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Spatial Mapping of Evapotranspiration Over Devils Lake Basin with SEBAL: Application to Flood Mitigation via Irrigation of Agricultural Crops

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Abstract

Excessive precipitation since 1993 has produced extensive flooding in the Devils Lake basin in northeastern North Dakota, USA. Irrigation of agricultural crops has been proposed as a flood mitigation tool. Ten test fields were equipped with center pivot irrigation systems to compare test field evapotranspiration (ET) with ET for crops in the predominantly-nonirrigated basin. An irrigation scheduling analysis indicated 2006 was a favorable year to estimate the maximum ET gains achievable via irrigation. An ET map for 2006 using the Surface Energy Balance Algorithm for Land (SEBAL) for 54% of the basin, and land use and soil survey data, were used to compare ET estimates at the test fields with ET estimates across the study area. May-Sept ET was estimated by SEBAL as 394 mm for wheat and 435 mm for corn across the study area, while corn ET at irrigated test sites was 452 mm. Because the 17-mm ET advantage by irrigating corn was substantially smaller than the 41-mm ET advantage for corn vs. wheat, we conclude widespread irrigation development to mitigate flooding is not justified. Coarse textured soils exhibited some seasonal ET deficits, but their small areal extents and parcel sizes offer virtually no opportunity for flood mitigation.

Introduction

The Devils Lake Basin in northeastern North Dakota, USA, encompasses an area of approximately 9480 km^2 and is a sub basin of the Red River of the North. The basin has experienced excessive precipitation since 1993, resulting in flooding, inundation of farmland and roads, and damage to infrastructure. From 1993 to June 2011, Devils Lake rose 9.7 m and increased in surface area by approximately 676 km^2 [North Dakota State Water Commission (ND SWC) 2013]. Approaches to alleviate the flooding have included pumped and controlled outlets to the Sheyenne River (ND State Water Commission 2012), protection of roads and infrastructure, and upper-basin water management and storage (ND State Water Commission 2011). Irrigation of agricultural crops has also been proposed as a method to remove water from the basin. The underlying hypothesis of the irrigation approach is that irrigated crops transpire more water than nonirrigated crops and, therefore, extensive development of irrigation in the basin would increase the rate of water removal.

Historically, the irrigated area in the basin has been relatively small, peaking during the 1977 through 2011 period in 1997 at 1630 ha (M. Hove, ND SWC, 2012 personal correspondence). The predominant, generalized soil map units, based on the State Soil Geographic database (STATSGO; Soil Survey Staff 2006) in the Devils Lake basin and their irrigation suitability classes indicate that over 80% of the soils are classified as conditionally-irrigable or nonirrigable. Limiting physical and chemical factors include the need for internal drainage, slow intake rates, and the potential for salinity accumulations (USDA-SCS 1982; Steele 2007). Most of this area is characterized by the Hamerly soil series, a somewhat poorly-drained soil influenced by shallow groundwater. Extensive development of irrigation in the basin on soils such as Hamerly would require subsurface drainage. In fact, less than 1% of the basin (0.7%) is overlain by soils that are commonly irrigated in North Dakota; these include the Arvilla, Embden, Hecla, Heimdal, Maddock, and Renshaw soil series (Steele and Hopkins 2009). Notwithstanding these constraints, the pressing economic hardships induced by prolonged, widespread flooding in the basin prompted the Devils Lake Basin Joint Water Resource Board (hereinafter referred to as the "Joint Board") to coordinate investigations of whether irrigation could alleviate basin flooding.

In order to assess and quantify the potential that irrigation might hold for mitigating flooding, comparisons of evapotranspiration (ET) measurements or estimates are required for a variety of crops and soils across the basin under irrigated and nonirrigated conditions. Bartlett and West (2002) compared ET estimates in the Devils Lake basin using a one-dimensional, daily, point-based water balance of the root zone for selected clusters of field sites in the basin. They used 1992-2001 weather data, the Jensen and Haise (1963) reference ET method, ET crop coefficient curves developed by Stegman et al. (1977) and Stegman and Coe (1984), county soil surveys and irrigation soil-water compatibility recommendations (Franzen et al. 1996), available soil water (AW) data from USDA-SCS (1982), and a procedure to limit estimated ET when available soil water (AW) decreased below 50% (Stegman and Coe 1984). They estimated ET for alfalfa, barley, edible bean, corn, sugar beet, soybean, wheat, sunflower, and potato under irrigated and nonirrigated scenarios. Bartlett and West (2002) estimated a 248-mm per year total utilization gain, partitioned as approximately 137 mm in ET, 48 mm in irrigation system inefficiencies (assumed to be predominantly evaporative and wind losses from sprinkler irrigation), 25 mm in post-season evaporation of water from the soil surface, and 38 mm in post-season soil water storage. Limitations of the one-dimensional water balance model included inability to consider contributions to ET from shallow groundwater and variations in ET over large areas.

Alternative ET measurement techniques overcome various constraints presented by point-based water balance techniques; these techniques also have limitations. For example, shallow water table contributions to ET have been estimated by frequent measurements of soil moisture and water table levels (Nachabe et al. 2005), but the area represented is essentially a point measurement and furthermore, a replenishing source of water is needed and thus this approach may not be applicable to large tracts of land with slowly-permeable soils. Eddy covariance and Bowen ratio methods (Monteith and Unsworth 1990; Farahani et al. 2007) provide measures of ET with footprints extending from tens to hundreds of square meters providing information on more area than point measurements; however, these systems are very expensive and labor-intensive and they are unable to estimate ET over large areas on the scale of many square kilometers.

The Surface Energy Balance Algorithm for Land (SEBAL) model developed by Bastiaanssen et al. (1998a; 1998b; and 2005) offers advantages compared to the generally accepted crop coefficient method in which crop ET is estimated by computing reference ET from meteorological data and multiplying the result by ET crop coefficients (K_c). SEBAL's advantages include: 1) it overcomes the point- or field-scale limitations of methods described previously, 2) information on crop type, cropping patterns, and irrigated or nonirrigated conditions are not needed to solve the energy balance equation; and 3) SEBAL computes actual ET (ET_a), inherently accounting for effects of soil spatial variability, salinity, contributions to ET from shallow groundwater, drought or water-logged soil conditions, disease, poor plant stands, and other factors affecting ET_a under field conditions. Including these factors in the standard K_c x ET_o computation requires considerable additional data (typically unavailable) as well as substantial time and effort. Evapotranspiration mapping is commonly used in the context of water conservation studies and is being applied to water resource management by various state agencies (Allen et al. 2005; Kramber et al. 2010). Various SEBAL validation studies have shown that the accuracy of cumulative ET_a estimates increases as additional images are processed, with seasonal ET_a totals typically agreeing within 5% of reliable, independent ground-based estimates (Bastiaanssen et al. 2005).

The Devils Lake Basin Water Utilization Test Project (henceforth referred to as the "Test Project"; Steele and Hopkins 2009) was conducted to determine whether irrigation of agricultural crops might be recommended as a flood mitigation tool while providing an economic benefit. The primary objectives of the Test Project were to: 1) determine how much additional water from surface water bodies in the Devils Lake basin can be consumed via sprinkler irrigation at selected sites, 2) evaluate the effects of irrigation on representative soil map units within the basin, and 3) extrapolate the results from the test project to the broader basin. This paper focuses on the first objective and describes the use of field experiments and ET mapping to quantify the additional ET which might be achieved by applying irrigation water to agricultural crops in the basin. It is important to note that this paper describes the innovative use of SEBAL to evaluate a potential solution for flooding in the Devils Lake basin and is not about advances in the SEBAL methodology. Comparisons of ET for irrigated and nonirrigated crops are intended to provide informed engineering and science to policy- and decision-makers regarding the prudence of widespread irrigation development as a flood mitigation tool. Specifically, if the ET comparisons find significant gains in ET via irrigation, then expenditure of public and private money to develop additional irrigation in the basin might be warranted. On the other hand, if the ET comparisons find no real flood mitigation value in irrigation development, this study could help avoid the fruitless expenditure of significant sums of money.

Materials and methods

Test Project Plan to Compare Irrigated vs. Nonirrigated Crop ET

The Joint Board solicited farmer participation in the Test Project and contracted High Plains Consortium, Inc. of Bismarck, ND, in 2005 to prioritize the 35 to 40 cooperator applications received by the Joint Board. Selection of ten final field sites was based upon representative soils, distance to water supply, and inclusion of soils recognized as marginal (saline and sodic conditions) for irrigation development. In this paper, a "Site" represents a field (e.g., a typical, square, 65-ha land parcel (160 acres or a "quarter section" land parcel in US land survey conventions) and a "Station" represents a monitoring location within a Site. Site numbering reflects the original numbering of applications for participation in the project; to avoid confusion, sites were not renumbered. Twenty-five field monitoring stations were distributed across the ten field sites in the project. The number of Stations per Site ranged from one to four. In addition to equipment to monitor rainfall and irrigation, soil moisture, and deep percolation at each Station, eighteen groundwater monitoring wells were installed at selected Stations, with a minimum of one well at each Site.

Installation of subsurface drainage systems and irrigation in excess of crop water requirements are often recommended for leaching of salts from the root zone, particularly in arid environments (Fangmeier et al. 2006). In North Dakota, off-season precipitation is generally considered sufficient to meet the leaching requirement and leaching practices have not been adopted. Installation of subsurface drainage systems was unacceptable to the project sponsors because of the potential for additional lower basin flooding.

Weather records indicate the 2006 season was one of the most favorable amongst recent years in terms of the potential for irrigation and increased ET compared with non-irrigated conditions. This was quantified by conducting irrigation scheduling simulations for alfalfa using water use tables (Lundstrom and Stegman 1988), an irrigation scheduling spreadsheet (Steele et al. 2010), and seasonal (30 April through 30 Sept) weather data for 1995 through 2008 from the North Dakota Agricultural Weather Network (abbreviated "NDAWN"; North Dakota Agricultural Weather Network Center 2010) station at Cando, ND (Lat 48.471°, Long -99.166 °, elevation 453 m), a site centrally located within the study area. Assumptions included a loam soil at field capacity on 30 April each season, 25-mm irrigation events whenever the soil moisture deficit (SMD) exceeded 50% [to avoid ET reductions attributable to soil water (drought) stress (Stegman and Coe 1984)], no in-season adjustments to SMD estimates, and no groundwater contributions to ET. Fully-transpiring alfalfa was simulated by artificially setting cut (harvest) dates to the end of the season; the ET tables and algorithms estimate reduced ET as the crop regrows after each harvest. Results of the weather analysis (Figure 1) indicate that the 2006 growing season had the highest estimated alfalfa ET, the lowest rainfall, and the largest seasonal irrigation requirement. It is important to note that the purpose of this weather analysis was to confirm that 2006 was the best season for the SEBAL analysis, not to revisit the ET simulations of Bartlett and West (2002).

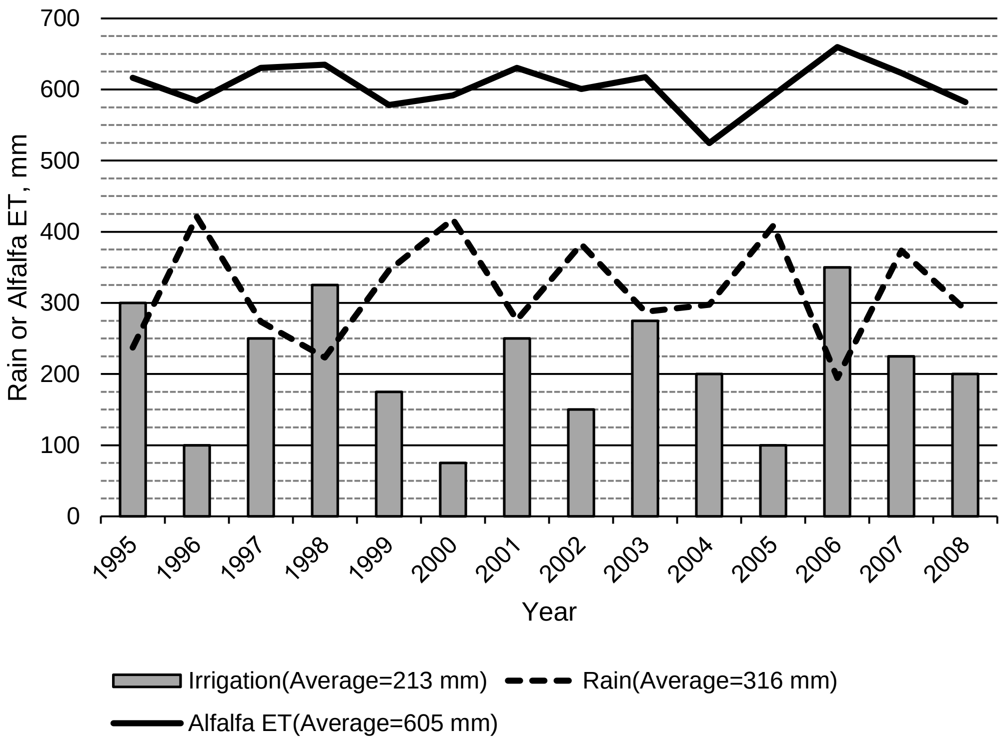

Figure 1. Rainfall, alfalfa ET, and irrigation requirements estimated for 1995 through 2008. Estimates are based on NDAWN weather data from Cando, ND.

Crops grown at the test sites in 2006, characteristics of the center pivot irrigation systems, and irrigation depth equivalents applied in 2006 are summarized in Table 1. All of the irrigation systems were designed to deliver 379 kPa water pressure at the pivot point and all systems could make a full revolution around the field in 8.9 hours or less. The operating pressures place the machines in "medium pressure" (210-415 kPa) rather than the "low pressure" (100-210 kPa) category of sprinkler irrigation systems category (Fangmeier et al. 2006). The higher pressure was intended to increase droplet and canopy evaporation possibilities for water disposal into the atmosphere and subsequent removal from the basin; however, quantification of droplet and canopy evaporation amounts was beyond the scope of this study. The relatively high-speed capabilities of the machines maximized the operators' ability to reposition them without irrigation for irregular crop or soil configurations.

Table 1. Crops, irrigation system characteristics, and irrigation applied in 2006 at the ten Test Project sites.

Site	Crop(s) in 2006	Field Portion[1]	Emergence Date[2]	Irrigation System Length[3], m	Irrigated Area[4], ha	Irrigation System Application Rate[3], mm d^{-1}	Irrigation[5] Applied in 2006, mm
1	Corn	All	20-May	328.3	33.9	8.6	258
2A	Corn	All	19-May	263.5	21.8	8.9	120
6	Corn	All	14-May	383.2	46.1	8.4	253
7	Corn	N	21-May	395.5	49.1	8.9	249
7	Soybean	S	15-Jun				
12	Corn	All	26-May	395.4	49.1	8.9	254
13	Potato	NW	24-May	395.4	49.1	6.6	136
13	Soybean	NE	12-Jun				
13	Wheat	S	15-Jun				
18	Corn	W	27-May	348.8	38.2	8.9	95
18	Soybean	E	8-Jun				
20	Alfalfa	All	1-May	364.8	41.8	8.6	201
35	Sunflower	NW, SW, most of SE	21-Jun	151.9	7.3	9.7	140
35	Specialty crops, e.g., squash, cabbage	NE, some in SE	(Unknown)				
36	(No Crop)	All	--	184.2	5.3	6.6	104

[1] Abbreviations: N = north, S = south, E = east, W = west, NE = northeast, etc.

[2] Emergence dates based on site operators' estimates. Alfalfa green-up date assumed 1 May to maximize water use estimates in the irrigation scheduling model.

[3] Data on irrigation system characteristics obtained from Bartlett and West Engineers, Bismarck, ND.

[4] Due to a field boundary, only a semicircle was irrigated at Site 36.

[5] Irrigation amounts are based on irrigation system flow meter readings and are expressed as rainfall depth equivalents (volume per unit area). Pumped volume at Sites 7 and 18 included water applied to the entire field at each site, i.e., volumes were not determined for different crops on each half of the field. Across all sites, a composite value of 199 mm was computed as the total volume of water pumped for all sites divided by total area irrigated. Flow meter data sources included NDSU Agricultural and Biosystems Engineering Department staff, information from site operators, and annual water use reports submitted to the ND State Water Commission.

Irrigation scheduling recommendations were developed by North Dakota State University (NDSU) personnel and forwarded to site operators weekly throughout each growing season. The recommendations consisted of ET estimates based on the "Checkbook" method of Lundstrom and Stegman (1988). The Checkbook method uses ET lookup tables (based on daily maximum temperatures and weeks past crop emergence) in a one-dimensional soil water balance to estimate the soil water deficit for irrigation scheduling. A spreadsheet version of the Checkbook method (Steele et al. 2010) was used to forecast ET weekly using daily maximum temperatures (NOAA-NWS, undated) for the city of Devils Lake. The site operators were instructed to apply irrigation amounts equivalent to the weekly forecasted ET minus rainfall received at each site.

Irrigation scheduling typically aims to meet crop water needs while optimizing water applications and pumping costs. However, because a goal of the Test Project was to determine whether irrigation could mitigate flooding in the Devils Lake basin, site operators were asked to apply as much irrigation water as possible. The following procedures were used to increase the potential amount of irrigation that site operators would apply.

1. Forecasted weather was obtained for Devils Lake, ND, a southerly location in the basin, to represent a liberal (high) set of ET estimates.

2. In the Checkbook spreadsheet (but not necessarily in the field), frequent artificial irrigations were inserted to simulate a well-watered crop transpiring at full, rather than drought-reduced, ET rates.

3. For the alfalfa at Site 20, we assumed uncut alfalfa throughout the season, thereby avoiding reduced ET estimates following cuts (Steele et al. 2010).

4. On 28 July 2006, in response to a request from the engineering firm retained by the Joint Board, we started asking site operators to increase their irrigations by 25% to maximize water applications. Groundwater levels were generally deep enough at the end of July that we did not expect the additional irrigations would cause soil water logging problems. However, the site operators and NDSU personnel continued to monitor field conditions and groundwater levels because, for example, the groundwater at Site 6, Station A1, was

> measured at 0.58 m below ground surface on 28 June, 0.02 m on 7 July, 0.14 m on 17 July, and -0.01 m (standing water above the soil surface) on 8 August 2006. The shallow, perched water table at this station was attributed to local depression-focused recharge and fine-grained lake sediments at depth in the southeastern quadrant of the pivot area, e.g., clay contents of 78.9% at 1.27-m depth. Station A2 at the same field site had groundwater depths of 2.55 m or greater throughout the project duration (Steele and Hopkins, 2009). We recognize that excessive irrigation applications could have reduced ET because of water logging, but shallow water tables were generally not observed throughout the sites and years of the project.

The Checkbook spreadsheet (Steele et al. 2010) was also used to perform a "what-if" analysis of the sensitivity of seasonal ET estimates to crop emergence dates for given weather and crop inputs. Specifically, noting the late emergence of wheat at Site 13 (Table 1), we assessed the impact of various wheat emergence dates on seasonal ET estimates compiled from the water use lookup tables in the Checkbook method. This was accomplished by selecting wheat as the crop and entering frequent artificial irrigations throughout the season to avoid triggering the drought stress algorithms in the spreadsheet. A similar sensitivity analysis of seasonal crop ET could have been performed using an irrigation scheduling spreadsheet such as the daily water balance model associated with the FAO-56 method Allen et al. (1998). However, the lengths of the initial, developmental, mid, and late-season stages of crop coefficients for wheat at mid latitudes are provided (Table 11, FAO-56) for more southerly locations and earlier planting dates than are common in the Devils Lake basin, thus requiring adaptation for this region. In contrast, the Checkbook water use tables were developed in North Dakota.

Use of SEBAL for ET Mapping

The SEBAL model was used in this study to compute ET_a for large areas of the basin. The SEBAL model uses ground-based weather data and satellite imagery to estimate ET as the residual of the energy balance at the Earth's surface.

Grass-based reference ET (ET_o) was estimated from spatially distributed meteorological data using the ASCE Standardized Penman-Monteith equation (ASCE-EWRI 2005). Values of ET_o were calculated based on a 0.12 m grass reference crop, a value of 70 s m^{-1} for the bulk surface resistance, and a value of 0.23 for albedo. Values of potential ET (ET_p) were calculated using the same procedures by replacing the bulk surface resistance of 70 s m^{-1} with a variable minimum bulk surface resistance derived from spatially distributed estimates of leaf area index, aerodynamic resistance, crop height, and albedo derived from the satellite imagery. For water and water surfaces in wetland areas, a specialized function was used to approximate the transfer of heat into water bodies. Weather data for this study, including solar radiation, air temperature, relative humidity, and wind speed, were obtained from NDAWN.

The crop coefficient (K_c) in SEBAL is calculated as the ratio between ET_p/ET_o and represents no acute stress. Note that unlike the traditional concept of K_c, which represents a crop free from stress, the crop coefficient calculated by SEBAL reflects the impact of chronic stresses prior to the image date that may have stunted crop development. The stress coefficient, K_s (ET_a/ET_p), takes into consideration acute stresses due to limited water supply (i.e., drought stress attributable to soil water depletion) and other environmental as well as management effects. The product of K_c and K_s (i.e., ET_p/ET_o x $ET_a/ET_p = ET_a/ET_o$) provides a combined crop coefficient representing actual field conditions.

In order to maximize coverage area, shifted Landsat images from path 31 row 26.5 were selected for analysis. Because cloud-free images are required for SEBAL, scenes from path 32 (west of path 31) row 26 were selected for those dates on which images from path 31 row 26.5 had substantial cloud cover. The overlap of paths 31 and 32 increased the temporal frequency of coverage, thereby increasing confidence in seasonal ET estimates. Some areal coverage was sacrificed to increase the temporal frequency of coverage; the footprint of the study area comprised approximately 54% of the basin (Steele and Hopkins 2009).

Instantaneous (hourly) ET values are extrapolated to daily and longer periods (e.g. months) using average weather conditions and the evaporative fraction for each satellite image overpass time, which is adjusted to account for advection effects on the day of image acquisition. Once the daily evaporative fraction is estimated for a given image date, the daily bulk surface resistance is calculated by rearranging the Penman-Montieth equation. Period outputs representing cumulative ET over a period of days were then developed for each image date based on the calculated bulk surface resistance and average weather conditions. For the area of overlap between the two Landsat path and row combinations processed, a total of 8 sets of period outputs were generated. The images used and the dates included in each period are presented in Table 2.

Table 2. Time periods used for extrapolation of daily ET grids.

Image Acquisition Date in 2006	Landsat 5 Path/Row	Period	Total Number of Days
20 May	31/26.5	1 – 31 May	31
28 June	32/26	1 – 30 June	30
7 July	31/26.5	1 – 16 July	16
23 July	31/26.5	17 – 31 July	13
8 Aug	31/26.5	1 – 14 Aug	15
15 Aug	32/26	15 – 31 Aug	17
9 Sept	31/26.5	1 – 15 Sept	15
25 Sept	31/26.5	16 – 30 Sept	15

Twenty-three NDAWN stations were selected to encompass both satellite paths and the surrounding areas. Incoming solar radiation (R_s), daily air temperature observations, relative humidity, mean daily wind speed, and daily wind gust factor data for each station were quality checked according to the guidelines specified in Appendix-D of ASCE-EWRI (2005). No data quality issues were identified for any of the selected stations during the period of interest.

Weather observations from the ground stations representing point measurements may or may not be representative of the surrounding area depending on the heterogeneity of the region. MeteoLook (Voogt 2006) was used to generate spatially distributed weather grids based on specialized interpolation of point weather observations to better represent the variability in the surface weather conditions that drive ET. MeteoLook is a collection of algorithms that interpolates point weather observations using knowledge of surface and terrain characteristics, such as elevation, surface roughness, albedo, incoming solar radiation, land wetness, and distance to water bodies, coupled with physically-based models.

Land use data were used in SEBAL to parameterize the roughness lengths for the land surface. In the absence of available land use data, roughness lengths may be approximated based on general knowledge of the study area.

Information describing general land use types within the study area was derived from the National Land Cover Dataset (NLCD) for the year 2001 (Homer et al 2004). The 2001 NLCD was developed using a series of Landsat images along with aerial photographs and ground-based reference data. The classification system includes a total of 21 classes. The NLCD for the study area includes 16 unique classes of land cover.

Estimated roughness heights for land use classes in the study area were assigned to each respective class from the land use map and a linear relation was used to adjust vegetation heights according to the approximate growth stage at the image date. This linear relation was derived using a Normalized Difference Vegetation Index (NDVI) grid for each image date and assuming the maximum vegetation height corresponds to an NDVI value of 0.75, and minimum vegetation height corresponds to an NDVI value of 0.25. Between these two extremes vegetation height was linearly varied.

SEBAL models were run for instantaneous, daily, and periodic time scales. Each set of periodic grids for ET_a, ET_p, and ET_o were spatially added to obtain seasonal totals. These seasonal totals were extracted for the overlap region in the basin area between the two different path and row combinations used. Cloud masks were prepared for all image dates to remove clouds and haze. These gaps were filled for seasonal total images using the average of the preceding and following period results, adjusted based on period length.

In this study, we compare SEBAL ET_a results for our irrigated test sites to SEBAL ET_a results for the predominantly non-irrigated areas across the basin. The resulting seasonal ET_a differences provide an estimate of the seasonal gain in ET that might be expected as a result of irrigation of agricultural crops that would otherwise not be irrigated.

For purposes of evaluating ET_a rates for selected crops, a cropland data layer (USDA-NASS 2007) for 2006 for North Dakota was clipped to the Devils Lake basin boundary for this study. A graphical model was written in the Model Maker of ERDAS Imagine software (ERDAS, Inc. 2008) to determine ET_a statistics for each specific agricultural crop. Aside from the irrigated sites in the Test Project, distinctions in ET_a between irrigated and nonirrigated crops in the study area were not made because location data for all irrigated land parcels were unavailable and because the miniscule proportion of irrigated land in the basin would not have significantly affected the ET_a results.

Additionally, ET_a values for wheat and corn were queried for selected soil map units (USDA-NRCS 2007) to enable comparisons across soil types. Selected soils included Barnes-Svea loams, Barnes-Buse loams, the Hamerly-Tonka complex, and the Hamerly-Wyard complex. A few additional soils were selected because of their irrigability, such as Arvilla sandy loam, Maddock-Hecla loamy fine sand, Towner-Barnes fine sandy loams, and Hecla loamy fine sand. Queries were made for spring wheat as the predominant crop, i.e., 29.8% of the basin area in 2006 (USDA-NASS, 2007). Soil map units were also queried for ET_a estimates for corn because, despite its relatively small contribution of 2.9% of the basin area in 2006, corn represents a full-season crop with approximately one more month of active ET compared with spring wheat. Under irrigated scenarios, corn is a major crop in terms of areal extent in this region.

ET_a statistics were determined for the Sites in the project using "areas of interest" in ERDAS Imagine as defined by the center location and radii of the center pivot irrigation systems. The median values of pixel ET_a within each area of interest (i.e., center pivot irrigated area) were compiled using the global median function in the ERDAS Imagine Model Maker.

The thermal band in Landsat 5 has 120-m resolution and is resampled by the USGS to 30-m pixels sizes. To address the possibility that thermal pixels at a given location might be contaminated by heat transfer processes outside field areas of interest, Clark et al. (2007) buffered field boundaries inward 105 m for Landsat 5 images with the assumption that pixel and field boundaries are generally parallel and that fields are rectangular in shape. In this study, cropped areas are predominantly laid out in rectangular fields oriented north-south or east west, so we used a two-pixel inward buffer of the NASS-CDL image (56-m pixel size) for each crop of interest. We buffered inward 105 m from the center pivot irrigation system boundaries at our field sites and for soil polygons of interest. For Sites 7, 13, 18, and 35, in which different crops were grown on different halves of the fields (Table 1), we buffered 105 m away from the field midlines in addition to the 105-m inward buffer on the perimeters of the irrigated areas.

Results and discussion

SEBAL Results and Performance Assessment

A bitmap of seasonal (May – September) ET_a is presented in Figure 2. Average values of seasonal total ET_a for selected land use classes were calculated for areas free of cloud cover throughout the period of analysis and are shown in Table 3. Additionally, NDAWN-reported Penman potential ET (PET) totals, averaged for the stations at Baker, Cando, and Crary, are provided along with the ASCE-EWRI (2005) standardized ET for a short reference crop (ET_o) calculated on a daily basis from the NDAWN data as previously described.

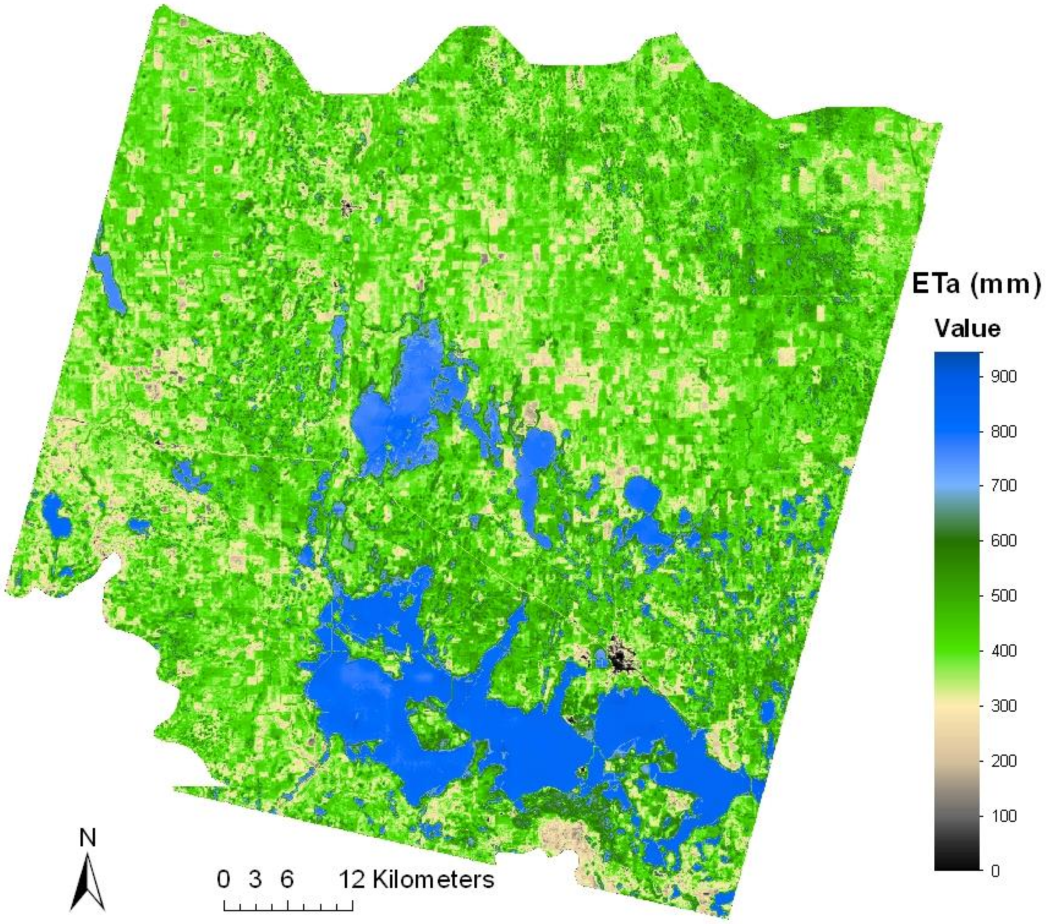

Figure 2. Seasonal ETa for the study area within the Devils Lake basin in 2006.

Table 3. May through September 2006 total seasonal ET_a averages for selected land use types and reference ET.

Land Use[1]	Average Seasonal ET_a (mm)
Cultivated Crops[2]	397
Pasture and Hay	424
Grassland	449
Forest	486
Wetlands	563
Water	781
NDAWN ET_o[3]	697
NDAWN Penman PET[4]	938

[1] Buffered as described previously.

[2] Predominant crops included spring wheat, soybean, and canola. See Table 4 for details.

[3] Grass-based; ASCE-EWRI (2005) ET_o based on NDAWN weather data.

[4] Alfalfa-based; average for Baker, Cando, and Crary stations.

Cumulative distributions of seasonal ET_a for selected land use types in the study area are presented in Figure 3. These distributions demonstrate the wide variability in ET_a within individual land use types across the basin. ET_a values less than about 760 mm for water are likely due to areas classified as water that are actually composed of vegetation or bare soil, as well as areas that dried out during the course of the season.

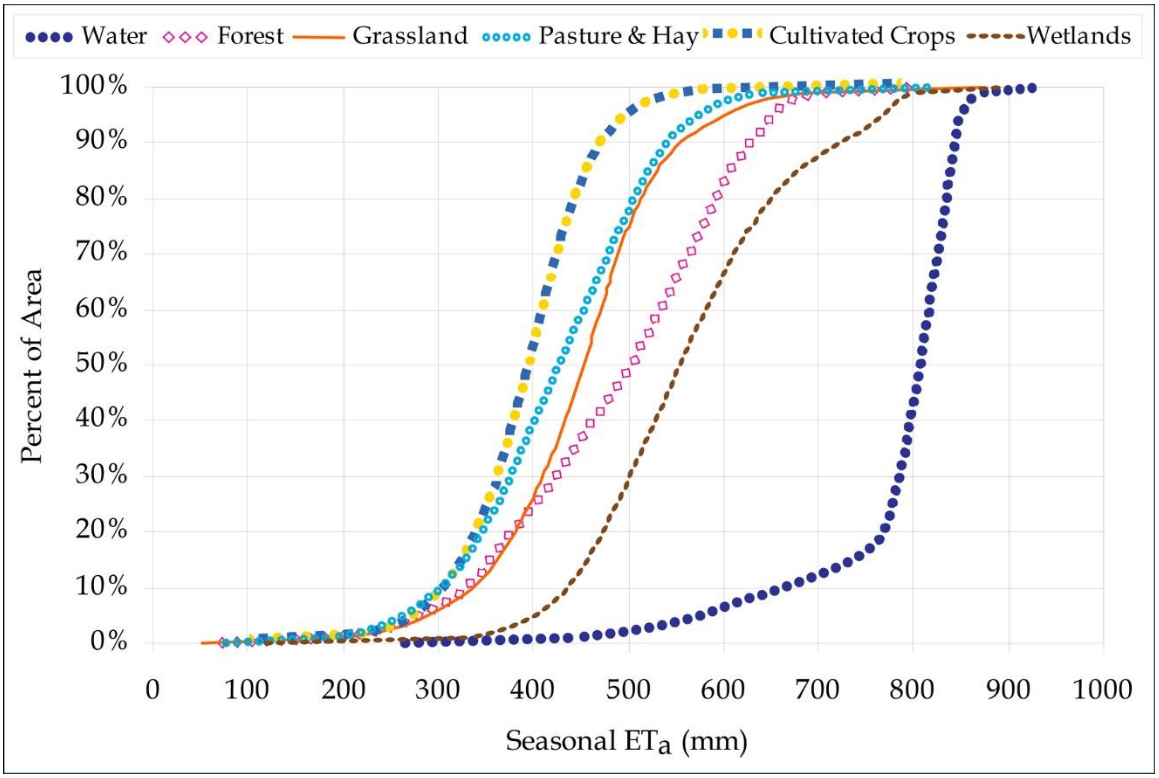

Figure 3. Cumulative distributions of seasonal ET_a by land use type in the study area, buffered as described previously.

Mean ET_a rates for cultivated crops are presented in Figure 4. The estimated mean ET_a rate for each period is shown as a point at the date corresponding to the middle of the period. Additionally, the histogram or relative frequency distribution of pixel ET_a values for each period is shown vertically along the axis of the mid period date. Figure 4 depicts the variability in ET_a rates and changes in the distributions of ET_a rates during the course of the season.

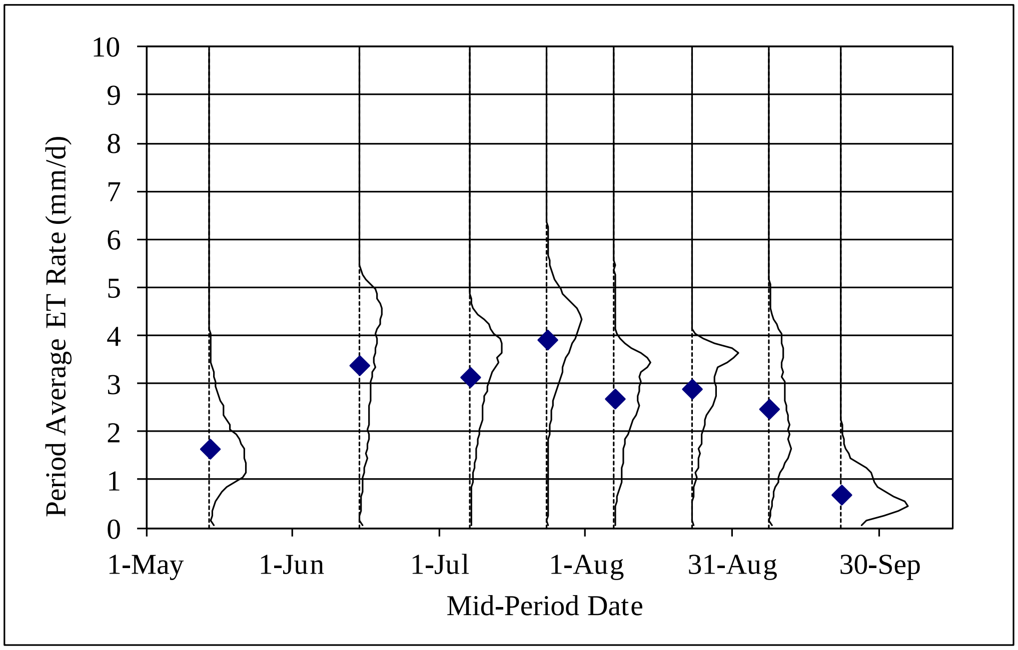

Figure 4. Distribution of period average ET_a rates for cultivated crops. Symbols represent mean ET_a rates.

For each period defined in Table 2, total ET_a values for grasslands and pasture were compared to average total ET_o values computed from nearby NDAWN stations (calculations were performed on a daily basis for the Baker, Cando, and Crary stations). Comparisons were made of both 97th percentile and median ET_a totals to evaluate how closely the remotely sensed ET_a values agree with theoretical values calculated for a short reference crop. Review of the cumulative distribution of the ET_a of grassland and pasture indicated that the 97th percentile was the point at which the curve began to flatten out (Figure 3). The greater 97th percentile values of ET_a for grasslands and pasture are expected to approach ET_o, while the median values of ET_a are expected to fall short of the idealized reference conditions. The 97th percentile relationship was $ET_{a(SEBAL\text{-}97)} = 0.9365 \times ET_{o(NDAWN)} - 0.5103$, with $R^2 = 0.8733$, where $ET_{a(SEBAL\text{-}97)}$ is the period total 97th percentile grassland and pasture ET_a and $ET_{o(NDAWN)}$ is the corresponding period total NDAWN ET_o. Seasonal total 97th percentile ET_a for grasslands and pastures in the study area was estimated by SEBAL to be 649 mm, while the average seasonal ET_o calculated for the Baker, Cando, and Crary stations was estimated to be 697 mm, a difference of approximately 6.9% of ET_o. Period total 97th percentile ET_a values for grasslands and pastures agree closely with calculated ET_o values from nearby NDAWN weather stations, suggesting that maximum ET_a values for grasslands and pasture are near the theoretical potential of a short reference crop. The median relationship was $ET_{a(SEBAL\text{-}M)} = 0.7296 \times ET_{o(NDAWN)} - 7.2761$, with $R^2 = 0.8724$, where $ET_{a(SEBAL\text{-}M)}$ is the period total median grass and pasture ET_a. Based on median ET_a values, grasslands and pasture typically evapotranspired at approximately 65% of ET_o during the study period. Differences between upper ET_a values and theoretical potential may be due to differences between actual and idealized growing conditions, such as water, drought, and/or salinity stresses, and due to inaccuracies in estimation of ET_a and ET_o.

Comparison of SEBAL ET Estimates for Irrigated and Nonirrigated Crops

In the following discussion, "ET" and "seasonal ET" refer to the May through September total of estimated SEBAL ET_a for the study area. Median values of seasonal ET_a for different land uses in the study area are summarized in Table 4. The values in Table 4 include irrigated and nonirrigated crops, although as mentioned previously, the very small irrigated proportion of land in the basin was not expected to influence the results. Spring wheat (crop #7) was the largest crop in area planted in 2006 and its median seasonal ET_a of 394 mm is used as a basis for comparison in this table. For example, the median seasonal ET_a for corn (crop #1) was 435 mm, an increase of 41 mm or 11% compared with spring wheat. Similarly, sunflowers (crop #4) exhibited ET_a estimates 2.5% higher than wheat. These results suggest that switching to a longer-season crop such as corn would be a way to remove additional water from the basin via ET compared with spring wheat. Even larger differences in ET_a appear to be attainable by switching from soybeans (with 9% of the basin area and ET_a 27% smaller than the ET_a estimate for spring wheat) to corn. We recognize the relatively high evaporation rates from water surfaces and wetlands, but the shifts to these land uses in the basin at the expense of agriculture would not be acceptable or economically feasible.

Median values of seasonal ET_a for the circular areas represented by Test Project irrigation systems are shown in Table 5. Sites 1 and 2A were outside of the SEBAL coverage area, the perimeter and midline buffering on the small irrigated area at Site 35 left no area for ET_a sampling, and Site 36 had no crop. The ET values in this table are compared with the median seasonal ET_a for spring wheat, 394 mm, from Table 4. The values in Table 5 indicate ET_a differences between Test Project sites and ET_a for spring wheat. The results are varied for corn, with an ET_a value approximately 21% and 26% greater than for spring wheat at Sites 6 and 7, respectively, 9% greater at Site 12, and essentially no difference estimated for Site 18. Like the results in Table 4, estimates of ET_a for soybeans were smaller than for wheat across the basin, despite the addition of irrigation at the Test Project sites. Spring wheat is typically planted earliest in the region, followed by corn and then by soybeans. Thus soybean fields necessarily miss early-season opportunities for ET by virtue of later planting dates. Additionally, for irrigation management, soybeans are considered to have a shallower rooting depth compared with wheat (Lundstrom and Stegman 1988).

The 49-mm gain in ET_a for irrigated wheat at Site 13 (Table 5) compared with wheat across the study area appears promising. However, some of this increased ET may be attributed to the very late emergence of the crop (Table 1). The 15 June emergence was most likely due to wet field conditions early in the season and the farmer's priority of planting the higher-valued potato crop before seeding the lower-value wheat crop. The Checkbook spreadsheet sensitivity analysis estimated a gain in seasonal ET of 16 mm for the 15 June emergence compared with, for example, an emergence on 7 May 2006.

At Site 18, the lower ET_a values were attributed to relatively high soil salinity as shown by detailed soil investigations (data not shown) and thus poorer crop growth at the site. Another factor resulting in lower ET at Site 18 may have been less aggressive irrigation by the site operator compared with other sites in the project; approximately 95 mm of irrigation water was applied at Site 18 compared to values near 250 mm at Sites 1, 6, 7, and 12 (Table 1). Less aggressive irrigation was also evident at the alfalfa site (20), partly attributed by the site operator to concerns about wheel ruts due to traffic from the irrigation system and alfalfa harvesting equipment on wet soil surfaces.

Median values of SEBAL seasonal ET_a for the Test Project sites at which corn was grown in 2006 are shown in Table 6 and are compared with those for corn—irrigated and nonirrigated—from Table 4. The gains in ET_a are promising at Sites 6 and 7. Wet soil conditions were a concern of the operator at Site 12 (Steele and Hopkins 2009) who for 2006 reported a gain of 1.26 Mg ha^{-1} (20 bushels $acre^{-1}$) in yield for irrigated corn and expenditures of US$ 148 ha^{-1} (US$ 60 $acre^{-1}$) for costs of pumping irrigation water. With corn then priced at about US$ 0.12 kg^{-1} (US$ 3 $bushel^{-1}$), the cost of pumping the water simply matched the additional income from the yield gain. In early 2007, the Site 12 operator indicated that the amount of irrigation applied the previous season was "…10 inches [254 mm] too much" (compare 254 mm in Table 1), implying that the large amount of irrigation would make the site very wet and difficult to farm in the spring of 2007.

The operator of Site 35 indicated that farmers would be unwilling to apply pre-season or post-season irrigations. He noted that perhaps if spring conditions were very dry, he might consider it, but then he would run the risk of not getting the crop planted. In the fall, he agreed with a project investigator that late-season irrigation is risky because harvest may be delayed. He noted that corn is a late crop, further making harvest difficult if contending with fall rains. In the fall of 2008, rainfall prevented the harvest of corn from portions or all of five of the Sites. An additional risk of late-season irrigation is a sudden freezing event before irrigation systems are drained.

Table 4. SEBAL seasonal ET$_a$ estimates for 2006 for predominant crops in the basin.

Crop #	Crop or Land Cover[(1)]	Median ET$_a$, mm	Difference from Spring Wheat ET$_a$, mm	Change from Spring Wheat ET$_a$, %	Extent in Basin, ha	Fraction of Basin, %	Extent in Study Area, ha	Fraction of Study Area, %	ET$_a$ Pixel Area Sampled[(2)], ha
1	Corn	435	41	10.5%	27,150	2.9%	19,265	3.8%	5,395
3	Soybeans	366	-27	-7.0%	86,876	9.2%	56,048	10.9%	15,465
4	Sunflowers	404	10	2.5%	19,893	2.1%	13,085	2.6%	4,188
5	Barley	374	-20	-5.1%	9,795	1.0%	6,564	1.3%	1,105
6	Durum Wheat	388	-6	-1.5%	348	0.0%	329	0.1%	119
7	***Spring Wheat***	***394***	*0*	***0.0%***	***283,273***	***29.8%***	***142,678***	***27.8%***	***47,766***
8	Winter Wheat	371	-23	-5.9%	3,920	0.4%	2,246	0.4%	361
11	Oats	403	9	2.4%	194	0.0%	77	0.0%	37
13	Canola	395	1	0.3%	58,790	6.2%	23,617	4.6%	6,548
14	Flaxseed	410	16	4.2%	3,945	0.4%	2,234	0.4%	392
17	Alfalfa	370	-23	-5.9%	1,506	0.2%	858	0.2%	118
19	Dry Edible Beans	286	-108	-27.4%	14,998	1.6%	11,129	2.2%	2,335
20	Potatoes	402	8	2.1%	160	0.0%	48	0.0%	30
28	Fallow/Idle Cropland/CRP	407	13	3.4%	196,438	20.7%	98,623	19.2%	17,283
29	Pasture/Range/Non-Ag	347	-46	-11.8%	3,586	0.4%	1,743	0.3%	235
30	Woods	611	217	55.1%	4,800	0.5%	2,628	0.5%	116
32	Urban	168	-226	-57.4%	39,002	4.1%	21,525	4.2%	959
33	Water	818	424	107.6%	87,696	9.2%	65,468	12.8%	40,598
34	Wetlands	639	245	62.3%	102,288	10.8%	43,018	8.4%	870
35	Clover/Wildflowers	357	-37	-9.4%	437	0.0%	286	0.1%	47
37	Peas	362	-32	-8.1%	3,839	0.4%	1,239	0.2%	239
38	Barren	402	8	2.1%	95	0.0%	45	0.0%	29
Totals					`	100%	512,753	100%	144,232
Maximums		818	424	107.6%	283,273		142,678		

(1) Crop identification was determined by the National Ag Statistics Service Cropland Data Layer for 2006 (USDA-NASS, 2007).

(2) Net area after buffering inward two pixels (56 m pixel size) from NASS-CDL crop boundaries.

Table 5. Seasonal ET_a estimates for 2006 for center pivot irrigated test project sites and comparisons to all spring wheat (irrigated and nonirrigated) in the study area.

Site #	Crop	Median ET_a, mm	Difference from Median Spring Wheat ET_a, mm	Change from Median Spring Wheat ET_a	ET_a Pixel Area Sampled(1), ha
6	Corn	476	82	20.8%	24.0
7	Corn (North Half)	497	103	26.2%	7.8
7	Soybeans (South Half)	388	-6	-1.6%	8.5
12	Corn	430	36	9.1%	26.3
13	Wheat (South Half)	443	49	12.4%	8.1
18	Corn (West Half)	394	0	0.1%	5.6
18	Soybeans (East Half)	317	-77	-19.5%	4.5
20	Alfalfa	384	-10	-2.5%	21.2
Maximums		497	103	26.2%	
Area-Weighted Averages		427	33	8.4%	

(1) Net area after buffering inward 105 m from pivot perimeters, 105 m away from split-crop midlines, and inward two pixels (56 m/pixel) from NASS-CDL crop boundaries.

Table 6. Seasonal ET_a estimates for 2006 for center pivot irrigated test project sites and comparisons to all corn (irrigated and nonirrigated) in the study area.

Site #	Crop	Median ET_a, mm	Difference from Median Corn ET_a, mm	Change from Median Corn ET_a	ET_a Pixel Area Sampled(1), ha
6	Corn	476	40	9.3%	24.0
7	Corn (North Half)	497	62	14.2%	7.8
12	Corn	430	-6	-1.3%	26.3
18	Corn (West Half)	394	-41	-9.4%	5.6
Maximums		497	62	14.2%	
Area-Weighted Averages		452	17	3.9%	

(1) Net area after buffering inward 105 m from pivot perimeters, 105 m away from split-crop midlines, and inward two pixels (56 m/pixel) from NASS-CDL crop boundaries.

Estimates of ET_a for spring wheat and corn on selected soils are summarized in Table 7. In this region, spring wheat is typically harvested by mid-August, whereas corn is harvested in late September or later. If early frost does not kill the crop, corn has approximately one more month of transpiration compared with wheat. Additionally, if late-season precipitation is lacking, irrigation can increase ET_a and crop yield on droughty soils.

Three of the top four predominant detailed soil map units in the basin—Buse-Svea loams, Barnes-Buse loams, and Hamerly-Wyard loams —exhibited median ET_a estimates essentially equivalent to median ET_a estimates for all map units in the study area. That is, the median ET_a estimates for these map units for both spring wheat and corn were within approximately 2.7% of the median estimates for all soils for the respective crops. The ET_a estimates indicate that these map units have sufficient water-holding capacity to sustain late-season crop water use, even under the low rainfall conditions encountered in the 2006 season. Thus the potential to increase ET_a via irrigation is limited for these map units.

The ET_a mapping process suggests some late-season potential for increasing ET_a with irrigation for map units such as the Hamerly-Tonka complex, the Swenoda fine sandy loam, and the Maddock-Hecla loamy find sands. For spring wheat, median ET_a estimates for these map units were 1.3% greater, 6.3% greater, and 3.5% less than, respectively, the median ET_a estimate for spring wheat for all map units in the study area (Table 7). For corn, however, these median ET_a values changed to values lagging the median ET_a estimate for corn for all map units in the study area by 5.1% and 2.9% for the Hamerly-Tonka and Swenoda , respectively, while buffering the Maddock-Hecla left no sampling area. These estimates attribute ET reductions solely to limited soil moisture under the basin's predominantly nonirrigated conditions; fertility, disease, pest, and other agronomic challenges were not reported for the 2006 growing season.

The median ET_a changes from wheat to corn for the Hamerly-Tonka complex and the Swenoda fine sandy loam may also be compared on a rainfall depth equivalent basis. The ET_a values for the Hamerly-Tonka complex and the Swenoda fine sandy loam went from 5- and 25-mm comparative advantages for spring wheat to 22- and 13-mm comparative disadvantages for corn. The shortfalls in ET_a may be considered deficits which could be made up via irrigation and thus they represent

ET "disposal" of water into the atmosphere via irrigation for flood mitigation purposes. Note that 22- and 13-mm deficits in ET_a are substantially smaller than the 137-mm gain in ET under irrigated conditions estimated by Bartlett and West (2002). Moreover, the ET_a deficits estimated in this study are for the dry conditions of 2006, whereas the ET gains estimated by Bartlett and West (2002) were averaged across ten years of weather data (1992-2001).

Note that the Maddock-Hecla loamy fine sands (SSURGO map unit symbol F384B) comprise only 1099 ha or 0.12% of the total basin area (Table 7). It can be concluded that while this map unit offers the potential for increased wheat ET_a if irrigated in a dry season, its negligible area makes its possible contribution to flood mitigation in the basin miniscule. Timely rainfall may make irrigation unnecessary even for drought-prone soils. Additional difficulties are that the Maddock-Hecla map units do not generally comprise contiguous areas of sufficient size on which to deploy center pivot irrigation systems. The SSURGO data indicate the median area of 99 map unit polygons for the Maddock-Hecla soil (F384B) is only 5.9 ha. The median Hamerly-Tonka and Swenoda parcel sizes are similarly small at 6.1 and 7.5 ha, respectively.

Singh and Irmak (2009) used SEBAL to develop K_c values for corn, soybean, sorghum, and alfalfa for irrigated and nonirrigated conditions in Nebraska on seven dates in 2005. Averages of their K_c values were, for values in the months of May through September, 13%, 7%, 9%, and 22% greater for irrigated corn, soybean, sorghum, and alfalfa, respectively, compared with the crop coefficient values for the same dryland crops. It is difficult to compare their gains in K_c values under irrigated vs. dryland conditions with the ET_a gains estimated in this study because 1) the averages do not reflect time weighting of the K_c values over variable-length intervals during the season; 2) ET_r varies with time throughout the season; and 3) K_c curves are typically developed for local use (Allen et al. 1998) and require additional analyses for use across wide geographic areas, such as the "Fraction of Season" based on growing degree day method employed by Stegman (1988).

Melesse et al. (2006a, b) used SEBAL to estimate spatially-distributed ET for a water balance study in the Devils Lake basin. They compared Devils Lake levels with temperature, precipitation, Palmer Hydrologic Drought Index values, ground water levels, and lake surface areas. Precipitation data were taken from seven NDAWN stations in or surrounding the basin and surface water runoff was modeled with the Curve Number methodology. Their study did not compare or contrast ET rates from irrigated and nonirrigated crops as a possible approach to flood mitigation.

It is important to contrast the water balance approach of Bartlett and West (2002), suggesting ample room for gains in ET (137 mm), with the SEBAL results of this study, indicating relatively small gains in ET achievable via irrigation. Bartlett and West (2002) did not model contributions from shallow groundwater to ET and did not mention soil water in excess of field capacity in slowly-draining soils as a possible source of water for ET. Thus their crop model indicated greater crop water (drought) stresses leading to greater differences in ET between irrigated and nonirrigated conditions. In contrast, SEBAL estimates ET under actual field conditions and inherently accounts for all water sources available to supply ET. The similarity of ET estimates for irrigated and nonirrigated crops in this study suggest that nonirrigated crops in the basin during the 2006 season had at least some of their ET needs supplied by shallow groundwater and/or soil water in excess of field capacity following rainfall events. We conclude that the relatively small gains in ET_a for irrigated crops do not justify widespread development of irrigation of agricultural crops as a flood mitigation tool in the basin.

From the beginning of the Test Project, ND SWC personnel doubted that irrigation would increase ET enough to justify widespread irrigation development in the Devils Lake basin for flood mitigation purposes. However, the ND SWC felt they could not defend their position on an experimental or modeling basis. We have since been encouraged by the ND SWC that the Test Project and the SEBAL ET modeling provided them that basis. The possible savings in tax expenditures from this outcome are significant. The next stages of using irrigation for flood mitigation in the basin were envisioned as pilot- and full-scale projects for development of 1600 ha and 8100 ha of irrigation estimated at US $5M to $6M and US $25M, respectively, with estimated public cost shares of 75% for construction and operation in each case (Bartlett and West 2002). Perhaps more significant than costs for equipment and operation are the negative impacts which irrigation of non-irrigable soils would likely have on soil physical and chemical properties, and hence, on soil productivity.

Installation of subsurface drainage in the test fields may have increased irrigated crop yield and ET by reducing soil salinity and improving root aeration. For example, lower yields and ET at Site 18 were partly attributed to elevated soil salinity, yet we did not have the option of installing subsurface drainage to leach excess salts from the profile. Hypothetically, test strips of drained and undrained conditions could have been installed in a side-by-side fashion at some of the sites to compare crop yield with spatial yield monitoring technologies and ET with the SEBAL mapping approach. In addition to the constraints on drainage mentioned previously, the time requirements for achieving yield and ET improvements under drained conditions would likely have exceeded the duration of this field study.

Table 7. Seasonal evapotranspiration estimates for 2006 from the study area for selected soil-crop combinations.

No	Crop	SSURGO Map Unit Symbols			Name of Soil Map Unit #1	Median ETa, mm	Difference from Median ET_a for Specified Crop for All Soils, mm	Change from Median ET_a for Specified Crop for All Soils, %	SSURGO Area of Listed Map Units in Basin, ha	Percent of Basin Area in Listed Map Units	ET_a Pixel Area Sampled for Specified Soil and Crop(1), ha
		1	2	3							
2	Wheat(2)	F143A	F143B	F143C	Barnes-Svea loams, 0 to 3% slopes	402	8	2.0%	130,059	13.7%	524.8
4	Wheat	F144B			Barnes-Buse loams, 3 to 6% slopes	393	-1	-0.2%	123,006	13.0%	642.2
6	Wheat	F100A	G100A		Hamerly-Tonka complex, 0 to 3% slopes	399	5	1.3%	65,731	6.94%	613.4
8	Wheat	F101A	G101A		Hamerly-Wyard loams, 0 to 3% slopes	397	3	0.7%	64,307	6.79%	473.5
10	Wheat	F107A			Hamerly-Barnes loams, 0 to 3% slopes	401	7	1.9%	30,054	3.17%	858.6
12	Wheat	F431A			Bearden silt loam, 0 to 2% slopes	395	2	0.4%	6,929	0.731%	377.6
14	Wheat	F430A			Bearden silty clay loam, 0 to 2% slopes	383	-10	-2.6%	5,392	0.569%	63.1
16	Wheat	F776B			Swenoda fine sandy loam, 0 to 6% slopes	419	25	6.3%	2,416	0.255%	19.1
18	Wheat	F271B	G271B		Arvilla sandy loam, 0 to 6% slopes	389	-5	-1.2%	1,444	0.152%	2.2
20	Wheat	F384B			Maddock-Hecla loamy fine sands, 0 to 6% slopes	380	-14	-3.5%	1,099	0.116%	2.9
22	Wheat	F737A	F737B	G737A	Towner-Barnes fine sandy loams, 0 to 3% slopes	No Data			921	0.0972%	
24	Wheat	G366A			Hecla loamy fine sand, 0 to 2% slopes	No Data			325	0.0343%	
1	Corn	F143A	F143B	F143C	Barnes-Svea loams, 0 to 3% slopes	447	12	2.7%	130,059	13.7%	94.2
3	Corn	F144B			Barnes-Buse loams, 3 to 6% slopes	444	9	2.0%	123,006	13.0%	54.5
5	Corn	F100A	G100A		Hamerly-Tonka complex, 0 to 3% slopes	413	-22	-5.1%	65,731	6.94%	33.8
7	Corn	F101A	G101A		Hamerly-Wyard loams, 0 to 3% slopes	432	-3	-0.8%	64,307	6.79%	68.4
9	Corn	F107A			Hamerly-Barnes loams, 0 to 3% slopes	425	-10	-2.4%	30,054	3.17%	57.1
11	Corn	F431A			Bearden silt loam, 0 to 2% slopes	456	21	4.7%	6,929	0.731%	32.4
13	Corn	F430A			Bearden silty clay loam, 0 to 2% slopes	433	-2	-0.5%	5,392	0.569%	8.2
15	Corn	F776B			Swenoda fine sandy loam, 0 to 6% slopes	423	-13	-2.9%	2,416	0.255%	1.1
17	Corn	F271B	G271B		Arvilla sandy loam, 0 to 6% slopes	441	6	1.4%	1,444	0.152%	20.7
19	Corn	F384B			Maddock-Hecla loamy fine sands, 0 to 6% slopes	No Data			1,099	0.116%	
21	Corn	F737A	F737B	G737A	Towner-Barnes fine sandy loams, 0 to 3% slopes	No Data			921	0.0972%	
23	Corn	G366A			Hecla loamy fine sand, 0 to 2% slopes	No Data			325	0.0343%	

(1) Net area after buffering inward 105 m from SSURGO soil polygons and inward two pixels (56 m/pixel) from NASS-CDL crop boundaries.

(2) "Wheat" in this table refers to spring wheat.

Conclusions

Irrigation was applied to ten irrigated fields in the Devils Lake basin of northeastern North Dakota, USA, to enable comparisons of ET_a estimates for irrigated and nonirrigated crops. The Surface Energy Balance Algorithm for Land was used to estimate ET_a for the 2006 growing season. Estimates of the 97th percentile of ET_a from SEBAL for grass and pasture agreed within about 7% of the ET_o based on weather stations within the basin.

The median ET_a estimate for corn, based on an area-weighted average from four irrigated test sites, was 17 mm larger than the ET_a for corn in the predominantly nonirrigated study area. Across the basin, corn exhibited gains in ET_a of approximately 41 mm or 11% compared with ET estimates for spring wheat, the most predominant crop in the basin. Based on the relatively small estimated increases in ET attributable to irrigation, it does not appear that widespread development of irrigation in the basin as a flood mitigation tool is warranted. Similarly, while some soil map units in the basin exhibited opportunities for ET gains if irrigated, their small areal extents and parcel sizes are not sufficient to justify additional irrigation development for flood mitigation purposes. Estimates of the gains in ET attributable to cropping and/or land use changes may be useful for future hydrologic studies and for hydrology-related policy and management decisions in the basin.

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