REDUCING OGALLALA WITHDRAWALS BY CHANGING CROPPING AND IRRIGATION PRACTICES IN THE TEXAS HIGH PLAINS

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ABSTRACT

Irrigated crop production in the Texas High Plains is dependent on the Ogallala Aquifer, which has declined by up to 50 percent in some areas since irrigation development began in the 1930-40s. About 6.5 million acre-feet (ac-ft) of water was pumped to irrigate 4.6 million acres in 2000, with most irrigation demand being for corn and cotton production. Cotton is produced primarily in the Southern Texas High Plains, with corn and winter wheat comprising most of the irrigated area in the Northern Texas High Plains. However, cotton production is expanding northward again and replacing corn in some areas because both crops currently have similar revenue potential but cotton has about half the irrigation water requirement, and may result in profitable yields under dryland and deficit irrigated conditions. In the Northern Texas High Plains, combined annual irrigation demand for corn and cotton could be reduced from 2.6 to 2.0 million ac-ft by replacing 50 percent of the irrigated corn area with cotton, and combined irrigation demand could be reduced to 1.6 million ac-ft if cotton irrigation applications were reduced to 50 percent of full crop evapotranspiration minus rainfall. In the Southern Texas High Plains, annual irrigation demand for cotton could be reduced from 1.4 to 1.0 million ac-ft if overall irrigations were reduced to 50 percent of full crop evapotranspiration minus rainfall. Deficit irrigation results in some yield penalty; however, if the crop is relatively drought tolerant, this may be offset somewhat by the reduced energy costs of pumping.

INTRODUCTION

The semi-arid Texas High Plains is a major producer of irrigated and dryland crops and comprises the southern portion of the U.S. Great Plains. Irrigation

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typically results in doubled to quadrupled crop yields compared to dryland production levels, making irrigated agriculture a vital component of the regional economy (Howell, 2001). Large-scale irrigation first became practical in the 1930-40s when internal combustion engines, turbine pumps, right-angle gear drives, and rotary well drilling became available for pumping groundwater (Musick et al., 1988). Irrigation accelerated during the major drought in the 1950s, peaking at around 6.0 million acres in 1974, and declined thereafter to 4.0 million acres in the Texas High Plains by 1989 (Musick et al., 1990).

Nearly all irrigation in the Texas High Plains was developed solely from the Ogallala (High Plains) Aquifer as surface water resources are inadequate for this purpose. The Ogallala underlies parts of eight states (South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas) and is one of the largest freshwater aquifers in the world. Over 90 percent of Ogallala withdrawals in the Texas High Plains are for irrigation; however, the Ogallala is essentially a closed basin and withdrawals have greatly exceeded recharge, resulting in severe decline of groundwater levels since irrigation development began. In some areas, more than 50 percent of the predevelopment saturated thickness has been pumped, and groundwater levels have dropped over 150 ft (McGuire, 2003). However, the combination of greater lift requirements, increasing unit energy costs, and relatively static commodity prices led to overall reductions in pumping rates after 1974, and rates of aquifer decline have abated in many areas. Increases in pumping energy costs will continue to affect upper limits in aquifer withdrawal rates and therefore crop productivity. These factors threaten the long-term economic viability of irrigated agriculture in the Texas High Plains.

The purpose of this paper is to explore the potential for reducing withdrawals from the Ogallala Aquifer by changing cropping patterns (i.e., conversion from corn to cotton) and reducing irrigation pumping for relatively drought-tolerant crops (i.e., cotton, grain sorghum, and wheat), where no net loss in irrigated land area is assumed. Specific objectives are (a) review recent irrigation inventories and practices in the Texas High Plains; (b) estimate irrigation demand by crop based on typical application fractions relative to evapotranspiration and precipitation; (c) estimate potential reductions in irrigation demand by converting fully irrigated corn to cotton for a range of cotton irrigation application fractions; and (d) examine the trade-off between reductions in irrigation demand (through deficit irrigation) and crop productivity. An economic analysis is presently beyond the scope of this paper; however, it is anticipated that the results presented herein will be useful in foreseen adoption rates and in long-term regional water resources planning.

STUDY AREA

The study area is in the Texas High Plains, which is defined as the 39-county area comprising the Texas Agricultural Statistics Service (TASS) Districts 11

(Northern High Plains) and District 12 (Southern High Plains) (Fig. 1). These districts generally overlie the Ogallala Aquifer in Texas. The Canadian River roughly bisects portions of the Ogallala Aquifer in the Northern District. Elevations above mean sea level (MSL) range from approximately 2,500 ft along the eastern boundaries to over 4,000 ft toward the northwest. The region is mostly semi-arid, with extremely variable precipitation (both temporally and spatially, averaging 16 to 22 inches west to east, respectively). The region also has high evaporative demand due to high solar radiation, high vapor pressure deficit, and strong regional advection. Soils are generally described as moderately permeable in the Southern District, slowly permeable in the Northern District south of the Canadian River, and a mix north of the Canadian River (Musick et al., 1988). Corn and wheat have traditionally been produced north of the Canadian River, with cotton being produced further south, although cotton has recently expanded northward into the corn-producing areas, which will be discussed further.

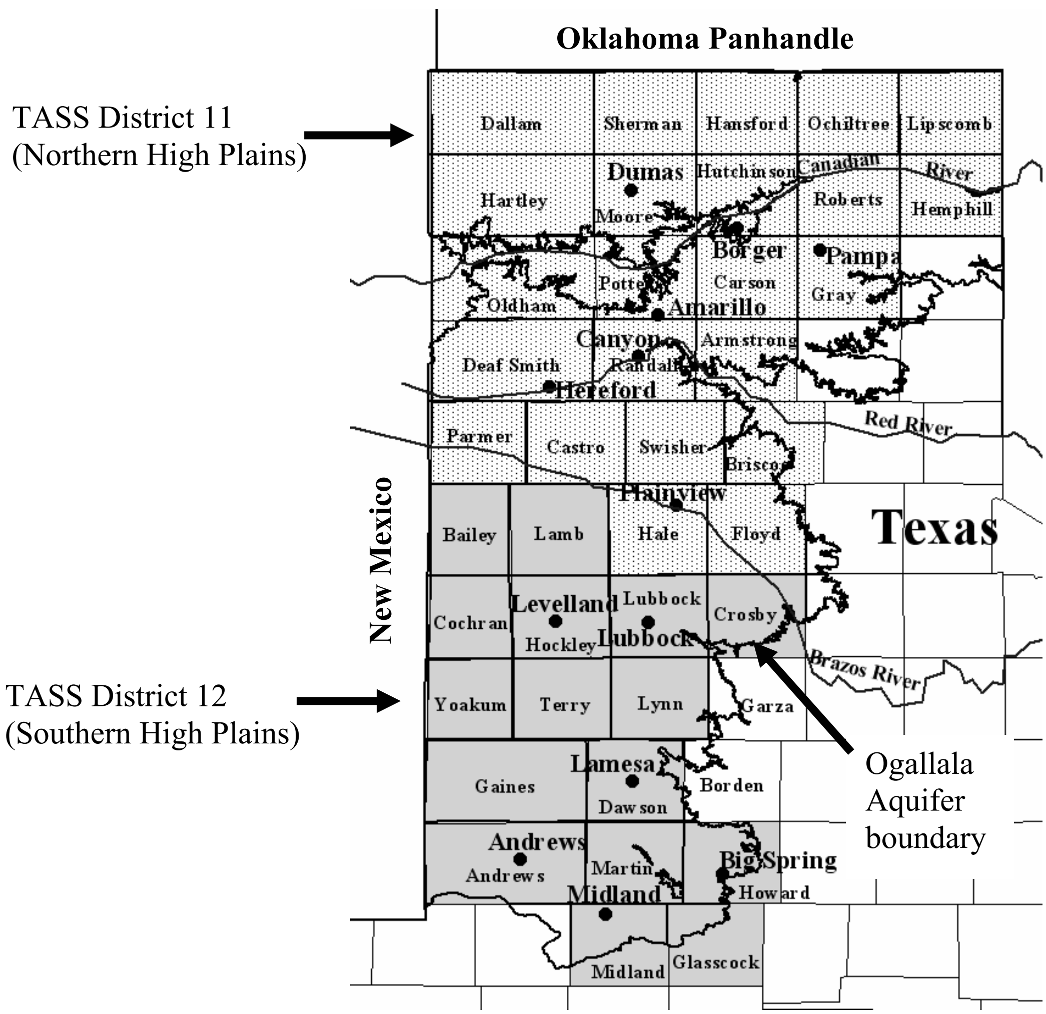


Figure 1. Study area.

IRRIGATION INVENTORY AND PRACTICES

Cropped and irrigated area data were obtained from the Texas Agricultural Statistics Service (TASS, 2006), and the Texas Water Development Board (TWDB, 2001). The TWDB has conducted irrigation surveys in Texas in cooperation with the Natural Resource Conservation Service and the Texas State Soil and Water Conservation Board about every five years since 1958; the most recent was in 2000. From the 2000 survey, the counties in the TASS Northern and Southern High Plains Districts contained a total of 4.6 million irrigated acres (Table 1). This is greater than 4.0 million irrigated acres estimated for approximately the same area (41 counties) in 1989 as reported by Musick et al. (1990), and it appears that total irrigated land area has somewhat stabilized after the 1974 to 1989 decline. About 6.5 million acre feet of water was pumped for irrigation in 2000, with an average depth of 16.9 inches pumped per acre, which was much greater than 4.5 million acre feet (13.5 inches per acre) reported for 1989 (Musick et al., 1990; and verified using 1989 survey data in TWDB, 2001). This was surprising in that it contradicts the general premise of declining irrigation pumping rates, and is likely the result of intensifying drought during the 1990s.

Table 1. Texas High Plains irrigation inventory, 2000 (TWDB, 2001).

TASS District	Drip (ac)	Sprinkler (ac)	Gravity (ac)	Total (ac)	Irrig. Use (ac-ft)	Avg. Depth (in)
11 (NHP)	1,300	1,855,700	937,400	2,794,300	4,164,200	17.9
	0.05%	66.4%	33.5%			
12 (SHP)	20,600	1,487,600	324,000	1,832,100	2,340,500	15.3
	1.12%	81.2%	17.7%			
Total	21,900	3,343,200	1,261,300	4,626,400	6,504,700	16.9
	0.47%	72.3%	27.3%			

Irrigation technology consisted of about 72 percent sprinkler (nearly all mechanically-move center pivot systems), 27 percent gravity (mostly graded furrow), and less than 0.5 percent drip (mostly subsurface drip irrigation, or SDI). The proportion of sprinkler irrigation has increased significantly from 44 percent in 1989 (Musick et al., 1990). In 2000, most of the drip area was in the Southern High Plains (20,600 ac) where cotton is primarily produced, but severe drought, declining water resources, increasing energy costs, and favorable cotton response under SDI prompted rapid expansion, with some estimates up to 250,000 ac by 2004 (J. Bordovsky, pers. communication). Preliminary data at Bushland, TX suggest that cotton fiber quality was better under SDI compared with sprinkler methods (Colaizzi et al., 2005), and SDI has been shown to enhance yield under very limited irrigation relative to sprinkler methods for a variety of crops and locations (Colaizzi et al., 2006). For these reasons and as cotton production expands in the Northern Texas High Plains, SDI may see even greater adoption in the near future.

Gross seasonal irrigation depths (I_d) applied to various crops in the Northern Texas High Plains were documented by the Texas Cooperative Extension AgriPartners program, which includes several hundred on-farm demonstrations of irrigation management based on crop evapotranspiration (ET_c) with cooperating producers (Table 2; New, 2003). I_d ranged from 8 in. for center pivot (CP)-irrigated winter wheat to 29 in. for gravity (surface)-irrigated grain corn; these were derived from totalizing flow meters (usually at the well head). ET_c data used in irrigation scheduling were disseminated to producers by the Texas High Plains Evapotranspiration Network (TXHPET; Howell et al., 1998a; Porter et al., 2005), which presently has seventeen agricultural weather stations at strategic sites in the Northern and Southern Texas High Plains. The TXPHET Network computes ET_c as

$$ET_c = ET_{os}K_c \tag{1}$$

where ET_{os} is the ASCE-Standardized Penman-Monteith equation for a grass reference (Allen et al., 2005) and K_c is the crop coefficient, which reflects both transpiration and evaporation under fully irrigated conditions. The K_c functions were developed at the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas, where large precision weighing lysimeters have measured water use of major irrigated crops in the region since 1987 (Evett et al., 2000; Howell et al., 1995; 1997b; 1998b; 2004; Steiner et al., 1991). The K_c functions are based on cumulative growing degree days (a.k.a. heat units), which are based on crop-specific minimum and maximum air temperature thresholds (e.g., Peng et al., 1989).

Table 2. Average gross irrigation depths, irrigation rates, and crop production of producers participating in AgriPartners Program, 1998-2002 (New, 2003).

Crop	CP I_d (in.)	Avg. FR (eq. 2)	Avg. CP Irrigation Production		Grav. I_d (in.)	Avg. FR (eq. 2)	Avg. Gravity Irrigation Production	
Grain corn	22	0.84	184	bu/ac	29	1.11	170	bu/ac
Silage corn	21	0.80	26	ton/ac	20	0.76	19	ton/ac
Cotton	12	0.90	940	lbs/ac	7	0.64	642	lbs/ac
Peanuts	20	1.48	4000	lbs/ac				
Grain sorghum	12	0.73	102	bu/ac	16	0.98	124	bu/ac
Soybeans	15	0.89	55	bu/ac	13	0.77	48	bu/ac
All wheat	8	0.49	67	bu/ac	10	0.62	75	bu/ac

I_d recorded by the AgriPartners program were generally less than the full irrigation requirement (ET_c minus effective precipitation). This was quantified in Table 2 as the application fraction of the full seasonal irrigation requirement (FR):

$$FR = \frac{I_d}{ET_{c-s} - P_s} \qquad (2)$$

where I_d is the gross seasonal irrigation applied, $ET_{c\text{-}s}$ is the seasonal crop evapotranspiration, and P_s is the seasonal precipitation, with all terms in units of depth (in.). FR is usually a trade-off between the irrigation system capacity (or well capacities) and irrigated area, which is often dictated by the drought sensitivity and price of the crop. FR also reflected expected rainfall, availability of stored soil water, type of irrigation system and system losses (e.g., wind drift, evaporation, runoff), and other operational constraints (e.g., soil permeability, labor availability, pump efficiency, energy costs, etc.). Average FR from AgriPartners data ranged from 0.49 for center pivot-irrigated winter wheat to 1.48 or center pivot-irrigated peanuts (Table 2). Grain yield response of winter wheat greatly diminishes for FR exceeding 0.50 (Schneider and Howell, 1997; 2001); hence a 0.49 FR probably represents optimal irrigation management. The relatively high FR for peanuts reflects that the soil surface must be maintained in a relatively moist condition during the pegging stage, which is not accounted for in K_c.

IRRIGATION DEMAND BY CROP

Estimates of the relative irrigation demand for each crop provided the rationale for examining certain changes in cropping patterns and FR, and hence their potential impact for reducing aquifer withdrawals. Data on irrigation water pumped by crop were not available; instead, irrigation demand by crop was estimated based on crop evapotranspiration, precipitation, irrigated crop area, and FR observed in the AgriPartners program, which were assumed to represent general irrigation practices given the constraints on pumping in the region. For each crop, irrigation demand in 2000 was estimated by

$$I_{v-i} = \frac{1}{12} \sum_{j=1}^{m} \sum_{k=1}^{n(j)} \left(ET_{c-ij} - P_k \right) FR_{ik} A_{ik} \qquad (3)$$

where I_v is the irrigation demand volume (ac-ft), ET_c is the crop evapotranspiration (in.) from equation 1, P is seasonal precipitation (in.), FR is the fraction of the full seasonal irrigation requirement (in.) from equation 2, A is the irrigated area (ac), *i* is the crop, *j* is the TXHPET station, *k* is the county, and *n(j)* is the total number of counties assigned to TXHPET station *j*. About 70 percent of annual precipitation in the Texas High Plains occurs during the growing season (May to September) in a bimodal pattern, with rainfall concentrated around planting and later in the season for summer crops. Some off-season precipitation stored in the soil profile will likely compensate for in-season P_k losses that are difficult to determine (e.g., runoff, evaporation, deep percolation) in equation 3. From Table 2, the FR for a given crop varied by the type of irrigation system used (i.e., center pivot or gravity), and the proportion of irrigation system type used varied by county (TWDB, 2001). Therefore, the FR for crop (*i*) in equation 3 was weighted by county (*k*):

$$FR_{ik} = \theta_{DRIP-k} FR_{DRIP-i} + \theta_{CP-k} FR_{CP-i} + \theta_{GRAV-k} FR_{GRAV-i} \qquad (4)$$

where θ is the fractional area of irrigation system type used in county *k*, and FR for each crop and type of irrigation system was taken from Table 2 (DRIP = drip, CP = Center Pivot, GRAV = Gravity). Since the proportion of drip irrigation was relatively small (Table 1) and $FR_{DRIP\text{-}i}$ data were lacking, it was assumed that $FR_{DRIP\text{-}i} = FR_{CP\text{-}i}$.

Irrigated crop area by county in 2000 (and corresponding irrigated + dryland totals) was provided by the Texas Agricultural Statistics Service (TASS, 2006), and summed for the Northern and Southern Texas High Plains Districts (Tables 3 and 4, respectively). Roughly half of the total cropped area was irrigated. Cotton, grain corn, and wheat comprised about 88 percent of the total irrigated area in the Northern High Plains, whereas cotton comprised 79 percent of the total irrigated area in the Southern High Plains. Total irrigated area summed to nearly 4.3 million acres for both districts (Table 3), which is less than 4.6 million acres estimated for 2000 by the TWDB irrigation survey (Table 1), but still greater than 4.0 million acres reported for 1989. The small discrepancy between TASS and TWDB total irrigated area may be due to minor irrigated crops not reported in TASS data (e.g., fresh market vegetables, orchards, or pasture).

With irrigated crop area by county known, irrigation demand was estimated using equation 3. Total irrigation demand for the Northern and Southern Texas High Plains was about 3.5 and 1.9 million ac-ft (Tables 3 and 4, respectively) or a total of 5.4 million ac-ft. Grain corn represented most of the irrigation demand in the Northern Texas High Plains, followed by cotton, whereas cotton represented most demand in the Southern Texas High Plains, followed by peanuts. The average application depths for the Northern and Southern Texas High Plains were 16.3 and 13.1 inches, respectively (Tables 3 and 4, respectively). These were less than the average depths computed using TWDB data (17.9 and 15.3 inches, respectively; Table 1), possibly suggesting that overall FR in the Texas High Plains was greater than FR for producers who participated in AgriPartners. On the other hand, the overall average depth for the Texas High Plains was 15.0 in. (Table 4), which was considerably greater than the TWDB 13.5-in. average for 1989. Despite some uncertainty in *absolute* irrigation demand estimates, the *relative* demand of each crop clearly shows that reducing the irrigation demand for corn and cotton will likely have the greatest immediate impact in reducing Ogallala withdrawals, with several other strategies considered next.

Table 3. Irrigated crop inventory and estimated irrigation demand (I_v) in 2000 for TASS District 11 (Northern Texas High Plains).

Crop	Total Cropped Area (ac)	Irrig. Area (ac)	Irrig. Area (%)	Est. Irrig. Demand (ac-ft)	Avg. Depth (in.)
Grain corn	842,300	825,500	98%	1,864,500	27.1
Silage corn	59,000	48,500	82%	96,800	24.0
Cotton	912,400	767,800	84%	713,500	11.2
Peanuts	2,100	2,000	95%	4,000	24.0
Grain sorghum	697,000	199,000	29%	266,700	16.1
Soybeans	78,000	70,000	90%	109,700	18.8
All wheat	1,930,000	657,500	34%	438,300	8.0
Totals for NHP	4,520,800	2,570,300	57%	3,493,500	16.3

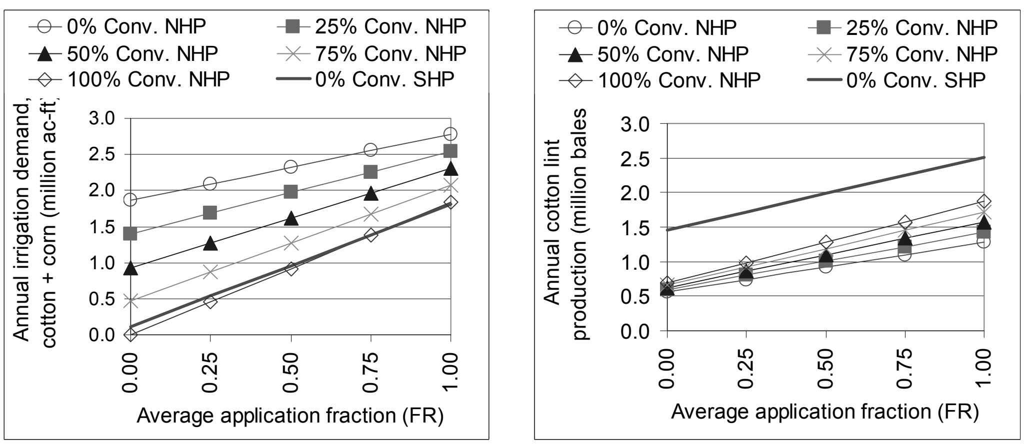
Table 4. Irrigated crop inventory and estimated irrigation demand (I_v) in 2000 for TASS District 12 (Southern Texas High Plains).

Crop	Total Cropped Area (ac)	Irrig. Area (ac)	Irrig. Area (%)	Est. Irrig. Demand (ac-ft)	Avg. Depth (in.)
Grain corn	48,700	47,700	98%	107,500	27.0
Silage corn	11,000	7,200	65%	12,100	20.2
Cotton	2,967,000	1,370,000	46%	1,384,100	12.1
Peanuts	189,000	149,200	79%	243,300	19.6
Grain sorghum	379,000	37,900	10%	37,400	11.8
Soybeans	7,900	7,700	97%	10,600	16.5
All wheat	460,000	109,100	24%	85,100	9.4
Totals for SHP	4,062,600	1,728,800	43%	1,880,100	13.1
NHP + SHP	8,583,400	4,299,100	50%	5,373,600	15.0

CONVERSION FROM CORN TO DEFICIT-IRRIGATED COTTON

Cotton production has recently expanded northward into areas where corn was traditionally produced in the Texas High Plains. The northern extent of cotton production was limited to the area around Hereford, TX (Fig. 1) until 1998, thereafter expanding to south western Kansas. Both crops have similar revenue potential, but maximum cotton yields are possible with about half the irrigation relative to corn; furthermore, profitable cotton yields are possible with limited (deficit) irrigation, unlike corn (Schneider and Howell, 1998; Howell et al., 2004). Although it appears recent cotton varieties require less heat units to reach adequate maturity, there is still inherent risk in producing cotton in a thermally-limited climate. Esparza et al. (2006) computed probabilities of accumulated heat units for cotton (60°F base temperature) for the 131 counties overlying the Ogallala Aquifer in Colorado, Kansas, New Mexico, Oklahoma, and Texas. They estimated a potential water savings of nearly 0.9 million ac-ft if 50 percent of the irrigated corn area was converted to cotton in counties receiving at least 1,800°F-days heat units on average. Of course, additional water savings could be realized with deficit irrigation, provided reductions in yield could be offset by reduced input costs of irrigation so as to maintain farm profitability.

Annual irrigation demand of cotton and corn was estimated in the Northern and Southern Texas High Plains for various irrigated corn-to-cotton area conversions (0 to 100%, Northern High Plains only since little corn is grown in the Southern High Plains), and for various application fractions of the full irrigation requirement ($0.0 \leq FR \leq 1.0$). In the Northern Texas High Plains, corn plus cotton irrigation demand in 2000 was estimated at 2.6 million ac-ft (Table 3). If 50 percent of irrigated corn was converted to cotton, corn plus cotton irrigation demand would be reduced to 2.0 million ac-ft, and if FR for cotton were then reduced to 0.50, corn plus cotton irrigation demand might be reduced to 1.6 million ac-ft (Fig. 2a).



a) b)

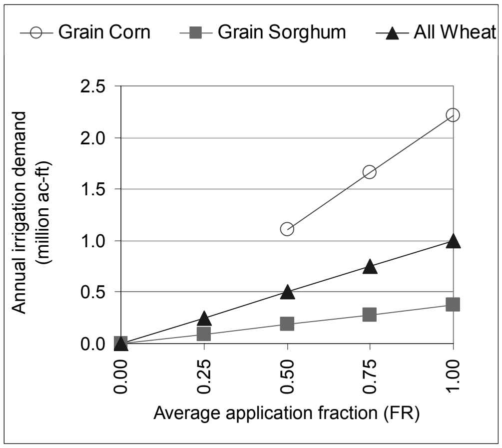
Figure 2. a) Estimated irrigation demand for cotton plus corn when the corn-to-cotton converted area and cotton FR are varied; b) corresponding total (irrigated + dryland) cotton lint production.

The resulting cotton lint production corresponding to irrigation demand was also estimated (Fig. 2b), where the baseline lint production was derived from 2000-04 county averages reported by TASS (2006). The relationship between crop productivity and crop water use (and irrigation applied) has been well-documented for the major irrigated crops in the High Plains. Production functions vary widely for the same crop under different seasons and locations; however, they are often significantly linear for numerous crops, including cotton (Wanjura et al., 2002; Bordovsky and Porter, 2003; Howell et al., 2004; Colaizzi et al., 2005). Also, yield vs. FR can be described fairly well by a single linear function for different seasons and locations. In the Northern Texas High Plains, annual cotton lint production was 1.28 million bales (2000-04 average) for no corn-to-cotton conversion, but this would increase to 1.57 million bales if 50% of irrigated corn was converted to cotton. If FR was then decreased to 0.50, lint production would be reduced to 1.10 million bales. Cotton lint production was greater in the Southern Texas High Plains even if all irrigated corn was converted to cotton in the Northern Texas High Plains.

DEFICIT IRRIGATION OF GRAIN CROPS

Corn, grain sorghum, and winter wheat are the major grain crops irrigated in the Texas High Plains. Only grain sorghum and winter wheat currently produce profitable yields under dryland or deficit irrigated conditions (Schneider and Howell, 1995; 1997; 2001; Colaizzi et al., 2004), whereas dryland corn will produce little or no grain yield (Schneider and Howell, 1998; Howell et al., 1997a). Grain sorghum was extensively irrigated in the Northern Texas High Plains during the 1960s, but has been increasingly converted to dryland (Musick et al., 1990), and irrigated area was only 29 percent of the total grain sorghum area by 2000 (Table 3).

Annual irrigation demand (Fig. 3a) and resulting total (irrigated plus dryland) grain production (Fig. 3b) for corn, grain sorghum, and all wheat were estimated for various FR in a manner similar to cotton (except FR for corn was not estimated below 0.50 due to its relative sensitivity to water shortages). Grain production for grain sorghum and winter wheat (Fig. 3b) was estimated based on two separate linear functions in order to account for a yield plateau sometimes observed around FR = 0.50 (Schneider and Howell, 1995; 1997; 2001; Colaizzi et al., 2004). Corn had a much greater potential for water savings compared with grain sorghum or winter wheat (Fig. 3a), but this came at the greatest expense in grain production (Fig. 3b). Efforts in improving water use efficiency of corn in conjunction with deficit irrigation will likely have the greatest impact in reducing Ogallala withdrawals, provided, of course, some level of farm profitability can be maintained. In the Northern Texas High Plains, these efforts will most likely fit into the agronomic, engineering, and managerial categories discussed by Howell (2001). Some examples include developing more drought-tolerant crop varieties, enhancing precipitation capture and reducing evaporative losses through tillage and residue management, adoption of irrigation systems with greater application efficiency and distribution uniformity, and demand-based irrigation management based on feedback systems (e.g., Peters and Evett, 2004).



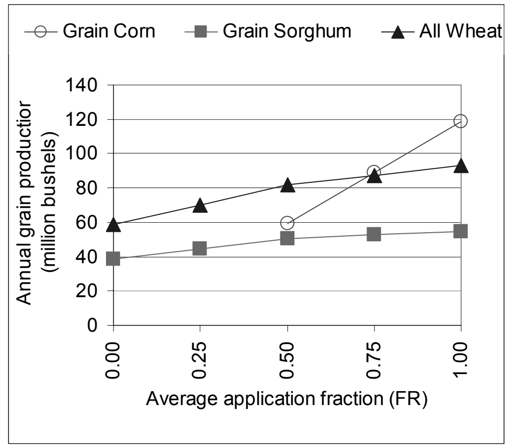


Figure 3. a) Estimated irrigation demand for varying FR of grain corn, grain sorghum, and all wheat; b) corresponding total (irrigated + dryland) grain production.

CONCLUSION

Irrigated agriculture continues to be a vital component of the economy in the Texas High Plains, but is faced with declining groundwater resources from the Ogallala Aquifer. As of 2000, about 4.6 million acres were irrigated in the 39-county area comprising the Northern and Southern Texas High Plains, with 6.5 million acre-feet of irrigation water being pumped according to Texas Water Development Board data. This was greater than 1989, when 4.0 million acres was irrigated with 4.5 million acre-feet of water, and likely due to intensifying drought during the 1990s. The proportion of gravity, sprinkler (mostly center pivot), and drip (mostly subsurface drip for row crops) was 72, 27, and less than 0.5 percent, respectively, with the vast majority of drip being in the Southern Texas High Plains where cotton is primarily produced. Most irrigation demand estimated in the Northern Texas High Plains was for grain corn (54 percent), followed by cotton (20 percent); in the Southern Texas High Plains, most demand was for cotton (74 percent), followed by peanuts (13 percent).

Conversion from corn to cotton in the Northern Texas High Plains, and deficit irrigation management of cotton in both the Northern and Southern Texas High Plains will likely have the greatest immediate impact in reducing Ogallala Aquifer withdrawals while maintaining acceptable economic returns. This is provided, of course, that international markets are favorable for U.S. cotton, and also that regulations are developed by local water districts to limit new irrigation expansion. Deficit irrigation management of corn could also have significant impact; however, corn is relatively sensitive to water stress, so deficit irrigation is not as feasible without improvements in water use efficiency through agronomic, engineering, and managerial efforts. The market for corn produced in the Texas High Plains is primarily fed cattle, which is expected to increase during the next decade and appears less volatile than cotton. Increased deficit irrigation management of grain sorghum and winter wheat will have the least impact in reducing irrigation water use because these crops are already produced mostly under dryland conditions, and the relatively small irrigated areas are seldom fully irrigated.

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