American Society of
Agricultural and Biological Engineers

An ASABE Section Meeting Presentation

Paper Number: RRV-07133

Crop Water Requirement for Major Crops in North Dakota and its Vicinity Area

Xinhua Jia, Thomas F. Scherer, and Dean D. Steele

Department of Agricultural and Biosystems Engineering, North Dakota State University, 1221 Albrecht Blvd., PO Box 5626, Fargo, ND 58105-5626.

Written for presentation at the
2007 ASABE/CSBE North Central Intersectional Conference
Sponsored by the Red River Valley Section of ASABE
North Dakota State University
Fargo, North Dakota, USA
October 12-13, 2007

Abstract. *North Dakota has a short growing season, high irrigation yield potential and climate conditions that vary from the east to the west. Accurate determination of crop water requirements for the different climate areas in the state is critical for irrigation scheduling, efficient water management and water permit management. Lack of recent research on water use by major crops in North Dakota along with significant changes in crop varieties requires an evaluation of existing crop water use models. For the last 15 years the irrigated crop area has been slowly increasing in the state, especially for high value crops. The major irrigated crops in North Dakota are corn, alfalfa, potato, sugarbeet, dry edible beans, small grains (wheat and barley) and soybean. Irrigation is scattered throughout the state with about 25 percent in the southeastern 5 counties, 25 percent in the center of the state and 15 percent in the northwestern part of the state. In the past, most of the research on crop water requirements was conducted in the southeast, and few in the east-central parts of the state and other regions. Actual crop evapotranspiration rates vary among crop types, varieties, growth stages, soil wetness, and climate conditions. This paper reviews past and current crop water use research for major irrigated crops in North Dakota and its vicinity area and provides information on future research needs.*

Keywords. Crop water requirement, corn, alfalfa, potato, sugarbeet, North Dakota.

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Introduction

Agriculture is the most important enterprise in North Dakota. Agricultural production continues to provide food and fiber for the nation as well as contributing to the nation's renewable energy portfolio. In 2006, North Dakota led the nation in the production of durum wheat, spring wheat, barley, flaxseed, dry edible beans, dry edible peas, lentils, sunflower, and canola, ranked second in the production of sugarbeet, and fourth for potatoes. In addition, soybeans and corn, and specialty crops such as safflower, rye, mustard, buckwheat, and millet are produced in the state. It is obvious that agricultural production in North Dakota is important for the nation and any positive yield changes will influence the food supply in the whole nation.

The majority of the agricultural crops in North Dakota (99%) are not irrigated, which implies that the crop varieties and agricultural practices have been adapted to the local natural weather conditions (precipitation and temperature) to ensure crop yield. Crop yield is not always guaranteed when dry conditions happen and crop yield is decreased due to limited soil moisture. Potato yield can be increased by 41-60 percent if irrigation is supplied to meet potential crop water requirement (USDA, 2007). However, installation of an irrigation system can be expensive. Energy costs and access to suitable water also limit irrigation development. Presently about 1 percent of the farmland in North Dakota (USDA, 2007) is irrigated. In 2007 corn was 44.6% of the total irrigated area in the state. Potatoes had 12.9%, forage and hay had 8.2%, and sugarbeet had 5.2% of the irrigated area. The top 4 irrigated crops according to its proportions (irrigated area/total area) are potatoes (34%), sugarbeet (5.3%), corn (4.6%), and alfalfa (3.2%) in 2007. These four crops probably have the greatest economic returns due to irrigation compared to other crops. Coon and Leistritz (2001) have reported that the potato industry in central North Dakota has been supported by 33 growers, who have contracts to grow about 15,000 acres (6070 ha) of irrigated potatoes. Each dollar spent in the production and processing of potatoes has generated $2.66 in the state economy.

Crop water requirement or evapotranspiration (ET) is defined as evaporation of water from land and water surfaces and transpiration by vegetation (Jensen et al., 1990). Evapotranspiration is important in water resources planning, efficient water management, and water permit management for both irrigated crops and dryland crops. Understanding crop water needs is important for optimal crop production by either meeting the crop water requirement or avoiding crop water stress during critical periods. Measurements of ET rates are difficult to obtain and in-situ measurements are time consuming and costly (Doorenbos and Pruitt, 1977). The ET rates vary among crop types, varieties, growth stages, soil wetness, and climate conditions.

The ET can be determined using direct and indirect methods. Direct ET measurement can be achieved by soil water depletion, lysimeter, water balance, energy balance, mass transfer, eddy correlation, combination of energy and heat, and mass transfer methods (Jensen et al., 1990). Normally, the actual crop ET (ET_c) is is determined indirectly, i.e., ET_c is estimated by relating a reference evapotranspiration (ET_r) to a crop coefficient (K_c). The relationship is represented by $ET_c = K_c \times ET_r$ (Doorenbos and Pruitt, 1977).

Reference evapotranspiration is defined as the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation (ASCE-EWRI, 2005). The ET_r can be calculated from weather data collected near a well-watered reference crop surface by automated weather stations. Many methods have been developed to estimate the ET_r. These methods can be categorized into four basic groups: combination, radiation, temperature, and pan evaporation methods. The combination methods were first derived in 1948 by Penman, who accounted for radiation (energy balance) and aerodynamic (heat and mass transfer) terms. The Penman equation was then modified or improved as the FAO Penman (Doorenbos and Pruitt, 1977), the Kimberly Penman (Wright, 1982), the Penman-Monteith (Allen et al., 1994), the FAO Penman-Monteith (Allen et al., 1998) and the ASCE-EWRI (ASCE-EWRI, 2005) equations. Radiation based ET_r equations include the Priestley-Taylor (Priestley and Taylor, 1972) and FAO radiation methods (Doorenbos and Pruitt, 1977). Temperature based ET_r equations include the Thornthwaite (Thornthwaite, 1948), Jensen-Haise (Jensen and Haise, 1963), FAO Blaney-Criddle (Doorenbos and Pruitt, 1977), and Hargreaves (Hargreaves and Samani, 1982). FAO class-A Pan (Doorenbos and Pruitt, 1977) and Christiansen Pan (Christiansen, 1968) methods are classified as evaporation methods. While the availability of reliable weather data is limited, temperature methods are applicable to provide reasonable ET_r estimates, however, comparing all the methods, the most current method, which was developed by the American Society of Civil Engineers, Environmental and Water Resources Institute (ASCE-EWRI; ASCE-EWRI, 2005), was the most accurate method (Itenfisu et al., 2003; Temesgen et al., 2005). Application of this method requires solar radiation, air temperature, relative humidity and wind speed as the input parameters.

The reference surface can be either a tall crop similar to a full-cover alfalfa or a short crop similar to a clipped, cool-season grass. The data collected from automated weather stations located on the reference surface can be used to calculate the reference ET rate. The ET_r represents the climatic conditions in the specified region. The single crop coefficient represents the crop characteristic due to crop resistance to transpiration. However, the crop coefficient is the most difficult parameter to estimate. Snyder and O'Connell (2007) summarized the difficulties in estimating K_c as caused by (1) the ET_c and the ET_r methods being used to calculate the K_c; (2) whether the soil water deficient has been considered; (3) quality of the ground cover; (4) growth stage; (5) soil properties (water table, drainage, etc.); and (6) irrigation methods. Use of K_c values requires knowledge of the conditions that the K_c values were developed, including the ET_c and ET_r methods, the crop type and variety, and the location. In addition, year to year differences may result from variable weather conditions. Therefore, it is desirable to obtain multiple years of data to ensure robust K_c values.

In North Dakota, direct crop water use has been measured using the soil water balance approach in the root zone or by measuring the crop water stress index (Lundstrom and Stegman, 1977; Stegman et al., 1976; Stegman, 1982; Stegman; 1986; Stegman et al., 1990; Steele et al., 1997). When crops are under stress during the flowering period, crop yield could be significantly reduced (Stegman, 1982; Stegman 1989). Most of the irrigation studies in North Dakota were conducted in the Oakes area, in the southeast corner of the state (Stegman, 1982; Steele et al., 1994; Steele et al., 1997). A few research projects have been carried out in the central and northwest regions of the state (Stegman et al., 1990; Rosenberry and Winter, 1997; Frank and Karn, 2003; Gerla, 2004). Irrigation is scattered throughout the state with about 25% in the southeastern 5 counties, 25% in the center of the state, and 15% in the northwestern part of the state. In this paper, crop water use estimates determined through the indirect method were examined, which is through the determination of evapotranspiration, reference crop evapotranspiration and crop coefficient curves. Crop evapotranspiration for the four major irrigated crops, potato, corn, sugarbeet, and alfalfa in North Dakota, will be reviewed. Comparison of different ET_c and ET_r methods for the crops are presented and recommendations for future ET research needs will be made.

Comparison of ET_r methods

In North Dakota, most of the crop coefficient curves used the Jensen-Haise (JH) reference ET equation, which uses temperature and incoming radiation data only for the calculation. Comparison among the JH equation with the later ASCE-EWRI grass and alfalfa equation, as well as the ET_r from the North Dakota Agricultural Weather Network (NDAWN; Enz, 1997), which is an alfalfa based Penman-Monteith equation, was made using the weather data downloaded from the Oakes Station in 2006. The results are shown in Figure 1.

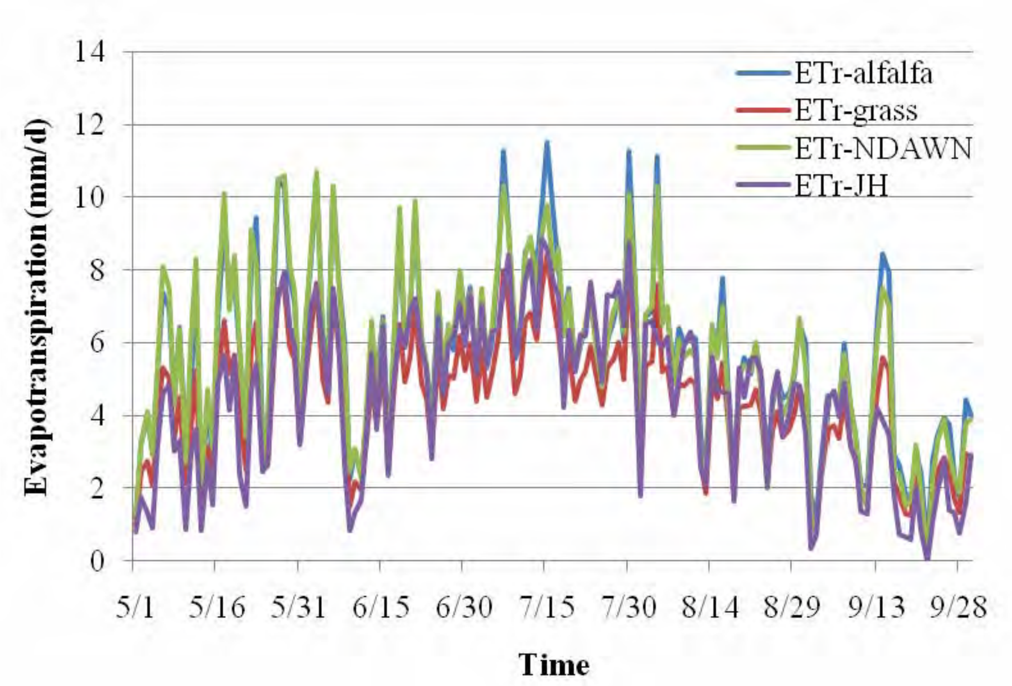

Figure 1. Comparison of reference evapotranspiration methods at Oakes, ND from May 1 to September 30 in 2006.

The seasonal ET_r in the growing season from May 1 to September 30 was 867, 664, 856, and 688 mm for ETr-alfalfa, ETr-grass, ETr-NDAWN, and ETr-JH, respectively. The major ET_r difference among the different methods is between the alfalfa and grass based ET_r. Even though the JH reference ET was developed using data collected from different crops, such as alfalfa, cotton, oats, and winter wheat, its value is close to the ASCE EWRI Penman-Monteith grass based ET_r method (664 mm vs. 688 mm for ETr-grass and ETr-JH, respectively). If plotting the alfalfa based ET_r versus the grass based ET_r (Figure 2), the difference is 30-31%, though these two methods are strongly related. The alfalfa based ET_r, either by the ASCE-EWRI or NDAWN, is higher than the grass based ET_r. Therefore, when applying the grass based crops coefficient curves using the current NDAWN alfalfa based ET_r, a 30% difference is expected.

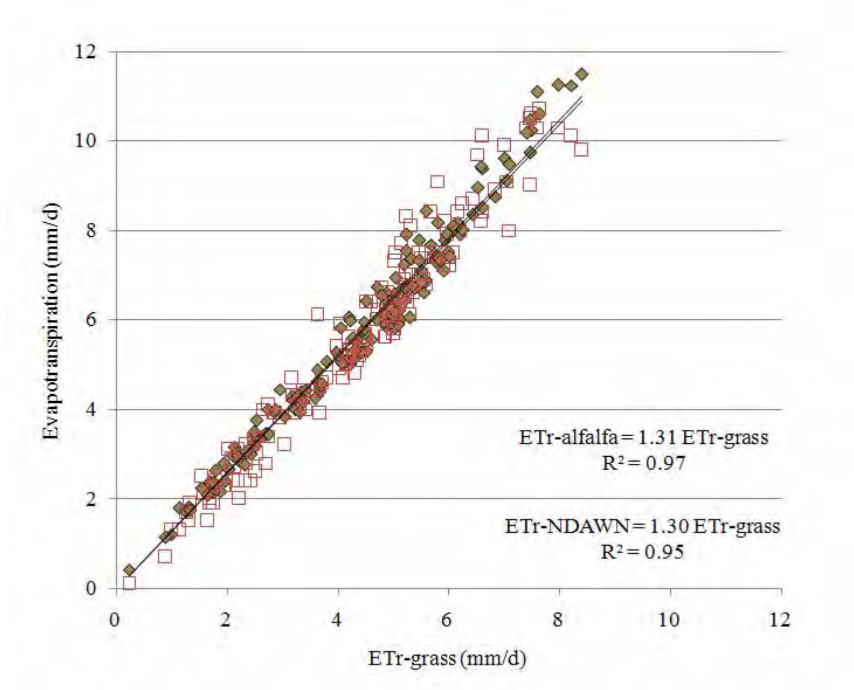

Figure 2. Reference ET of alfalfa versus grass at Oakes, ND from May 1 to September 30 in 2006.

Stegman et al. (1977) developed six crop coefficient curves (sugarbeets, corn, spring wheat, soybean, potatoes, and alfalfa) for southeast North Dakota using the Jensen-Haise equation for ET_r. The ET_c values were obtained from small plot studies near Oakes, ND, though the soils at each plot might have been different. The data for each crop were lumped over all soil types from which ET_c data were obtained. The crop water use was obtained by soil water balance with soil moisture data measured by neutron probe on a weekly schedule. The measurement was made prior to or 2-3 days after irrigation, which implies that the data were collected from field capacity to the dry end of the soil moisture curve. Data from periods of excessive rainfall or irrigation were deleted. According to the K_c concept in FAO 56 (Allen et al., 1998), the ET_c during this period corresponded to the basal crop coefficient (K_{cb}) values in the dual K_c approach. If considering soil water evaporation, the K_c should be higher than the K_{cb}. Irrigation was supplied by center pivot systems. Rainfall and irrigation amounts were measured by catch cans. Weather data were obtained from a station at the Oakes research site. Crop cover and phenology were noted visually and recorded by photographing the ET sampling sites on dates of soil water measurements. The K_c curves were plotted as functions of “Days Past Emergence”.

It should be noted that Oakes is located at the southeastern corner of the state and it is helpful to compare ET values at Oakes to those from a location in the western part of the state. Figures 3 and 4 show the monthly totals of ET_r (ETr-NDAWN) and rainfall amounts at Dickinson and Oakes stations: Dickinson is in the south central part of the state. Data are average values from 2002 to 2006 and were obtained from the North Dakota Agricultural Weather Network. During the major growing season (from May 1 to Sept. 30) of the five years, the Oakes station has 160 mm less ET_r, but 151 mm more rainfall.

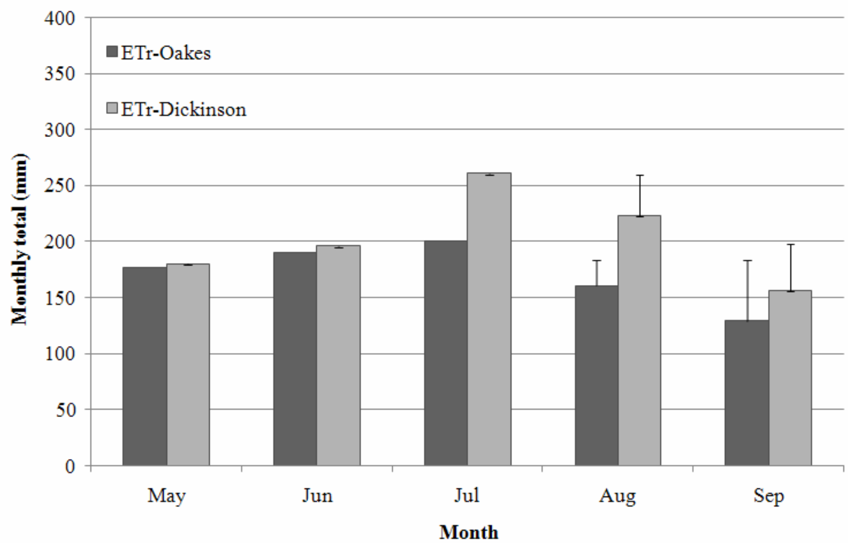

Figure 3. Comparison of monthly ET_r in the growing season from 2002 to 2006 at Oakes and Dickinson, ND.

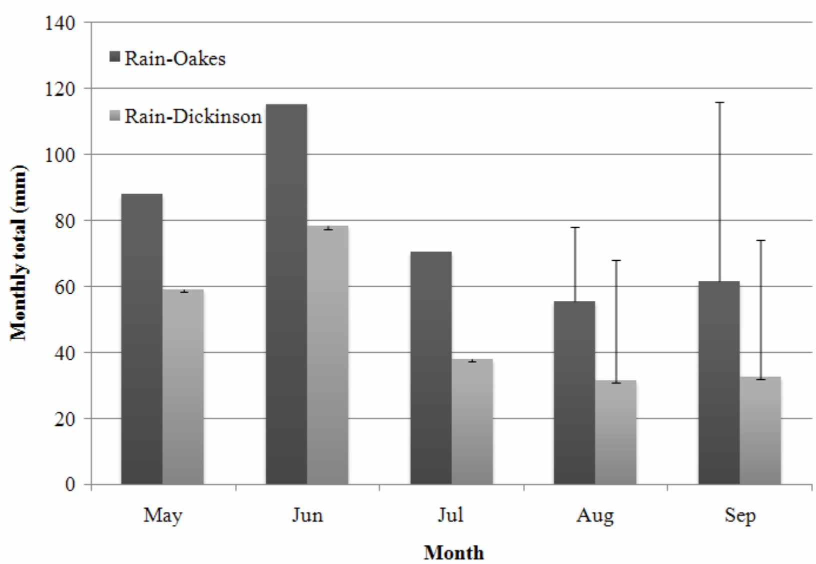

Figure 4. Comparison of monthly rainfall in the growing season from 2002 to 2006 at Oakes and Dickinson, ND.

Corn

In US, corn is the second largest consumer of irrigation water (first is alfalfa hay). In many places, corn could not be grown without irrigation. In North Dakota, corn is planted in most counties, but the largest planted and harvested area is in the southeast corner of the state (570,000 acres, 41%) (USDA, 2007). Table 1 lists the corn harvested and irrigated areas and yield for different areas of the state (USDA, 2007).

Table 1. Comparison of all and irrigated areas and yields for corn in different areas of North

Dakota in 2006

Area	All area harvested (Ac)[1]	Irrigated area harvested (Ac)	Irrigated/All	All yield (Bu/Ac)[2]	Irrigated yield (Bu/Ac)	Increase
Northwest	10,000	1,000	10.0%	77.0	115.0	33.0%
North Central	59,500	3,600	6.0%	80.3	136.1	41.0%
Northeast	135,000	3,500	2.6%	89.5	132.9	32.7%
West Central	35,000	5,000	14.3%	74.0	169.0	56.2%
Central	148,000	9,000	6.1%	92.8	158.9	41.6%
East Central	385,000	10,200	2.6%	116.1	157.8	26.4%
Southwest	265,000			41.5		
South Central	31,000	5,300	17.1%	47.4	100.9	53.0%
Southeast	570,000	36,200	6.4%	130.1	172.1	24.4%
State Total	**1,400,000**	**73,800**	**5.3%**	**111.0**	**158.8**	**30.1%**

1 1 Acre = 0.4 hectare

2 1 Bu/Ac = 63 kg/ha

In 2006, of the total harvested 1.4 million acres (0.57 million ha) of corn for grain in state, 73,800 acres (29866 ha) (5.27%) were irrigated. The irrigated corn areas were scattered in almost all regions, however, 49% of the irrigated corn was in the southeast region. On average, the irrigated corn yield was at least 30% higher than for the dryland corn (in Table 1, all yields include the yields for irrigated corn). The greatest yield increases due to irrigation were seen in the west and south central parts of the state, possibly due to less precipitation amounts and lower water holding capacity soils in these regions. Looking at the corn yield in 2006, irrigation can increase the corn yield by 56% for the west central and 53% for the south central areas, but only 24% for the southeast where the Oakes station is located.

Stegman et al. (1977) stated that when the ground cover is incomplete during the early growing season, the K_c value for corn is only about 0.2, but the peak K_c was about 1.1. If weather data were available, the ET_r calculated by Penman method exceeded the Jensen-Haise estimates by an average 10.5%. Steele et al. (1996) developed four mean fifth order polynomial K_c curves based on 11 years of data collected at Oakes, in southeastern North Dakota. The actual ET_c was measured by four non-weighing lysimeters. The change of soil moisture content was measured by neutron probe on a weekly schedule. The ET_r was calculated by Jensen-Haise (Jensen and Haise, 1963) and Penman-Allen (Allen, 1986) methods. The K_c curves were developed based on days after planting (DPP) and cumulative growing degree days after planting (CGDD). Large seasonal K_c changes were observed between the different ET_r methods. The K_c based on DPP was more accurate than the CGDD method, which implies that K_c was strongly related to the solar energy received at the surface. However, none of the polynomial K_c curves have a high correlation coefficient (R^2), indicating unexplained sources of variations. Caution should be exercised when using these crop curves. Steele et al. (1997) further stated that none of the crop curves should be used for irrigation scheduling without in-season soil moisture content correction at least on a monthly basis, because the estimated ET_c by these curves is overestimated. In FAO 56, corn basal crop coefficients are 0.15, 1.15, and 0.5 for initial, mid, and end (harvest) periods in the corn growing season, respectively in sub humid climates (Allen et al., 1998). Comparison of corn crop coefficients using Stegman et al. (1977), Steele et al. (1996) and Allen et al. (1998) are shown in Figure 5.

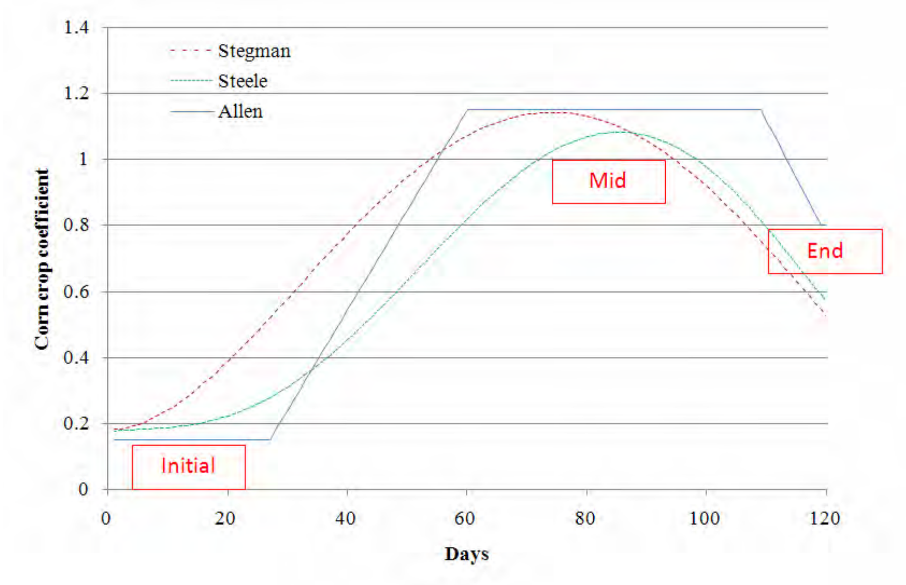

Figure 5. Comparison of corn crop coefficients

Figure 5 shows that the K_c by Steele et al. (1996) was delayed about 10 days from Stegman's K_c curve, but the time lag is largely accounted for by the fact that Stegman's curve was based on days past emergence while Steele's curve was based on days past planting. The lower peak value on Steele et al.'s curve compared with Stegman's curve is attributed the method of determining deep percolation as part of the respective one-dimensional water balances. Steele et al. (1996) used nonweighing lysimeter measurements of deep percolation (DP), whereas Stegman et al. (1977) did not have lysimeters and assumed deep percolation amounts were zero for the time periods selected to determine the K_c points. The effect of this assumption can be seen from the water balance equation

$$\text{Inflow} - \text{Outflow} = \text{Change in Storage}$$

or

$$R + I - ET - DP = (S_2 - S_1)$$

where R is rain (L), I is irrigation (L), and S_i is soil moisture (L). Solving for ET gives

$$ET = R + I - DP - (S_2 - S_1)$$

It can be seen that if DP is assumed to be zero when it is not, ET would tend to be overestimated and the result is that Stegman's K_c curve has a higher peak K_c value than Steele's curve.

If using these three curves and the same ET_r equation, the resulting ET_c values would be 518, 426, and 499 mm for Stegman, Steele, and Allen, respectively. However, if using a different ET_r equation, the difference could be up to 117 mm difference between the alfalfa and the grass based equations.

Alfalfa

The top ten counties growing alfalfa for hay are Dunn, Stutsman, Kidder, McHenry, McKenzie, Stark, Williams, Morton, Bowman, and Burleigh. All of them are located in the south central to southwest part of the state (Figure 6), where precipitation is much less than the ET_r (Figures 3 and 4). Alfalfa yields can be significantly increased for these production areas if sufficient water can be supplied. However, the irrigation water availability is normally limited.

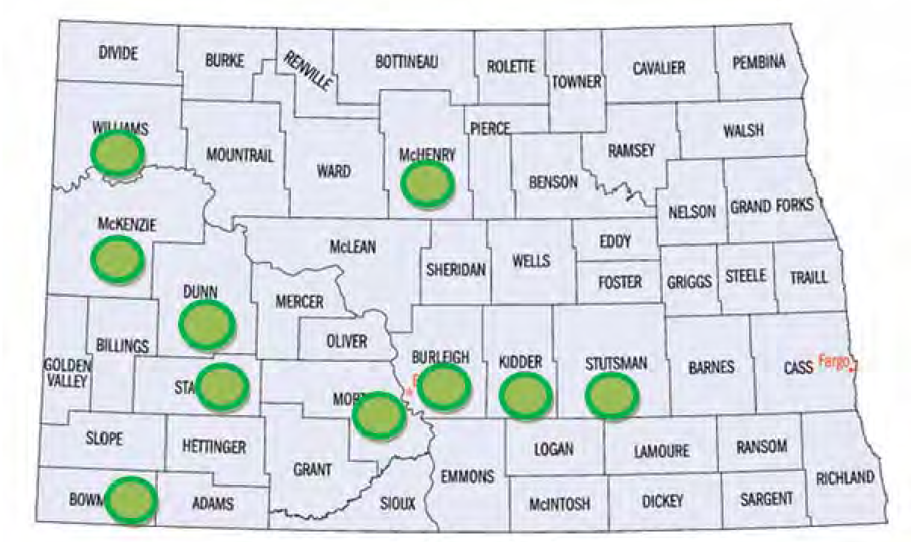

Figure 6. Locations of top ten counties (green dots) with irrigated alfalfa for hay in North Dakota, 2006 (modified from USDA, 2007).

Stegman et al. (1977) developed alfalfa crop curves as functions of "Days After May 1". After the alfalfa is cut the K_c typically fell about 0.4 and then increases again to the level of the curve in 21 days with a peak K_c at 1.1. Benli et al. (2006) measured the basal crop coefficient of alfalfa with a weighing lysimeter at Ankara Research Institute of Rural Services, Turkey during 1995-1997. The reference ET_r was calculated from Penman-Monteith, Modified Penman, FAO-radiation, Hargreaves and pan evaporation methods. All cutting periods values during the three years were lumped together and a fitting curve between K_{cb} and the growth stage was obtained. The estimated basal crop coefficients after an individual cutting period were 0.71, 1.78, and 1.51 for initial, mid and late season, respectively. These values were higher, probably because the station is located in a semi-arid area. The FAO 56 calculated K_{cb} (Allen et al., 1998) for sub-humid climates, are 0.3, 1.15, and 1.10 immediately following cutting, at full cover, and immediately before cutting, respectively. However, these values were developed for moderate climate condition with moderate relative humidity and mild wind speed (RH_{min}=45% and U_2 = 2 m/s), while for most of the locations in North Dakota, a much higher wind speed and lower relative humidity might be expected. Therefore, the K_{cb} should be adjusted locally prior to use.

Sugarbeet

The FAO 56 calculated K_{cb} for sugarbeet (Allen et al., 1998) for sub-humid climates, are 1.15 and 0.5 for mid and end growing stage. Stegman et al. (1977) developed polynomial coefficients for sugarbeet curves, using a similar procedure as described for corn crop coefficients. The resulting equation is crop coefficient vs. days post emergence for southeast North Dakota. The peak K_c value was 1.1 after full canopy cover was achieved. Similarly, the ET_c was determined using the soil water balance method and the ET_r by the Jensen-Haise equation. A linear relation was obtained between fresh root yield and seasonal ET accumulation by Stegman and Bauer (1977). The production response averaged 1.5 t/ha/cm of water use for a three year period. A 54 T/ha yield was obtained with a seasonal ET_c of 560 mm when the minimal ET exceeded 200 mm. Both sugarbeet ET research projects were done at the Oakes research site in the southeastern part of the state. About 94% of the harvested sugarbeet area is located near the eastern border of the state, along the Red River. The northeast counties are the leading sugarbeet producers in the state. In the eastern part of the state, sugarbeets do not have to be irrigated. However, irrigation is needed in the western part of the state.

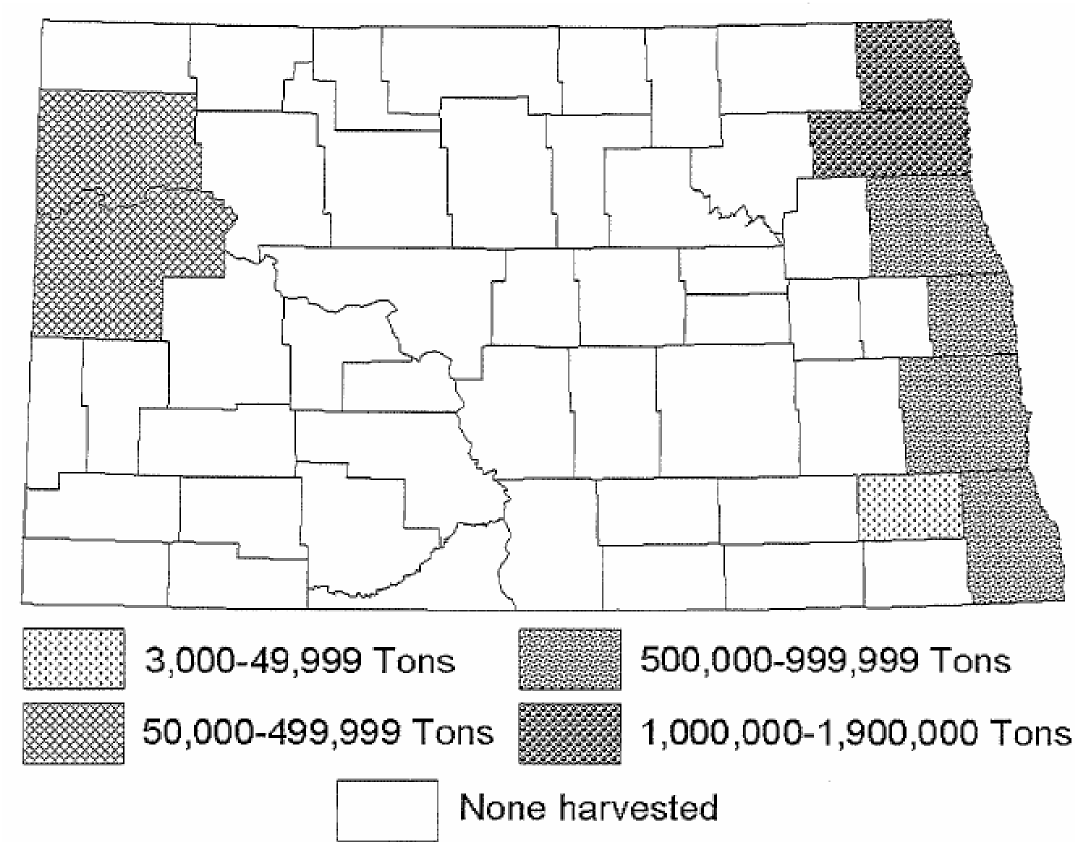

Figure 7. Sugarbeet production in North Dakota, 2006 (NDSU, 2007).

Potato

In proportion to total harvested area, potatoes have the largest percentage of irrigated acres. Except in the northeast region, potatoes in most areas of the state were irrigated. However, the northeast region has planted more than 70 percent of the potatoes in the state (70,000 acres of the total 98,000 acres in 2006) but this includes irrigated areas. The statewide average irrigated potato yield of 413 cwt/ac is 89% larger than the average yield (irrigated and nonirrigated) of 218 cwt/ac (1 cwt/ac = 112 kg/ha)

The FAO 56 reported K_c values for potatoes are 1.15 and 0.75 for reproductive and maturity stages, respectively (Allen et al., 1998). Kashyap and Panda (2001) conducted an experiment in a sub-humid area of India for the development of potato crop coefficients. A weighing lysimeter was used for the actual potato ET_c measurement. Ten ET_r methods were evaluated using weather data from a grass surface comparing the ET_r from a grass surface from a weighing lysimeter. Most of the combination methods performed better than all others. Using the Penman-Monteith method (Allen et al., 1998) for ET_r, the crop coefficients for potatoes at different stages were 0.42, 0.85, 1.27, and 0.57 for initial, crop development, reproductive and maturity stages, respectively. These values are similar to the FAO 56 values, except during the reproductive stage.

Sahin et al. (2007) determined crop coefficients for sugarbeet and potato under cool season semiarid climate in Turkey. From May to October in 2003 and 2004, ET_c was measured by the water balance approach, and the ET_r by FAO Penman-Monteith. Seasonal ET_c was 493 mm for sugarbeet and 445 mm for potato. The seasonal crop coefficient was 0.65 for sugarbeet, and 0.60 for potato. These values are much lower than the reported values by Stegman et al. (1977) and Allen et al. (1998).

Conclusion

Based on the review of crop water requirement of major crops in North Dakota, there are still research needs to determine crop water requirement for major crops and evaluation of crop ET using current methods.

Future research needs

- More crops are switched to irrigation systems, but not all the crops, or at least the most important or impact crops, have been studied for their water requirement during the growing season.
- Several studies have been carried out in the past, however, the methodologies used to calculate the ET_c and ET_r are different and they should be evaluated to be compatible with other methods.
- North Dakota's soil and water conditions are different from other regions and local research is needed to support the rapidly changing emphasis of crops grown, particularly the switch to higher value crops. In order to maintain the ND crop land more productive and sustainable, the crops should be managed in a way to use the water more efficiently.

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