water extraction from the Ogallala aquifer. Today, agriculture uses about 95% of total water withdrawn from the aquifer. Crop rotations and integrating crop and livestock systems could reduce irrigation water use and diversify income compared with a monoculture. This region was historically a grazing land ecosystem offering opportunities for pastoral systems and benefits from diversification. Long-term comparisons of two irrigated systems [a cotton (*Gossypium hirsutum* L.) monoculture and an integrated cotton–forage–beef cattle system] in the Texas High Plains have demonstrated water savings of about 25% achieved through integration, while remaining economically viable and diversifying income sources. Additional benefits included reduced soil erosion, lower chemical inputs including a 40% reduction in N fertilizer, improved soil microbial and enzymatic activities, enhanced C sequestration, and greater rainfall infiltration than the monoculture system. Greater annual crop yields can shift short-term profitability to the monoculture system, but long-term sustainability is likely to depend on environmental benefits and water savings achieved by integrated systems. Challenges include existing large investments in local infrastructure focused on monoculture systems, producer adoption of alternative strategies, enhanced knowledge and management skill required, and a need for more research. Dryland agriculture will increase with remaining water diverted to other uses including livestock, municipalities, manufacturing, and energy generation. Technological advances can increase water savings but can also decrease system resilience with dependence on nonsustainable external buffers. Regional resource and economic stability will likely depend more on internal resilience of appropriately integrated plant and animal agricultural systems.

INTEGRATED SYSTEMS are about bringing crops and livestock into an interactive relationship with the expectation that together, as opposed to alone, they will generate positive effects on outcomes of interest, such as profitability, overall productivity, and conservation of nonrenewable resources. It is, however, much more than this. The "system" includes the environment, soil characteristics, landscape positions, genetics, and ecology of plants and animals. It involves management practices, goals and lifestyles of humans, social constraints, economic opportunities, marketing strategies, and externalities including energy supplies and costs, and impacts of farm policies. Systems also reflect natural resources available and the impact on their use, wildlife issues, target and nontarget plant and animal species, microorganisms, and indeed all of the definable and indefinable factors that ultimately interact to result in an outcome that is never constant (Allen et al., 2007b).

Integrated systems have elements of chaos, where the system appears to be wandering, always exhibiting new and different behavior; but over time, a deeper order is exhibited (Wheatly, 1999). This order was always inherent in the system, but was not revealed until the chaotic movements are plotted in multiple dimensions over time. To begin to understand and visualize the order inherent in a system requires that we shift our vision from the parts to the whole (Wheatly, 1999). Behaviors inherent in a system are not revealed quickly and too often interpretations based on only a few years of observation have led to wrong conclusions because the behavior of the system had not had time to express itself or only a part of the behavior pattern was revealed. A system as a whole possesses a definite set of characteristics including input requirements, productivity, environmental impact, and economic return, but it is difficult to understand completely which system components are contributing to these outcomes. To understand the whole, it is necessary to look further into its parts, but not in the traditional reductionist approach. The individual part must be examined, understanding that it is what it is only because of its interrelationships with the other parts within the system and to isolate it from the system is to cause it to cease to exist in the same way.

The purpose of this paper was to look specifically at integrated crop and livestock systems in arid and semiarid environments under irrigated conditions from a global perspective. Specifically, their current and likely future role in conservation of water and other natural resources, economic and productive potential, and impact on societal issues as compared with monoculture crop and livestock systems was of interest. Thus, it was necessary to look first at the characteristics of these ecosystems to understand what systems are appropriate, how they might behave, and what their impact might be.

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Abbreviations: LEPA, low-energy, precision application; PLS, pure live seed; SDI, subsurface drip irrigation.

ARID AND SEMI-ARID REGIONS

Locations, Ecology, and Challenges

Arid (desert) and semiarid (steppe) regions of the world occupy over one-third of the land surface area and are home to about 400 million people (Williams, 1999; Fig. 1). Ecosystems that fall within Köppen's classification of "Dry Climates" are characterized by low precipitation and large daily temperature fluctuation (FAO, 1997). Many of these regions are, or were, grazing lands. Semiarid regions lie between desert and the more humid climates. Sporadic precipitation is a frequent feature and annual precipitation, ranging from less than 100 to 500 mm, may come in a relatively few intense events. Desert climates cover about 12% of the earth's land surface, typically straddle the Tropic of Capricorn and the Tropic of Cancer, and lie approximately between 18° to 28° latitudes in both hemispheres. They are characterized by intense, dry heat, light winds, and annual precipitation less than 25 to 250 mm.

These dry climates are often fragile ecosystems, and are at risk from both natural and human-induced changes. Water available for use in these regions is often in short supply, and largely because of increasing human pressure, many of these ecosystems are threatened by increasing challenges of salinity (Williams, 1999). Drought is an inherent characteristic. Too often regarded as an isolated anomaly, drought is instead a natural and recurring feature of these ecosystems and management strategies must be robust enough to absorb these extremes as normal. Both wildlife and livestock management have dealt with this historically in nomadic systems where herds and flocks moved, following the shifting rainfall patterns (Williams, 1981). In recent times, these opportunities have been restricted by political and imposed physical boundaries, changing land uses, dissection of landscapes by highways and alternative land uses, and efforts to impose more sedentary lifestyles. At least in some regions, transporting livestock to new grazing lands partially overcomes this problem, but this adds costs, is not always an available option, and does not resolve restrictions to wildlife migration patterns.

Use of arid and semiarid lands has shifted and intensified as global populations have increased. In developing countries, increased ruminant animal production will be needed especially (Box, 1981). From the 1970s to the mid-1990s, meat consumption in developing countries increased almost three times as fast as in developed countries, whereas milk consumption increased twice as fast (Delgado, 2005). This increase was largely attributable to population growth, urbanization, and income growth and a continued increase is anticipated well into the 21st Century "creating a veritable 'livestock revolution'" (Delgado, 2005). With the corresponding increase in need for food and feed production, crop farming intrudes increasingly into grazing lands, resulting in over grazing of remaining lands (Delgado, 2005).

Arid and semiarid lands will come under increasing pressure from effects of global climate change as well as a growing global population. In general, these ecosystems are least able to absorb the intensification of cropping and the shift to either a sedentary system or a system that requires higher inputs designed to overcome constraints normal to the ecosystem. Most often this input is water. Where water for irrigation is available, intensification of both crop and livestock production has been possible, but water use must be evaluated in terms of impact on economics, energy demand, salinization, long-term stability of water and other natural resources, and essentiality of competing uses. Through irrigation and other technologies, some degree of resilience and stability can be interjected into these variable and fragile ecosystems, but this comes at both a financial and an ecological cost. The interrelationships among water resource management, resilience building, and rural livelihoods are not well understood (Rockström, 2003). With the future projected to be characterized by increasing numbers and severity of weather events, floods, drought, and increased population, it is necessary to

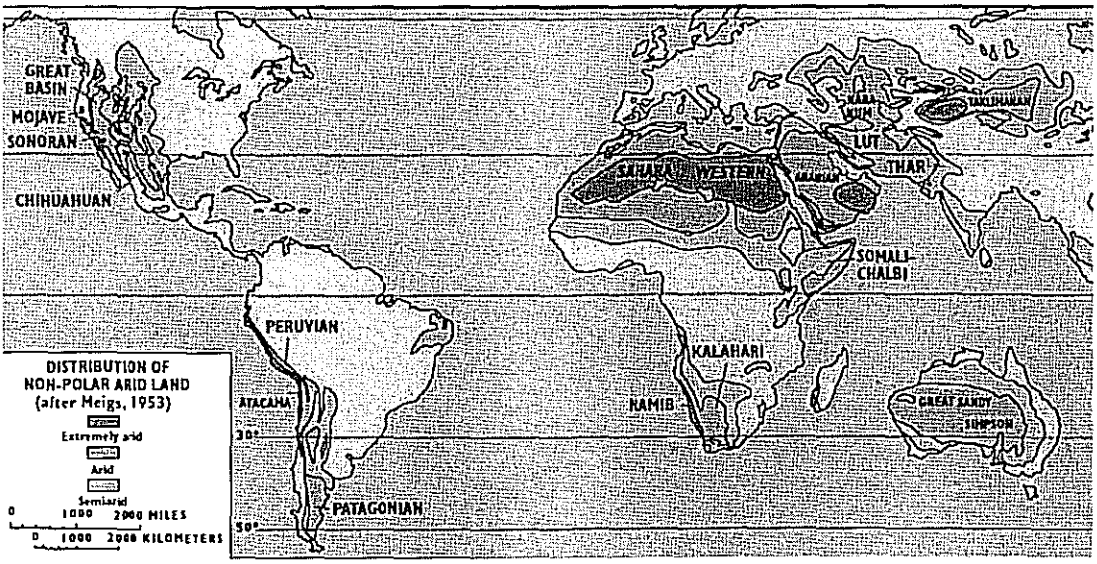

Fig. 1. Global distribution of nonpolar arid and semiarid land (adapted from USGS, 1997).

understand how resilience derived through interventions such as irrigation can assist in absorbing these climatic shocks and how this affects long-term ecological, economic, and social stability. Attempts to improve resilience of these variable and fragile environments through such technologies as irrigation can induce loss of resilience through consumption and degradation of the natural resource base (Redman, 1999) and increase local and regional dependence on infrastructure for commodities produced from an altered and nonsustainable ecosystem. Use of water for irrigation is facing increasing competition for low-cost, high-quality water for alternative uses and, without proper management, can be detrimental to the environment and endanger sustainability (Howell, 2001).

External strategies such as irrigation technologies should be contrasted with internal buffering strategies inherent in system designs that may provide greater resilience in the long-term. Ruminant livestock have long been important in these ecosystems and are recognized for their role in resilience building and sustainable agricultural systems (Oltjen and Beckett, 1996). Land too poor or too erodible to cultivate can yield animal products including draft power, food, and fiber through conversion of forage by ruminant livestock. As livestock production is intensified, however, there is a potential ecological cost. In the U.S. Northern Great Plains, beef cattle management systems rely heavily on exogenous energy sources, primarily from fossil fuels (Heitschmidt et al., 1996). These authors suggested that as energy costs escalate either more energy efficient systems will be required or there must be increased value in livestock to offset these costs. When livestock systems include irrigation, there are additional energy costs in lifting and/or transporting and delivering water from its source to the field. Irrigation of pastures has been suggested to be highly inefficient (Rosegrant et al., 2005), but water and precipitation use efficiencies in the U.S. Southern High Plains were higher for systems producing forage and lowest for rotations with a high frequency of oilseed crops or continuous small-grain production on a mass-produced basis under dryland conditions (Nielsen et al., 2005).

Water consumption by livestock and the impact of livestock on water quality must also be considered. Water is consumed by livestock directly to meet daily needs and as temperatures increase, water requirements of livestock also increase (National Research Council, 1996). This must be factored into the total water requirements of an integrated, irrigated crop–livestock system. Delivery equipment to supply water within the system may increase as livestock move out of traditional grazing lands and into cropping paddocks where livestock water was not previously required by crop monocultures. Health and safety issues arise in prevention of livestock-related pathogens from entering general water systems. Additional concerns include prevention of agricultural chemicals associated with crop production from entering livestock water supplies. Low water quality, contaminated water, and inadequate water supply for livestock can be a cause of poor performance, nonspecific disease conditions in livestock, and death losses (Carson, 2000). Grazing animals can have either a positive or a negative impact on water quality (Hubbard et al., 2004). With good forage cover of soils, erosion and movement of nutrients into surface and groundwater is minimized. With overgrazing, erosion, sediment, and pathogen transport into surface waters can negatively impact water quality and safety. Land application of animal wastes from confined animal feeding can lead to leaching and runoff with nutrient contamination of both surface and subsurface water sources (Edwards, 1996; Hao and Chang, 2003). Uneven return of excreta from grazing animals also contributes to spatial nonuniformity of fertility and growth response for a following crop, particularly in a nutrient-poor soil. Under livestock grazing, however, total export of nutrients is considerably lower than with crop harvest and removal, and the grazing animal provides a "short-cut" to mineral cycling from plant material to plant available nutrients. Grazing animals can supply other services to the overall system including weed control, insect pest reduction, biomass management, and through grazing, removal of plants with allelopathic effects that would suppress yields of the following crop (Hou et al., 2005).

Thus, arid and semiarid ecosystems constitute a major portion of the worlds land mass and are increasingly impacted by social, economic, and political issues, population increases, changing dietary habits, and global climate change. To stabilize and increase their agricultural potential to meet growing global demands has depended primarily on water for irrigation. Dependence on such external strategies such as water is not sustainable over time and in the future, production stability will likely depend more on internal buffers inherent in integrated systems. Grazing animals offer opportunities for resilience building and more sustainable agricultural systems but are not without an economic and environmental cost. Stability inherent in integrated systems designed to more closely balance inputs and outputs and to capture complimentary benefits through the interrelationships of their components are more complex but offer more resilience over time than traditional monoculture systems. The challenge will be to identify feasible systems that are sustainable in the long-term and that can provide a level of production and economic return to support both individuals and communities.

Irrigated, Integrated Crop–Livestock Systems

Agriculture is the single largest consumer of water (Rosegrant and Cline, 2003; Qadir et al., 2003). Of the freshwater on earth, 65 to 75% is used for irrigation (Bennett, 2000; Rosegrant et al., 2005). Worldwide, over 250 million ha of land are irrigated, representing about 20% of the world's arable land, which produces over one-third of global food supply (Trout, 1998; Matson et al., 1997; FAO, 2004). About 79% of irrigated land is in developing countries and has contributed to the increased crop yields of the Green Revolution (Trout, 1998). However, in much of the world, the growth in crop yields has slowed due to increasing water scarcity and declining investments in agricultural research, irrigation, and rural infrastructure (Rosegrant and Cline, 2003).

While the hydrologic cycle is adequate to supply the current world's needs for fresh water (Pimentel et al., 1999), the distribution of this water is uneven, with water demands exceeding supply in nearly 80 countries that include more than 40% of the global population (Bennett, 2000). About one-half of the world's irrigated agriculture occurs in India, China, and the USA (Howell, 2001; FAO, 2004). Use of irrigation has expanded throughout the world in most arid/semiarid regions (Bucks et al., 1990). Sources of water for irrigation include groundwater in aquifers, surface water from rivers, streams, lakes and ponds, snow melt from mountains, and rainwater harvesting (Li et al., 2000). Of the water on earth, about 97% is in the oceans and is saline (Turner, 2001). Less than 1% is fresh water that is accessible in surface and groundwater reservoirs, and much of the water in underground aquifers is old and very slow to recharge (USDA Forest Service, 2000). The potential for recharge of groundwater depends primarily on climatic conditions (Qadir et al., 2003), with the lowest amounts occurring in hot, dry climates with high evapotranspiration rates. Recharge in these regions may be 2% or less (Tyler et al., 1996; Bouwer, 2000). Recharge is challenging to measure and predict but provides a target for sustainable extractive use. In several arid and semiarid regions of the world, where groundwater is the primary water source, extraction of water has greatly exceeded the recharge potential and groundwater is disappearing at an alarming rate (Pimentel et al., 1999). Examples include the Punjab of the Indian subcontinent, the North China Plains, and the Southern High Plains of the USA; all agricultural regions of major importance (Seckler et al., 1999; Allen et al., 2005). In parts of Africa and in the Middle East, water has already been depleted and these regions are no longer able to meet their food requirements (Seckler et al., 1999). Other regions are becoming water deficient (Allan, 2001). A part of the solution to water distribution can come through importation of food and feed, which represents an importation of water from other, less deficient regions (Allan, 1996; Qadir et al., 2003).

Irrigation can have several environmental impacts, especially in arid areas, due to changes in local hydrology that result from diverting and applying water, including depletion of stream flows, changes to riparian environments, rising or falling groundwater, creation or depletion of wetlands, and degraded soil or water quality from salinity or other elements (Trout, 1998). Quality of water available for irrigation plays an important role in determining both the method of application and the ultimate impact on the environment. In semiarid areas where groundwater is saline and alternative surface irrigation sources are used, the result can be a rise in the water table with the potential for soil salinization, necessitating installation of appropriate drainage systems (Agarwal et al., 1986). Including livestock in the system, particularly by concentrating land application of animal wastes accumulated from confined feeding, can increase soil salinity and, especially under irrigated conditions, result in leaching of soluble salts that could contribute to groundwater pollution (Hao and Chang, 2003).

In Asia, arid and semiarid regions are located primarily in the south. Some systems include irrigation but soil salinity is a major concern (Devendra and Thomas, 2002). Livestock plays a multipurpose role and small-scale, crop–livestock systems are an integral part of agriculture in this region. The importance of livestock exceeds that of food production alone, providing economic stability, a "cash crop," and assistance to alleviate seasonality of food production by crops. Livestock provide draft power, convert low-quality plant resources to high-quality meat and milk, contribute to weed control, and provide needed nutrients through manure to increase soil fertility.

Arid and semiarid regions of North America include the Great Plains lying east of the Rocky Mountains and extending from Canada into Central America and four distinct deserts (Fig. 1). Around 10 million years ago, the water-bearing sands of the Ogallala aquifer were deposited east of the then-forming Rocky Mountains across the High Plains region (Fig. 2). Today, this aquifer extends from South Dakota into Texas. The Ogallala Aquifer is the most intensively used aquifer in the USA,

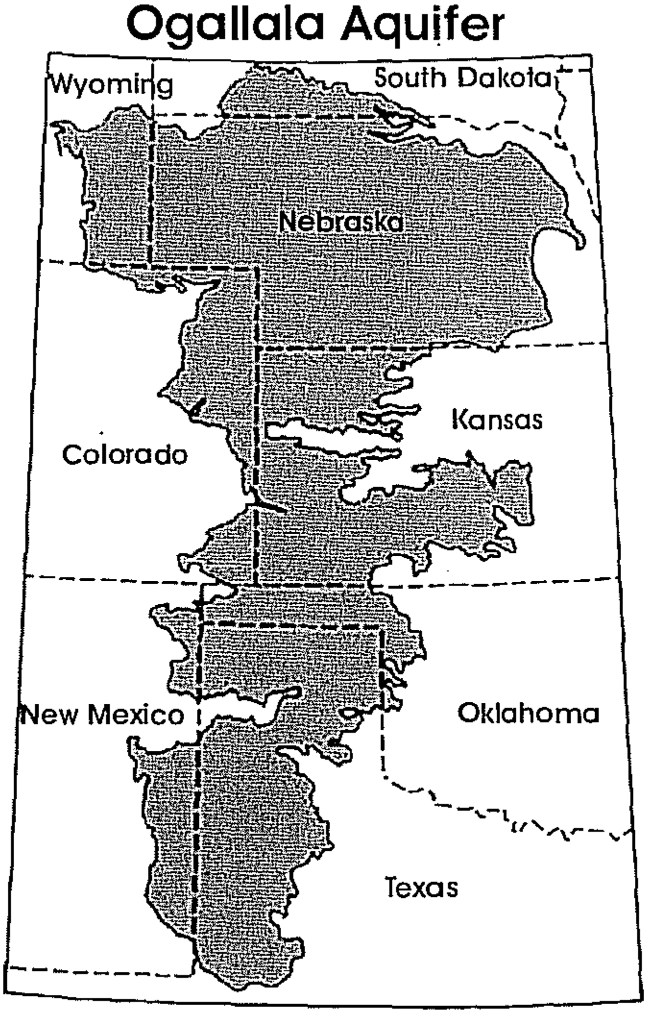

Fig. 2. The Ogallala Aquifer of the U.S. High Plains.

providing 30% of the total withdrawals from all aquifers in the USA for irrigation (Maupin and Barber, 2005). Known today to be a largely finite, exhaustible resource, the Ogallala is a prime example of groundwater exploitation (White, 1992). This region attracted settlers where precipitation was adequate for a few years but with swings in weather patterns, the region was susceptible to an "in and out migration" (Kromm and White, 1992). Regional economic and social stability was sought through irrigation with water first diverted from streams and later extracted from the underlying aquifer. Today, both local and regional stability are at risk as the resilience achieved through irrigation is threatened by the decline in water table depth and capacity, escalating costs of energy required to extract that water, changes in regulations governing water use, impacts of government programs, declining soil fertility, commodity prices, international trade agreements, and public attitudes. The Southern High Plains, located primarily in Texas, are an excellent example of the mosaic of interactive and shifting components that will dictate change and the need to design agricultural systems that can accommodate these changes.

The Texas Southern High Plains

The Texas Southern High Plains exemplifies many of the challenges of irrigated agriculture in a semiarid environment and the opportunities to capture synergistic effects of integrated agricultural systems. Geographically it is part of the North American Great Plains but is located primarily in Texas (Fig. 2). This nearly level, treeless, semiarid grassland (Webb, 1981) is a remnant of the alluvial plain formed as the Rocky Mountains were rising about 65 million yr ago (Weeks, 1986).

The Ogallala aquifer is the major water-bearing unit of the Texas High Plains (Weeks and Gutentag, 1984). Lateral water flow is limited and access to the more northern part of the aquifer is cut off by the Canadian River that dissects the Texas Panhandle isolating the Southern High Plains. Thus, the ancient waters of the Ogallala in the Southern High Plains are effectively a finite resource. Although today water is found at different depths within the Texas High Plains, about 80% of the water lies within 120 m of the surface (Urban, 1992). The quality of this water is suited for most purposes and its presence has shaped the use and economy of the region during the past century.

Climatically, the region is semiarid, having a dry steppe climate with mild winters. Mean annual precipitation over the area ranges from about 355 mm in the west to about 559 mm at the eastern edge. Precipitation occurs often as thunderstorms, occasionally producing tornadoes, high winds, and hail. Intensity of rainfall events leads to runoff and localized flooding and hail events can result in complete crop losses. About two-thirds of the annual rainfall occurs just before or during the growing season, with May and September generally receiving peak rainfall amounts. Killing frosts can occur in spring following periods of mild temperatures that, along with wind and hail, can stress both plants and livestock. The nearly constant wind that sweeps across the plains desiccates young crops and contributes to wind erosion of soils. March to May is the windiest period generally and coincides with land preparation and planting of cotton, a predominant crop in this region.

Soils of the Texas High Plains are fine-textured, highly erodible sandy loams, clay loams, with some areas of clayey loams of uniform texture (Livingston, 1952). At varying depths throughout the region a thick layer of caliche, a clayey-limey stratum, occurs that limits root penetration (Brooks et al., 2000). This region evolved as a grassland variously characterized as mixed-prairie, short-grass prairie, and in some locations as tall-grass prairie (Gould, 1975). The major species that made up this grassland system included buffalograss [*Buchloe dactyloides* (Nutt.) Engelm.] blue grama [*Bouteloua gracilis* (H.B.K.) Lag. ex Steud.], and sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.]. Wildlife and most of the early human occupants of this region followed a nomadic lifestyle, moving where precipitation provided growth of forages to attract and sustain the large grazing animals that included bison (*Bison bison*), pronghorn (*Antilocapra americana*), and with Spanish exploration during the 1600s, the reintroduction of the horse (*Equus caballus*).

By the late 1800s, hand-dug wells and windmills provided sufficient quantities of water from the Ogallala for livestock and crops. By the 1930s and 1940s, with the advent of rural electrification and gasoline engines, irrigated agriculture expanded. By the 1970s, 69% of the total irrigated cropland in Texas was located in the High Plains (Urban, 1992). In 2004, over 1.7 million ha of crops were irrigated, including 0.8 million ha of irrigated cotton, over one-half of all cotton planted in this region (Texas Agricultural Statistics Service, 2004). The Texas High Plains also had become home to a vast cattle feeding industry that today accounts for about 25% of all the cattle on feed in the USA (Texas Agricultural Statistics Service, 2002; USDA-National Agricultural Statistics Service, 2003).

By the late 1970s and early 1980s, it was apparent that water in the Ogallala had begun to decline and concerns mounted over the future use of this resource. Improved irrigation technologies, including low-energy, precision application (LEPA) by center pivot systems and subsurface drip irrigation (SDI), were refined during the last part of the 20th Century. These systems improved efficiencies of water use to over 90% and reduced waste of water, but more wells continued to be drilled adding to the total withdrawal of water and the aquifer continued to decline (Segarra and Feng, 1994). By the end of the century, water had become a major concern to the future sustainability of agriculture in this region. Today, over 95% of the water extracted from the aquifer is used for irrigated agriculture (Gutentag et al., 1984; Llano Estacado Regional Water Planning Group, 2001), which accounts for more than 70% of crop revenues from irrigated agriculture in the Texas High Plains (Arabiyat et al., 1999). Withdrawal rates between 1993 and 2003 were 399 mm yr^{-1} averaged over 1200 wells in the 15 counties surrounding Lubbock, TX (High Plains

Undergroundwater Conservation District, 2003). Recharge to the aquifer is minimal, however, with most estimates suggesting less than 25 mm yr^{-1} (Brooks et al., 2000; Gutentag et al., 1984) to a maximum estimate of 50 mm yr^{-1} in some areas (Jim Conkwright, Manager, High Plains Undergroundwater District No. 1, 2005, personal communication). Less than 1% of precipitation percolates through the root zone in this region, effectively making this a nonrechargeable water source (Brooks et al., 2000). Clearly, water consumptive practices that characterized this region during the past century cannot be continued much longer. While extreme local variation in groundwater depletion is occurring, estimates based on current use rates suggest that by 2020, about 80% of the Southern High Plains will have insufficient water to operate most irrigation systems (Kromm and White, 1992). More recent projections suggest that between 2010 and 2060, total remaining surface and groundwater will decline by 55% with regional needs for irrigation unmet by 2030.[1] Increased water conservation efforts and changing land use are expected to slow the rate of water use. Government regulation and competing uses for water by industries and municipalities will likely influence water policy in the near future. The philosophy that "...the highest and best use is using water to produce microchips instead of potato chips" will likely have a large impact on the future of water use (Schmidt, 2005).

In the Texas High Plains, the progression of water use practices has been and will likely continue to be from: (i) wasteful irrigation technologies before the 1970s when water was thought to be an inexhaustible supply, (ii) development of highly efficient irrigation systems that failed to reduce total water withdrawn because of continued proliferation of wells, (iii) emphasis on crop genetics and management strategies to increase water use efficiency, (iv) development of crop rotations and integrated crop–livestock systems with components that required less irrigation water to reduce overall use, (v) inclusion of sufficient dryland acreage to offset withdrawals, and finally to (vi) a return in larger part to dryland systems. Today, the Texas High Plains operates somewhere within Phases 3 to 6.

While several factors may alter the course of events, the fact of change is inevitable. The water resources on which past and current systems depend will not be present in the same capacity in the future. In the Texas High Plains, wind power to generate energy and existence of lower-lying aquifers may, at least for a time, extend existence of irrigated systems. However, much of this water would require desalinization and handling of the waste product. Regardless of alternative water sources, systems with greater internal and environmental stability must be found. Economics, environmental costs, and societal constraints will shape the future. Arabiyat et al. (1999) suggested that use of the most efficient irrigation technologies, if restricted to the most productive land sites and combined with anticipated genetic improvements in water-use efficient plants, would reduce total water withdrawn for irrigation to sustainable levels while maintaining current levels of profitability. However, availability and ownership of remaining water supplies, rapidly escalating energy costs to extract the water, degree of dependence on uncertain farm programs, and market prices are driving the exhaustion of economically exploitable underground water supplies. The Texas High Plains currently generates a combined annual economic value of crops and livestock that exceeds $5.6 billion ($1.1 crops, $4.5 livestock; Texas Agricultural Statistics Service, 2002). About 5.5 million stocker cattle (Texas Agricultural Statistics Service, 2002, 2003) are shipped into the High Plains each autumn to eventually enter area feedyards, but other than grazing young wheat (*Triticum aestivum* L.) fields, little integration of livestock and crop production exists. Historically, the value of integrating crops and livestock to reduce economic risk and to capture synergistic effects characterized most farming systems (Hardesty and Tiedeman, 1996). In the Texas High Plains and in the USA in general, agricultural production systems moved dramatically away from diversity and toward monocultures and isolated plant and animal industries partially due to government policies.

Concerns are growing over the ability to maintain long-term intensive monoculture agriculture (Matson et al., 1997). Currently, there is an increasing shift back toward integrated systems to address the challenges of the 21st Century. Specifically, agriculture in the 21st Century will increasingly be asked to continue providing an abundant supply of safe and wholesome food and fiber at a reasonable cost and that is environmentally benign and assures the future economic and social sustainability of rural areas. The most scientifically sound and objective way to accomplish this will likely be by exploiting the many advantages and benefits of production systems that are well integrated and diverse. The concept of integrated systems must be viewed not only on an individual farming entity basis but also from a landscape perspective where the mosaic of crop and livestock systems contribute to the diversification of the regional system.

COMPARISON OF IRRIGATED CROP AND LIVESTOCK SYSTEMS IN THE TEXAS HIGH PLAINS

In 1997, research began to test an integrated crop and beef cattle system compared with a cotton monoculture (Fig. 3). For more detailed descriptions of the first 7 yr of this research see Allen et al. (2005). This research provides an example of the need to test systems over time and how changing of a system component can affect the overall system behavior. This ongoing research is located at the Texas Tech Agricultural Field Research Laboratory (101°47′ W, 33°45′ N, 993 m elevation). Long-term (1911–2004) annual precipitation at this site is 470 mm, with about 75% of precipitation occurring from April through October. Evapotranspiration rates

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[1] Texas Water Development Board. 2006. Summary of Llano Estacado (O) Region, p. 97–108. *In* Water for Texas 2007—Draft. Vol. II. Texas Water Develop. Board, Austin, TX.

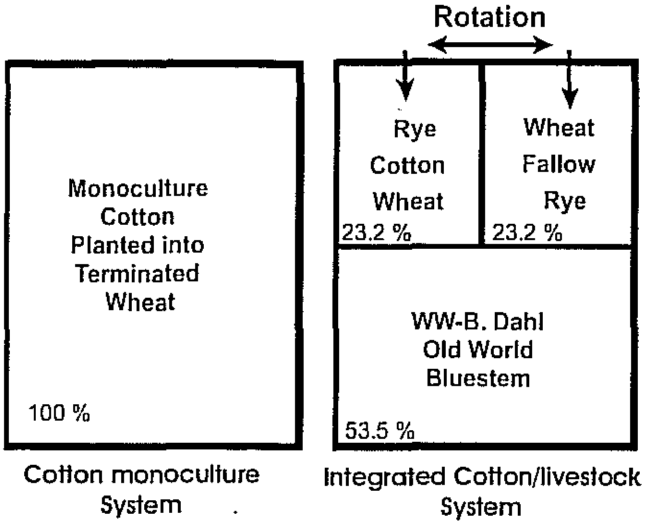

Fig. 3. System design for a cotton monoculture and an integrated cotton–forage–livestock system (adapted from Allen et al., 2005).

are about five times the annual precipitation. Both systems are irrigated from the Ogallala aquifer by subsurface drip irrigation. Fertilizers are applied based on yield goals and pesticides on recommendations of integrated pest management specialists (Allen et al., 2005). Both systems are replicated three times in a randomized block design.

The First Five Years

Cotton Monoculture System

This system consisted of cotton planted annually into a terminated wheat cover crop (Fig. 3). Cattle were not part of this system. During the first 5 yr, wheat was planted in furrow bottoms between listed rows each autumn after cotton harvest. In spring, wheat was chemically killed before planting 'Paymaster (PM) 2326RR' cotton into tops of listed beds. At the time this research began, this was the primary cotton variety used in this region. Cotton was harvested in November and wheat was again planted into furrow bottoms as a cover crop to reduce wind erosion of soils.

Integrated Cotton–Livestock System

This three-paddock system was designed for production of both cotton and stocker steers and integrates grazing into all paddocks at some point within each year (Fig. 3). About 54% of the total system was established in the perennial warm-season grass 'WW-B. Dahl' old world bluestem [*Bothriochloa bladhii* (Retz) S.T. Blake; Fig. 3]. This grass provided grazing intermittently for steers from January to July and a grass seed crop was harvested in October. The remaining 46% of the system was divided into two equal-sized paddocks where cotton was grown in alternate rotation with small grains. Rye (*Secale cereale* L.), planted in early September provided grazing for steers along with dormant old world bluestem from January to mid-April when rye matured. Rye then provided a cover crop to no-till plant Paymaster (PM) 2326RR cotton. Following cotton harvest in November, wheat was no-till planted into cotton stalks. Wheat provided grazing for steers in spring after rye grazing was terminated. Following graze-out of wheat, steers returned to old world bluestem pasture and the wheat land was fallowed until rye was planted in September. Weaned Angus crossbred steers were purchased each January and grazed within the system as described above from January until mid-July when they entered a feedyard for finishing.

Results

Stocker steers bought in January at about 250 kg gained 153 kg during the 192-d grazing season and were ready to move to a feedyard for finishing in mid-July. Total grazing days on rye, wheat, and old world bluestem averaged 33.5, 25.3, and 122 d, respectively, with a system stocking rate of 1.75 steers ha^{-1}. The grazing season was intended to coincide with the period of time in which precipitation was likely to reduce needs for irrigating pastures. Forages provided a part of the system that required less input of irrigation than the crop component. Irrigation of rye, wheat, and old world bluestem averaged 290, 172, and 270 mm, respectively, whereas irrigation water applied to cotton alone averaged 516 and 419 mm in the integrated and continuous cotton system, respectively. Including forages in the system reduced total system irrigation water used by about 23% for the overall system (Table 1). Rosegrant et al. (2005) suggested that irrigation of pasture is extremely water-inefficient and that scarcity of water in the future is likely to shift use of irrigation away from pastures, with the exception of high-value forage crops such as alfalfa (*Medicago sativa* L.). This is likely often

Table 1. Irrigation water, cotton lint yield, net returns above variable costs of production of a cotton monoculture and an integrated cotton–forage–livestock system (data adapted from Allen et al., 2005, 2007a).

Item	Monoculture cotton	Integrated system	SE
Irrigation water, mm			
1999–2002 (Year 2–5)†	481	372**	7
2003 (Year 6)	420	334	19
2004 (Year 7)	296	145**	26
2005 (Year 8)	350	269	19
Cotton lint yield, kg ha^{-1}			
1999–2002	1036	1062	29
2003	1750	2180	141
2004	1555	1300‡	66
2005	1442	1755**	15
Net returns above variable costs, U.S. \$ ha^{-1}§			
1999–2002	190.91	362.17	
2003	958.44	777.14	
2004	875.26	414.01	
2005	580.83	224.12	

** Indicates difference between means within a row ($P < 0.01$).

† Year 1 was unique due to establishment of crops, adjustments in irrigation and cropping systems, was before entry of cattle into system and was, thus, excluded from these analyses (Allen et al., 2005).

‡ Indicates difference between means ($P < 0.06$).

§ Pumping depth was 90 m. Economic analysis was based on production costs relative to 1998 unless a new production practice entered the system. In this case, the current market value was included for that practice. This was done to examine differences between systems and variation within system over time. Thus, the values in Table 1 do not reflect true differences based on actual market values for these years. Prices used were: cotton lint (\$1.21 kg^{-1}), old world bluestem seed (\$39.60 kg^{-1} PLS), steers (\$1.92 kg^{-1}). Returns do not include government payments.

the case but in the current research rye and wheat provided high-quality feed to support high gains of steers at a time that dormant old world bluestem was low in energy, crude protein, and digestibility, thereby substituting for the costs of supplementation. Additionally, the old world bluestem produced a seed crop in addition to grazed forage that contributed to the profitability of this system and to the value of irrigation water on a per unit basis. This C_4, warm-season, water use efficient forage comprised about 54% of the total system and contributed to the overall reduction in water use compared with the monoculture. As water becomes more scarce, it is likely that at least the forage component of integrated systems will move toward dryland production unless there is a high monetary value to the products produced, such as a seed crop.

During the first 4 yr that followed the establishment year (1999–2002), conditions were relatively stable and results of both systems varied little. Climatic conditions, while variable among years, were generally representative of this region. Yield of cotton lint was similar between the two systems and averaged 1050 kg ha^{-1} (Table 1). Integrating cotton and livestock production reduced N fertilizer applications by about 40%, reduced other chemical inputs, and increased net returns above variable costs of production by 90% (Table 1), compared with the cotton monoculture (Allen et al., 2005). These results reflected a 90-m pumping depth to extract irrigation water and constant prices.

Results indicated that progress toward reducing water use while improving profitability was possible. Furthermore, soil erosion potential of the cotton monoculture at 19 Mg ha^{-1} yr^{-1} was nearly twice the tolerable levels of 11.2 Mg ha^{-1} yr^{-1} that meet the definition of sustainable resource management (Collins, 2003; Fryrear et al., 2001). Erosion potential of the perennial grass pasture was nearly zero and that of no-till cotton within the integrated system rotation was less than 7 Mg ha^{-1} yr^{-1}. Other benefits that accrued to the integrated system included measurements of soil health. Soils from perennial pastures were higher in soil organic C, aggregate stability, microbial biomass, soil enzyme activities, and had higher numbers of protozoa and fungi than soil where continuous cotton was grown (Acosta-Martinez et al., 2004). Differences also were present in the cotton–small grain rotations within the integrated system but depended on the stage of the rotation. Pretty (1999) suggested that agricultural systems that deplete soil organic C or erode soils while producing agricultural products externalize costs that others must bear, whereas one that sequesters C in soil and reduces erosion contributes to the global good by mediating climate change and the private good by enhancing soil health.

Systems function as the interactive interrelationships among all of their parts. Within the first 5 yr of this research, the integrated system exhibited stability across the normal range of annual variations such that with the exception of yield of grass seed, other system components varied little among years. Sequencing of forage species provided a uniform flow of grazing opportunity such that no supplementation was required as hay, silage, or other stored feeds. This forage sequence also provided quality required to meet the nutritional needs of the steers, with the exception of the first few weeks in winter when cattle entered the system and grazed primarily dormant old world bluestem. A total of 34 kg steer^{-1} of a 44% crude protein supplement was provided at this time. Little difference was observed in cotton yields between systems or among the first 5 yr (Table 1). Production of grass seed from the old world bluestem demonstrated the greatest variation among years ranging from 0 to 50.6 kg pure live seed (PLS) ha^{-1} with a mean of 21.1 kg PLS ha^{-1}. Managed under the conditions of this experiment, this appeared to be a robust system with predictable results.

Years 6 and 7

The nature of systems is to potentially respond in dramatic ways to even subtle changes in a component or components. Beginning in Year 6, several changes occurred that shifted the function of both systems. By 2002, cotton genetics in wide use in the Texas High Plains had changed to the longer-staple, picker types. During the first 5 yr of the research, varieties had been held constant to investigate the behavior of these systems. In Year 6, 'FiberMax 989BR' cotton was used in both systems. Chemical weed control was more aggressive than in previous years where effects of grazing on weed presence was an objective. During Year 6 (2003), the region experienced the second lowest annual precipitation (224 mm) in nearly 100 yr (Fig. 4). Although higher than average precipitation was received in June, no precipitation occurred during July. Total precipitation at the research site during 2003 was 304 mm and temperatures were above normal.

With the change in cotton varieties and other management strategies imposed on the cotton areas of both systems, high temperatures suited to cotton growth, and the ability to provide water through irrigation, yield of cotton increased in both systems (Table 1) and with this increase, profitability of both systems increased (Table 1). No changes were imposed on management of the forage or livestock component of the integrated system, thus, the shift in cotton yields affected only about 23% of the integrated system while it affected 100% of the continuous system. The increased profit from cotton in the integrated system was not sufficient to match the increased profitability of the continuous cotton system based on prices used (Table 1).

Total irrigated water use by both systems was lower than in previous years in spite of the drier year (Table 1). The decrease in irrigation for continuous cotton was due in part to the discontinuation of wheat planting in furrow bottoms and a corresponding saving of irrigation water that had been a part of this system. Few producers in this area currently use a cover crop in cotton production because of depletion of water from the soil profile, but this increases vulnerability to soil erosion. Lower irrigation water applied to both systems also reflected precipitation received in June and to technological improvements made in the irrigation system that

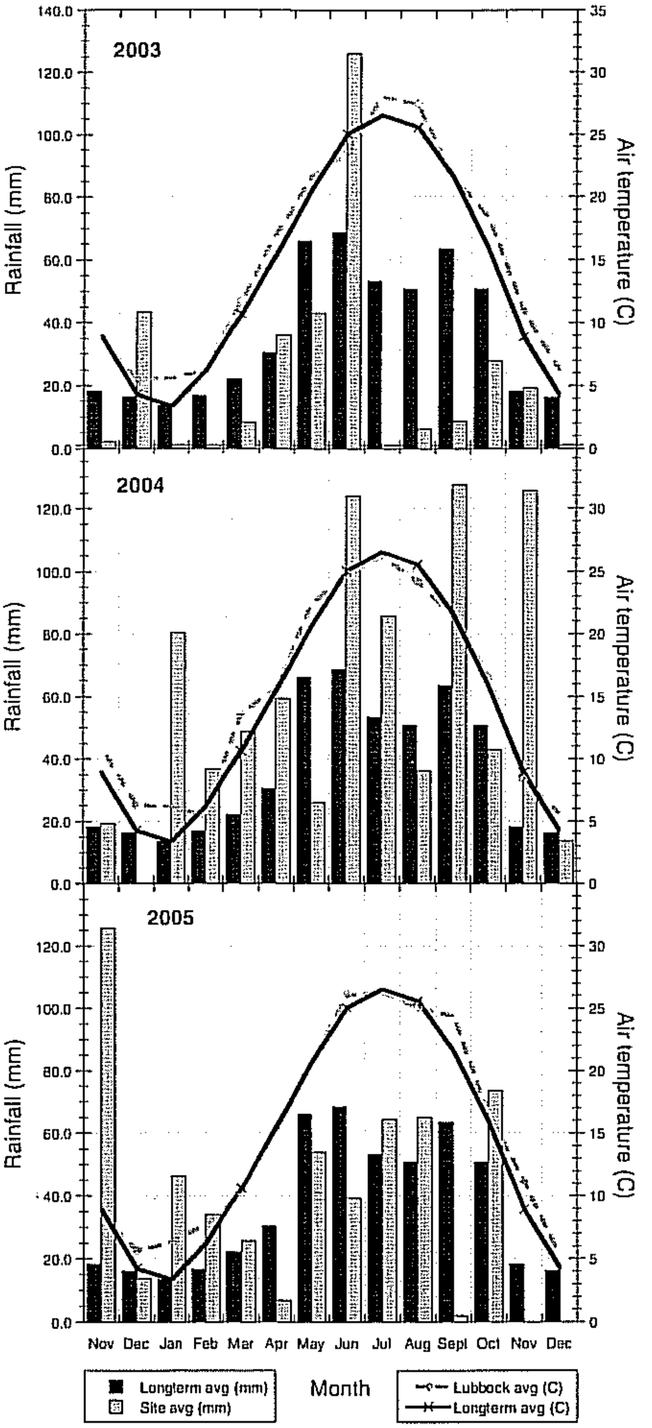

Fig. 4. Precipitation and temperature during Year 6, 7, and 8 comparing a cotton monoculture with an integrated cotton–forage–livestock system and the long-term precipitation (1911–2004) and temperature (1971–2000) for Lubbock, TX (about 16 km from research site).

allowed reduced water use, but the overall system differences remained similar to previous years. Yields of grass seed and stocking rates of cattle were similar to previous years.

Year 7 (2004) was characterized by unusually high annual precipitation (687 mm at the research site) and slightly lower temperatures in August, a critical time for cotton production (Fig. 4). Irrigated water use for both systems declined (Table 1). Water applied through irrigation to the integrated system was less than one-half of that applied to the continuous cotton, reflecting lower water requirements of the forage components. In this year of above average moisture, excess forage growth allowed a hay harvest event to occur on the old world bluestem. No grass seed was harvested because hay harvest delayed flowering and seed maturity until rainfall, followed by frost prevented a seed crop. In this year of cooler temperatures, cotton yields in the integrated system declined and were lower ($P < 0.06$) than those of the continuous cotton system (Table 1) likely related to lower soil temperatures with this no-till system. Cotton yields in the monoculture system also declined slightly compared with the previous year, suggesting that temperature was a more limiting factor than moisture in this high rainfall year. Lack of a grass seed harvest, a low margin of profit for hay, and the decline in cotton yields lowered profitability for the integrated system compared with the continuous cotton system (Table 1).

Years 6 and 7 are important in understanding the need to observe the chaotic patterns of system behavior over time and to simulate production over years based on an array of climatic conditions. Year 8 (2005, Fig. 4, Table 1) represented a return to more average climatic conditions with precipitation slightly below normal. Cotton yields in the integrated system were higher than for the cotton monoculture. However, no seed were harvested from old world bluestem in 2005 in the integrated system. Total cattle gain per system hectare was 268, 231, 224, 250 kg for the mean of 1999 to 2002, 2003, 2004, and 2005, respectively. Duch-Carvallo (2005) found that profitability of the integrated system was more sensitive to changes in cattle gains than either cotton or grass seed production. The lower gains of steers over Year 6, 7, and 8 affected profitability of this system more than cotton yields.

Five years of similar behavior were followed by 3 yr of a different pattern of response reflecting more extreme variation in weather, changes in cotton management strategies, and in cattle performance. Changes in forage and livestock management are now needed to evaluate their impact on system behavior.

Thus far, results indicated that when all other factors are relatively constant and cotton lint yields reached 1500 kg ha^{-1}, profitability was greater for the monoculture system. When cotton lint yields were about 1000 kg ha^{-1}, profitability was greater for the integrated system. The average irrigated cotton lint yields in the Texas High Plains during 1997 to 2004 was 630 kg lint ha^{-1} (Texas Agricultural Statistics Service, 1997, 1998, 199, 2000, 2001, 2002, 2003, 2004). Thus, most cotton currently being produced in this region under irrigated conditions is not achieving sufficient productivity to reach this level of profitability. Furthermore, when net returns over variable costs were calculated per unit of irrigation water used, the integrated system had a higher net return at every pumping depth in every year (Allen et al., 2007a). Not only must less total irrigation water be used in the future, but the value of the water invested in terms of agricultural commodity produced per unit of water must increase as well. The integrated system is accomplishing both of these objectives, but irrigation water used by the integrated system remains substantially above sustainable use levels. It does, however, demonstrate that improvements can be made and further research is needed. Today, if cotton monoculture yields can be increased, income in the short run is increased, but it carries the cost of increased water pumped from the aquifer, increased soil erosion, decreased soil quality, a higher risk from the lack of diversification, and the likely compromise of a long-term future.

The Texas High Plains is an example of the use of irrigation to provide resilience and stability to a variable ecosystem. It is also an example of instability created by dependence on a resource that is finite. Furthermore, the cropping and livestock systems that evolved have created infrastructures that now contribute to this instability through the need to continue current practices to realize returns on investments made in these infrastructures.

Economic Perspectives

Using experimental data from the integrated and conventional cotton production systems, 10-yr simulations were conducted to evaluate the variability of net revenues above total cost of production. The results of this exercise indicated that, assuming a 46-m pumping lift, the expected per hectare net revenues above all production costs for the continuous cotton production system would be negative and amounted to an annual loss of about \$128.50 ha^{-1} yr^{-1}. Simulations for the integrated production system also indicated that the expected per hectare net revenues above all production costs would be negative, estimated to be a loss of \$32.12 ha^{-1} yr^{-1}. The simulations revealed that the conventional production system would on the average require 414 mm yr^{-1} and the integrated system would require 329 mm yr^{-1}. Given these expected levels of water utilization, the annual net revenue above all costs of production per 100 m^3 (approximately 1 acre–in of water) would be negative \$3.10 per 100 m^3 for the conventional cotton production system, and negative \$1.23 per 100 m^3 for the integrated production system.

The negative expected level of revenue for the conventional cotton production system reported above is not surprising. In a recent study, Sanders (2003) reported that given current commodity price expectations, net revenues above all production costs per 100 m^3 of water ranged from −\$5.82 to −\$1.33 for irrigated wheat, corn (*Zea mays* L.), and grain sorghum [*Sorghum bicolor* (L.) Moench] production in the Texas High Plains. Sanders also found that for irrigated cotton production, depending on the cotton price scenario assumed, the expected level of net revenues above all costs of production could be anywhere from −\$4.24 to +\$14.61 per 100 m^3 of water used. Given these figures, a relevant question to ask is: Why would producers be willing to essentially pay money to give away their water in terms of the crops they produce? The answer to this question has to be: either because they are just not aware that this was happening, or because the figures above do not take into account all the "benefits" producers get from producing the agricultural commodities they produce. The former answer seems to be much less likely than the latter. That is, agricultural producers know exactly how much it costs to get water from the aquifer (from \$4.00 to \$12.00 per 100 m^3, depending on the type of energy used and the depth to the water table) and they know how much net revenue above all costs of production they get once they sell their water in terms of the crops they produce. For this reason, there must be other "benefits" producers get that are not being accounted for in the above figures. Possible "benefits" may include government farm program benefits related to direct government payments, credit accessibility, disaster payments, crop insurance benefits, etc. Regardless of the reasons, producers, lenders, and policymakers must be made aware of what the trade-offs are, so that informed and deliberate decisions are made by them with respect to how they should sell their water, either in the form of the commodities (fiber, grain, or beef) they produce or consider selling it in other forms and markets, such as to municipalities to be used for human consumption or industrial purposes.

Ultimately, this is an intergenerational issue that must be decisively and objectively addressed. Yes, current laws that delineate property rights are well established and clearly identify the rights and privileges of the owners of underground water resources. However, the nonsustainability nature of this resource in the Texas High Plains warrants the investment of a significant effort to reconcile the "private" desire to maximize profitability of water mining in the short run vs. the "social" desire to conserve water in the long run for purposes of future economic sustainability. If the owners of the resource were to be convinced by society to conserve some or all of their water for future use, they should be compensated fairly for postponing the utilization of their water resources into the future.

Given the fact that in the long run (100 yr) the most likely possibility for agriculture in the Texas High Plains is "dryland" agriculture, wise and deliberate strategic investments today must be made, so that the expected decreases in income associated with the transition from irrigated to dryland agriculture does not jeopardize the economic viability of the Texas High Plains (Terrell et al., 2002). It is feasible that with accentuated water scarcity, innovation through the development of new technologies to overcome water scarcity will be able to make up for some of the likely water shortages to be endured. Adoption of the integrated production system highlighted above would help in facilitating the transition to dryland agriculture in the Texas High Plains.

SOCIAL AND EDUCATIONAL CHALLENGES

Large-scale irrigation in dry climates is credited, in many cases, with bringing immeasurable wealth to a region. However, sustainability of irrigated areas in dry climates has been questioned. As Reisner (1986) stated in his classic book, *Cadillac Desert* (p. 3): "Westerners call what they have established out here a civilization, but it would be more accurate to call it a beachhead. And if history is any guide, the odds that we can sustain it would have to be regarded as low. Only one desert civilization, out of dozens, that grew up in antiquity, has survived uninterrupted into modern times."

Once irrigation-dependent communities emerge in dry climates, and natural resources are depleted, then often those communities become at-risk. Most crops have a multiplier effect within a community in terms of economic contribution. With increased production come related agribusiness support industries, followed in many cases by value-added enterprises to capture and maintain as much wealth from the production of raw commodities as possible. A growing trend is the establishment of Internet-based marketing agencies that cater to consumer demands. There is also often a heavy dependence on production by local retailers, wholesalers, and the supportive real estate complex within a community, as well as tax-supported health care, schools, and other governmental organizations.

Understanding producer behavior in the context of extension systems is complex at best. At a very basic level (i.e., psychosocial behavior), most behavioral scientists would agree that producer behavior in dry climates is not unique when it comes to the extraction of limited natural resources. Consequently, much can be learned from the interaction of producer behavior with extension systems in other climatic zones. Leeuwis (2004) contended that challenges for agricultural extension practice are due in part to challenges to farmers and agriculture at-large. He stated that, "The conclusion that most of the innovations needed in present day agriculture have collective dimensions (i.e., they require new forms of interaction, organization, and agreement between multiple actors) has important implications for extension practice and extension theory" (p. 11).

Similarly, Rivera and Alex (2004) argued that Extension can no longer be viewed as a unified service, but must be viewed as a network of information and knowledge sources. Implicit in this assertion is that numerous information sources including local or indigenous knowledge must be utilized in Extension programming.

The transfer of innovations to the adoption stage is often one of the most challenging aspects of the agricultural knowledge system. However, recent research has indicated that the producer population in the Southern High Plains is segmented into subgroups with different motivations and cultural ties (Kistler et al., 2005). The first group, referred to as Forward Thinking Pragmatists, was characteristic of producers with a strong desire for alternatives that were economically and environmentally sustainable. Producers in this group felt that economic concerns drive their decisions about changes they make in their farming systems. Although producers in this group were also concerned with environmental and conservation issues, it was still an economic decision that would cause them to adopt sustainable practices. These economic concerns seemed to be grounded in a healthy skepticism.

Another group (Optimistic Integrators) was interested in integrated practices to increase flexibility and concerned with water and conservation issues. They were open to the idea of a sustainable integrated crop–livestock system as an alternative and were willing to invest the energy required to learn about new alternatives. These producers also desired to farm less and place more emphasis on soil health, rather than mass production.

The final group (Traditionalists) identified themselves as cotton farmers. They valued technology that allowed them to continue growing cotton on a larger scale. They saw no need for alternatives; consequently, they were not as concerned with water and environmental issues as were the other two groups. The traditionalists did not feel restricted by the biophysical constraints of diminishing water resources and were optimistic that they would be able to pass their operations on to future generations. This group of producers discounted the outlook of water depletion from the Ogallala Aquifer.

Kistler et al. (2005) argued that future extension programming must be established around social learning theory, placing the Optimistic Integrators and Forward Thinking Pragmatists in the center of outreach programs. In a qualitative study of more than 100 individuals committed to work on behalf of the common good, Daloz et al. (1996) concluded by stating, "it is significant that we found constructive engagements with otherness to be the single most critical element undergirding commitment to the common good in the lives of those we studied. There is a vital need in every sector of the commons to encourage meeting and dialog..." (p. 215).

According to Koelen and Das (2002), social learning theory contends that farmers make decisions based on a combination of normative social influence (i.e., community expectations and peer perceptions) and informational social influence (research-based knowledge). Normative social influences tend to become more important to group members in situations that are highly complex, where ambiguity is experienced, or there is a lack of complete information, such as in the case of the many water conservation decisions that farmers are faced with on a continuous basis.

In 2004, the previously referenced research at the Texas Tech Field Research Laboratory directly led to a \$6.2 million grant from the Texas Water Development Board to field test and demonstrate the value of integrating crop and livestock systems to reduce water withdrawal from the Ogallala Aquifer. This producer-owned and driven Demonstration Project is located on 26 farms incorporating over 1600 ha in Hale and Floyd Counties in the Texas High Plains and is funded for 8 yr. These sites range from intensive cotton monocultures to cropping rotations, integrated crop and livestock systems, and forage–livestock systems. They include both irrigated and dryland examples. These sites are being intensely monitored for total water use, total productivity, and economic return.

To increase awareness, knowledge, and adoption of appropriate technologies, a Farming Systems Research and Extension (Hildebrand and Russell, 1996) approach is being implemented including numerous educational approaches. This approach involves a number of stages including the use of on-farm research demonstrations, where farmers teach farmers and researchers collect real-world data for monitoring purposes.

In terms of the farmer–participants, a major goal is the establishment of a Community of Practice (Holmes and Meyerhoff, 1999). Consequently, it is important that the group of farmer–participants coalesce into a Community of Practice for the purpose of collective learning and action. People have multiple points of view, needs, domains of expertise, and agendas. Consequently, it is extremely important to focus on communications structures (sharing of experiences, ideas and information) through a continuous dialog of responsibilities, goals, and roles. When farmers begin to think about their individual farming systems in relation to their neighbors who share a common water resource, then they often make decisions based on both the good of the whole as well as the good of the individual (Rose et al., 2003).

Research with producers in the Midwest (Tucker and Napier, 2002) and on the Southern Great Plains (Doerfert et al., 2004) indicated that other farmers were one of the highest rated sources of information about soil and water conservation (in the Midwest) and water conservation (in the Southern Great Plains). The farmer–participants were intimately involved in teaching other farmers. The monitoring data collected from the demonstration farms coupled with personal testimonies of the farmer participants will serve as powerful information as other farmers consider modifying their practices. The researchers anticipate that a great deal of local or indigenous knowledge will emerge by way of anecdotal information, which will serve to compliment the scientific knowledge generated by monitoring the demonstration areas. Field days and Farmer Field Schools will be conducted at the research and the demonstration sites to reach a broad audience of regional producers and the general populace. These programming opportunities will include tours, testimonies by the farmer participants, and updated knowledge based on the data being collected.

Although this alternative approach to extension programming is still being implemented, anecdotal feedback from the producers has been positive. Not all communities are within a state of readiness for empowerment (Baker et al., 2006), nor is it easy to assess community readiness. However, interest continues to grow in nonlinear constructivist approaches that attempt to place the farmer in the center of programming.

IMPLICATIONS FOR THE FUTURE

Vörösmarty et al. (2000) projected increases in population and economic development within the next 25 yr will likely have greater impact on supply and demand of water than projected global climate change. Anticipated increases in relative water demand will pose substantial challenges to water infrastructure and water services throughout much of the world. In arid and semiarid regions, water scarcity will be an additional challenge. Globally, the move to crop and livestock specialization that has characterized agricultural progress during the last half-century has contributed directly to increased food and fiber production, but at the cost of declining water and other natural resources and environmental degradation. Solutions to many of these challenges may come through a return to a more diversified, integrated crop and livestock systems approach, but research is needed at a landscape scale to develop the knowledge required to implement this approach such that production of food can keep pace with a growing global population.

Integrated systems research requires time and is expensive to establish and to conduct. When irrigation is added, either as a treatment variable or as a water delivery system to all components, this cost and potential environmental impact is magnified. Where livestock are involved, surface irrigation systems present unique challenges in geometry of paddocks, movement of traveling irrigation systems including both center pivot and linear units, placement and types of fencing that can be used, and wetting of soil surfaces that may be more vulnerable to animal traffic. The type of irrigation system and placement of water will influence both plant and animal responses and must be considered in interpreting results. Subsurface irrigation systems are highly efficient and avoid many logistical problems of surface systems when livestock are involved, but are expensive and less effective in sandier than heavier-textured soils. In most soils, water also can be lost downward though the soil profile below the rooting depth without proper management. Lateral movement of water away from drip tapes is limited and wetting soil surfaces between irrigation tapes is unlikely where water is limited and evaporation rates are high. This is a particular concern in establishment of annual forages with narrow row spacing or in broadcast planting. Timely rainfall is needed to support germination.

Technologies exist to deliver water with precision application and efficiencies that approach 100%, but these systems are costly to install and expensive to maintain and may require an infrastructure that is not available, practical, or cost effective. Flood irrigation and hand-watering in small holdings may be the only reasonable delivery system. Overland transport of water from the source can result in major water losses through leakage and evaporation unless delivered by enclosed pipelines that also add cost in construction and maintenance. Increasingly, water available for irrigation will be subject to regulation.

Integrated systems research requires large inputs of space, facilities, an interdisciplinary team of people, and a commitment to long-term research. It must include economic analysis and societal implications, as well as basic and applied science in numerous fields. Because of this, there will never be many integrated crop–livestock systems comparisons under replicated research conditions and especially not under irrigation. Therefore, it is imperative that we invest in such research wisely and when we make such a commitment, that we understand that it must be conducted over time. Every system is unique to its make up and location, but understanding of the principles that drive its behavior generates transferable knowledge.

Irrigation will face increasing competition from industries and municipalities (Matson et al., 1997; Schmidt, 2005; Rosegrant et al., 2005). As human uses for water continue to escalate and global supplies are impacted in both quality and quantity, there must also be recognition that ecosystem function and survival of all plants and animals depends on water. In 2002, the Council of Scientific Society Presidents in Washington, DC, adopted a position that stated in part, "A committed, enlarged, and focused research and development program is essential to meet [water] needs for daily existence, avoid mass migrations and the collapse of regional economic systems, ensure food and water security and safety, and enable human use of water without destroying the ecosystems on which we depend" (Council of Scientific Society Presidents, 2002). This has particular relevance to the world's semiarid and arid regions where water is in short supply and is crucial to existence.

Ancient villages in southern Jordan were abandoned because they became vulnerable to human-induced loss of resilience in their productive natural resource base (Redman, 1999). Today, there is evidence that history is repeating itself across the landscape of West Texas, with short-term resilience built on irrigation from a finite water source and economic dependence on monocultures with public and private financial commitment to related infrastructures. This has led to a loss of long-term resilience. Rural communities are declining. Land use is changing, sometimes to higher-valued recreational uses, but also to abandonment when profitability can no longer sustain the residents. There is still time to conserve our natural resource base, in particular the soil and water resources, in anticipation that technologies of the future can make more efficient use of these resources to meet the needs of our global community.

While our arid and semiarid lands will continue to play a major role in meeting the needs of humanity on a global scale, it is risky to depend on irrigation in these regions to meet the escalating needs for food and fiber. To do so is resource and energy expensive, is not likely sustainable in the long term, and can result in degradation of the natural resource base, at least under the technologies of today. Irrigated agriculture is vital to our global food supply. Without benefit of irrigation in dry climates, millions of hectares of rain forests and marginal lands in more humid environments will need to be cleared to meet the food needs for the world's growing population (Trout, 1998). However, long-term stability, both regionally and globally, is going to depend on protection of agricultural lands in climatic regions best adapted to production of intensive agriculture with a minimum of dependence on irrigation and soil amendments. This could allow a return of arid and semiarid lands, dependent on external inputs for resilience, to dryland agricultural systems consistent with protection of the natural resource base. In most cases, this will likely be a return to dryland pastoral-based systems integrated with cropping components with limited irrigation consistent with water replacement potential.

Solutions will require bold action. A focused, visionary, and aggressive research, educational, and training program is essential to generate and translate appropriate knowledge into economically and environmentally viable practices. Funding must be made available through both public and private agencies to support long-term, landscape-scale integrated systems research that has regional and global relevance. Partnerships must be forged among practitioners, university scientists, industry, organizations, government agencies, and the public to conduct the needed interactive research and educational programs. Institutional policies must support the interdisciplinary team and nontraditional partnerships required to conduct such programs over time. Three- to five-yr experiments cannot suffice and 30- to 50-yr experiments may not be long enough. Linkages among long-term integrated agricultural research sites in differing ecosystems will be essential to understanding system behavior both spatially and temporally and to maximize returns on investments in research.

As the world's attention focuses increasingly on the need to feed a growing global population, there must be a parallel concern for the sustainability of that food production and the protection of our natural resources and environment. There will be no single solution—rather there must be an integration of parts to create a site and time specific integrated system. This system must function as a whole whose outcome must reflect advances in all aspects of management and technology of the systems components to yield the desired result, but must be made compatible with ecological heath and the economic opportunities and societal needs of the specific region in which it exists. Monoculture plant and animal systems have allowed major advances in technologies and economies of scale, but increasingly are extracting a nonsustainable environmental cost. At least some of the solutions can be found in integrating plant and animal agriculture and in this, the world's semiarid regions have an important role to play.

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