Landscape Evapotranspiration Estimation Using Remotely Sensed Data for Operational Applications in Agriculture and Hydrology

Gabriel Senay[1]

12/16/2007

For Presentation at the NIDIS Remote Sensing Workshop. February 6-7 2008, Boulder, Colorado.

Evapotranspiration (ET) is an important component of the hydrologic budget because it expresses the exchange of mass and energy between the soil-water-vegetation system and the atmosphere. Prevailing weather conditions influence potential or reference ET through variables such as radiation, temperature, wind, and relativity humidity. In addition to these weather variables, actual ET (ETa) is also affected by land cover type and condition and soil moisture. ETa's dependence on land cover and soil moisture, and its direct relationship with carbon dioxide assimilation in plants, makes it an important variable to monitor and estimate crop yield and biomass for decision makers interested in food security, grain markets, water allocation and carbon sequestration.

Although the estimation of ETa is the ultimate goal of many researchers for hydrological and agronomical applications, it is often difficult to quantify and requires expensive instrumentation. However, different hydrological modeling techniques are used to estimate ETa. The two broad modeling techniques can be grouped as either based on surface energy balance (e.g., Bastiaanssen et al., 1998; Allen et al., 2005; Su et al., 2005; Senay et al., 2007) or water balance principles (e.g, Allen et al., 1998; Verdin and Klaver 2002; Senay and Verdin 2003).

In this paper, two models for ETa estimation, using water and energy balance methods, are summarized along with a review of their merits and status for operational applications. The two approaches have one major difference: the water balance model focuses on tracking the pathways and magnitude of rainfall in the soil-vegetation system, whereas the energy balance model monitors changes in landscape temperature to estimate ETa. Both models use the concept of a reference ET to estimate the potential ET under unlimited water conditions using an idealized reference crop with a standardized bulk and aerodynamic resistance factors for vapor transport. Thus, the main difference in the two approaches is in the calculation of a correction factor to take into account the impact of soil moisture to estimate ETa as a fraction of the reference ET (ETo). The water balance model uses a vegetation water balance approach to track soil moisture changes, whereas the energy balance model uses land surface temperature changes.

A brief introduction is provided on the **Veg**etation **ET** (VegET) water balance model (Senay, 2008) and the Simplified Surface Energy Balance (SSEB) approach (Senay et al., 2007) in the sections that follow. The two approaches have their own merits and limitations, and they can be used independently or in combination. The choice of model depends on the availability of data and on the objective of the project. Both methods require reference ET that can be generated using meteorological data. In addition, the availability of rainfall and land surface phenology (LSP) is important for the VegET water balance model, but the SSEB energy balance approach requires thermal data. These differences in data inputs are important and define the applications and constraints that apply to each. For example, the presence of cloud cover adversely impacts the SSEB model, but it does not impact the VegET model, which explicitly takes cloud information into consideration in the satellite-based rainfall estimation process. This feature guarantees a reliable daily ETa estimation anywhere in the world irrespective of cloud cover. This can be a significant advantage during the growing season in many parts of the world. On the other hand, the SSEB model has

[1] SAIC, contractor to U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center / Gographic Information Science Center of Excellence (GIScCE), South Dakota State University, Sioux Falls, SD, USA. Work performed under USGS contract 03CRCN0001.

the advantage of estimating ET irrespective of the water source, whereas the VegET model only estimates "rain-fed" ET. This difference creates the opportunity to identify landscapes that meet their ET from external (irrigation) or groundwater sources. The two ET estimation approaches and their potential applications are summarized below.

Landscape ET using the VegET Model: Water Balance

The most widely used water balance technique for operational monitoring is the FAO algorithm that produces the crop water requirement satisfaction index (WRSI). WRSI shows the relative relationship (ratio/percent) between the supply (from rainfall and existing soil moisture) and demand (crop demand to meet its physiological needs) using observed data from the beginning of the crop season (planting) until the current date.

The Famine Early Warning System Network (FEWS NET) demonstrated a regional implementation of the FAO WRSI in a grid-cell modeling environment in Southern Africa (Verdin and Klaver, 2002). Furthermore, Senay and Verdin (2003) enhanced the geospatial model by introducing the concept of maximum allowable depletion (MAD) and the soil water stress factor from irrigation engineering for better estimation of ETa as a function of soil water content. The Senay and Verdin (2003) version of the model has been operational since 2000 with daily and 10-day outputs for Africa, Central America and Afghanistan. Graphics of model output are posted operationally at http://earlywarning.usgs.gov/adds/.

VegET is a model recently developed for estimating actual evapotranspiration in non-irrigated cropland and grassland environments as an enhancement to the USGS/FEWS NET crop water balance model (Senay and Verdin, 2003). VegET blends concepts from irrigation engineering with a remote sensing datastream to estimate actual ET quickly and accurately at low computational and data costs anywhere in the world.

A key innovation in the VegET model is the inclusion of the land surface phenology (LSP) parameter which describes the seasonal progression of vegetation growth and development. LSP can be observed by spaceborne sensors and is a key biogeophysical parameter that links the water and carbon cycles with anthropogenic activities, providing an important approach to change detection in terrestrial ecosystems (e.g., Goward et al. 1985; Reed et al. 1994; Tucker et al. 2001; de Beurs and Henebry 2005).

VegET monitors soil water levels in the root zone through a daily (or longer times steps) water balance algorithm and estimates actual ET (ETa) in rain-fed cropland and grassland environments. Key input data to VegET are precipitation, reference ET (ETo), soil water holding capacity, and land surface phenologies (LSPs). ETa is calculated as the product of reference ET (ETo), soil stress coefficient (Ks), and LSP coefficient (Kp), as shown in Equation 1.

$$ET_a = K_s * K_p * ET_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

The soil stress coefficient is determined from a soil water balance model (Allen et al., 1998; Senay and Verdin, 2003). The land surface phenology coefficient (Kp) is comparable to the crop coefficient (Kc) widely used by agronomists (Allen et al., 1998) with the key difference being that Kp is a variable derived from remotely sensed data (Senay, 2008). Kp represents both the spatial and temporal dynamics of the landscape water use patterns on a grid-cell basis. LSPs are characterized and converted into Kp parameter functions for each modeling grid cell using the average weekly maximum normalized difference vegetation index (NDVI) derived from the Advanced Very High Resolution Radiometer (AVHRR) satellite data from 1989 to 2004 (Eidenshink, 1992). Soil water holding capacity is derived from the State Soil Geographic Database (STATSGO) (http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/) for the United States or from FAO's Digital Soils Map of the World. The reference ET (ETo) is produced at USGS/EROS at a daily time step using the standardized Penman-Monteith equation (Allen et al., 1998) for the globe (Senay et al., 2008).

Precipitation is a key driver of the water balance model, and a combination of coarse (25km for 1996–2004; ftp://ftp.cpc.ncep.noaa.gov/precip/wd52ws/us_daily) and finer spatial resolution (5km for 2005 to current) daily total rainfall data from NOAA National Weather Service is used (http://www.srh.noaa.gov/rfcshare/precip_about.php). Despite the differences in spatial resolution of the precipitation data from different time periods, use of either dataset in VegET has been shown to result in comparable seasonal ETa values. Similarly, a coarse precipitation dataset does not prevent the modeling of ETa at a higher spatial resolution using finer resolution LSPs because the spatial variability of ETa at a subwatershed or field scale is more a function of the LSP than the rainfall distribution.

All of these data streams have already been used by the VegET model during its development and testing. Figures 1 and 2 show sample seasonal ETa maps for 2005 and 2006 and validation results using flux tower data in the conterminous United States. Preliminary results indicate that the VegET ETa output captures both the spatial and temporal variability of ET in the conterminous United States. Furthermore, preliminary comparison with county crop yield data also show a strong correlation (explaining up to 60% of the spatial variability in crop yield) between seasonal ETa and wheat yields in South Dakota (Senay and Henebry, 2007).

Landscape ET using SSEB Approach: Energy Balance

Surface energy balance methods have been successfully applied by several researchers (Bastiaanssen et al., 1998; Allen et al., 2005; Su et al., 2005) to estimate crop water use in irrigated areas and across the general landscape. Their approach requires solving the energy balance equation at the land surface (Equation 2) where the latent heat flux, also referred to as ETa, is calculated as the residual of the difference between the net radiation to the surface and losses due to the sensible heat flux (energy used to heat the air) and ground heat flux (energy stored in the soil and vegetation).

$$LE = Rn - G - H \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

LE = Latent heat flux (energy consumed by evapotranspiration) (W/m^2)
Rn = Net radiation at the surface (W/m^2)
G = Ground heat flux (W/ m^2)
H = Sensible heat flux (W/ m^2)

The estimation of each of these terms from remotely sensed imagery requires quality, calibrated datasets. Allen et al. (2005) described the various steps required to estimate actual ET using a surface energy balance method that employs the *hot* and *cold* pixel approach of Bastiaanssen et al. (1998) in the SEBAL model. For net radiation, SEBAL requires meteorological data on incoming and outgoing radiation, and the associated surface albedo and emissivity fractions for shortwave and long wave bands are also needed. The ground heat flux is estimated using surface temperature, albedo, and normalized difference vegetation index (NDVI). The sensible heat flux is estimated as a function of temperature gradient above the surface, surface roughness, and wind speed.

Although solving the full energy-balance approach has been shown to give good results in many parts of the world, the data and skill requirements to solve for the various terms in the equation are prohibitive for operational applications in large, data-sparse regions. As an alternative, a Simplified Surface Energy Balance (SSEB) approach was developed at USGS/Center for Earth Resources Observation and Science (EROS) for operational applications (Senay et al., 2007). The SSEB approach produces actual Evapotranspiration estimates using a combination of ET fractions generated from thermal imagery and global reference ET over homogeneous areas with similar climate zones where differences in surface temperature are mainly caused by differences in vegetation water use rates. Further modification of the model will allow the application of the method in complex topography where elevation-induced surface temperature variations will be taken into account.

The method involves two basic steps: ETa is simply a product of the ET fraction (ET_f) and ETo, Eq. 2. In the case of the MODIS data stream, ET_f (Eq. 4) is calculated for each 8-day average MODIS Thermal image. Although it is possible to use daily data, due to cloud cover the 8-day average data is the preferred option. ETo is available at EROS on a daily time step, calculated globally from assimilated meteorological datasets of the Global Data Assimilation System of NOAA (Senay et al., 2008).

$$ETa = ET_f * ETo \qquad \ldots\ldots\ldots\ldots\ldots(3)$$

Where ETa is actual ET, ET_f is ET fraction, and ETo is reference ET.

With the simplifying assumption that *hot* pixels experience very little ET (Allen et al., 2005) and *cold* pixels represent maximum ET in the study area, the 8-day average temperature of *hot* and *cold* pixels can be used to calculate proportional fractions of ET on a per pixel basis. The *hot* and *cold* pixels are selected using an NDVI image as a guide to identify dry and bare areas for the *hot pixels.* Similarly, the *cold* pixels are selected from well-watered, healthy, and well-vegetated areas. The ET fraction ($ET_{f,x}$) is calculated for each pixel “x” by applying the following equation (Equation 4) to each of the 8-day MODIS land surface temperature grids.

$$ET_{f,x} = \frac{TH - Tx}{TH - TC} \qquad \ldots\ldots\ldots\ldots\ldots(4)$$

Where TH is the average of the representative (3 to 5) *hot* pixels selected for a given scene; TC is the average of representative (3 to 5) *cold* pixels selected for within the same scene; and Tx is the land surface temperature value for any given pixel in the composite scene.

Figure 3 shows a seasonal ETa map for the Great Plains regions of the United States, produced from an aggregation of 8-day ETa images using the SSEB model. Temporal profiles of selected sites have shown the potential use of the model for identifying the timing and magnitude of “flash-drought” occurrences. A formal validation of the SSEB model is currently being conducted using lysimeter data and in comparison with other Surface Energy Balance models such as METRIC (Allen et al, 2005). Preliminary comparison with the METRIC model has shown a strong correlation ($r > 0.98$) between the two models. Funding is being sought to set up the SSEB model in an operational mode to produce 8-day ETa images for the conterminous United States. Table 1 shows a summary of the input/output data characteristics of the two models.

Table 1: Modeling and Data Characteristics of VegET and SSEB.

	VegET	**SSEB**
Modeling Approach	Water Balance	Energy Balance
Target Monitored/Output	ET, Soil Moisture, Runoff	ET
Spatial Resolution	Limited by LSP data MODIS: 250 m AVHRR: 1 km	Limited by Thermal data (MODIS/AVHRR: 1 km) Landsat: 60 m (local application)
Spatial Extent	Global: Potentially	Global: Potentially
Frequency of Product	Daily	8-day
Delay	1 day	About 2 weeks for MODIS
Period of Record	Limited by Rainfall data 1996–current: NexRad/Station Blend 1979–current: GPCP (Global Precipitation Climatology Project).	Limited by Thermal Data AVHRR:1989–current MODIS: 2000–current
Web access	VegET model output is NOT online yet, but comparable outputs from the USGS/FEWS NET site: http://earlywarning.usgs.gov/adds/	Product is not online
Geographic Projection	Currently outputs are in lat/lon	Currently outputs are in lat/lon
GIS Environment	Yes	Yes
Description of product	Appropriate for rainfed agriculture or grassland environments.	Superior application in irrigated systems.
Challenge/Limitations For operational Implementation	No major limitation is anticipated to go operational on this model. Automation of the model can be setup within 3 months of time. Funding is required.	Cloud cover is an issue, but the 8-day product overcomes this problem compared to the daily products. Automation of data processing is not yet implemented. However, this can be achieved within a period of 1 year. Funding is required.

References

Allen, R.G., L. Pereira, D. Raes and M. Smith (1998). Crop Evapotranspiration. Food and Agriculture Organization of the United Nations, Rome, Italy. FAO publication 56. ISBN 92-5-104219-5. 290pp.

Allen, R.G., M. Tasurmi, A.T. Morse and R. Trezza (2005). A Landsat-based Energy Balance and Evapotranspiration Model in Western US Water Rights Regulation and Planning. *Journal of Irrigation and Drainage Systems* 19 (3-4): 251-268(18).

Bastiaanssen, W.G.M., M. Menenti, R.A. Feddes and A.A.M. Holtslag (1998). A remote sensing surface energy balance algorithm for land (SEBAL): 1) Formulation. *Journal of Hydrology* 212 (213):213-229.

de Beurs, K.M. and G.M. Henebry (2005). A statistical framework for the analysis of long image time series. *International Journal of Remote Sensing* 26(8): 1551-1573.

Eidenshenk, J. C. (1992). The 1990 conterminous US AVHRR data set. *Photogrammetric Engineering and Remote Sensing* 58(6):809-913

Goward, S.N., C.J. Tucker and D.G. Dye (1985). North American vegetation patterns observed with the NOAA-7 advanced very high resolution radiometer. *Plant Ecology* 64(1):3-14.

Reed, B.C., J.F. Brown, D. VanderZee, T.R. Loveland, J.W. Merchant and D.O. Ohlen (1994). Measuring phenological variability from satellite imagery. *Journal of Vegetation Science* 5(5):703-714.

Senay, G.B. and J. Verdin (2003). Characterization of yield reduction in Ethiopia using a GIS-based crop water balance model. *Canadian Journal of Remote Sensing* 29(6):687-692.

Senay, G.B. (2008). Vegetation evapotranspiration (VegET) estimation using vegetation index enhanced water balance algorithm for landscapes. In preparation.

Senay, G.B., M. Budde, J.P. Verdin and A.M. Melesse (2007). A coupled remote sensing and simplified surface energy balance approach to estimate actual evapotranspiration from irrigated fields. *Sensors* 7:979-1000.

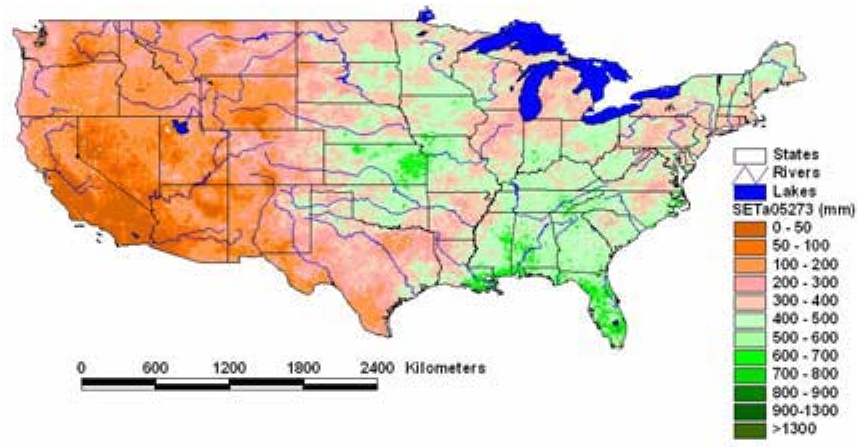
Senay, G.B. and G. Henebry (2007). Evaluating Vegetation Evapotranspiration (VegET) Modeling Results in South Dakota. Proceedings of the Eastern South Dakota Water Conference. October 29–31, Sioux Falls, South Dakota.

Senay, G.B., J.P. Verdin, R. Lietzow and A. M. Melesse (2008). Global daily reference evapotranspiration modeling and validation. *Journal of American Water Resources Research*. In Press.

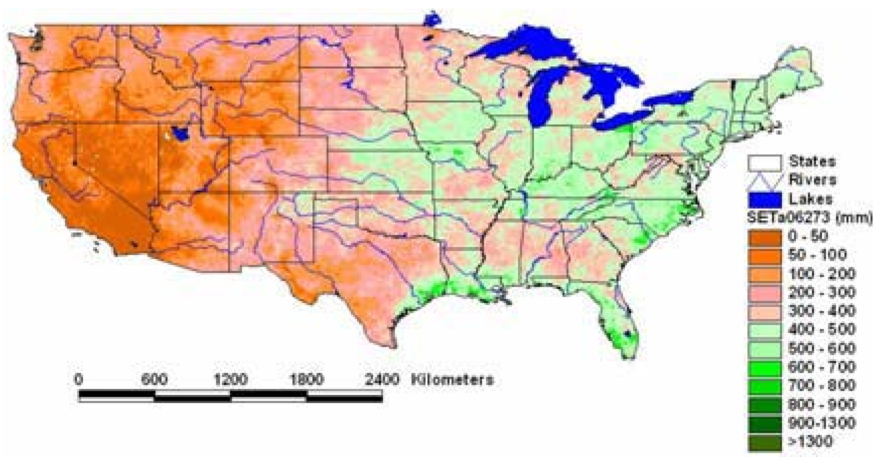
Su, H., M.F. McCabe, E. F. Wood, Z. Su and J. Prueger (2005). Modeling Evapotranspiration during SMACEX: comparing two approaches for local and regional scale prediction. *Journal of Hydrometeorology* 6(6): 910-922.

Tucker, C.J., D.A. Slayback, J.E. Pinzon, S.O. Los, R.B. Myneni and M.G. Taylor (2001). Higher northern latitude Normalized Difference Vegetation Index and growing season trends from 1982 to 1999. *International Journal of Biometeorology* 45:184-190.

Verdin, J., and R. Klaver (2002). Grid cell based crop water accounting for the famine early warning system. *Hydrological Processes* 16:1617-1630.

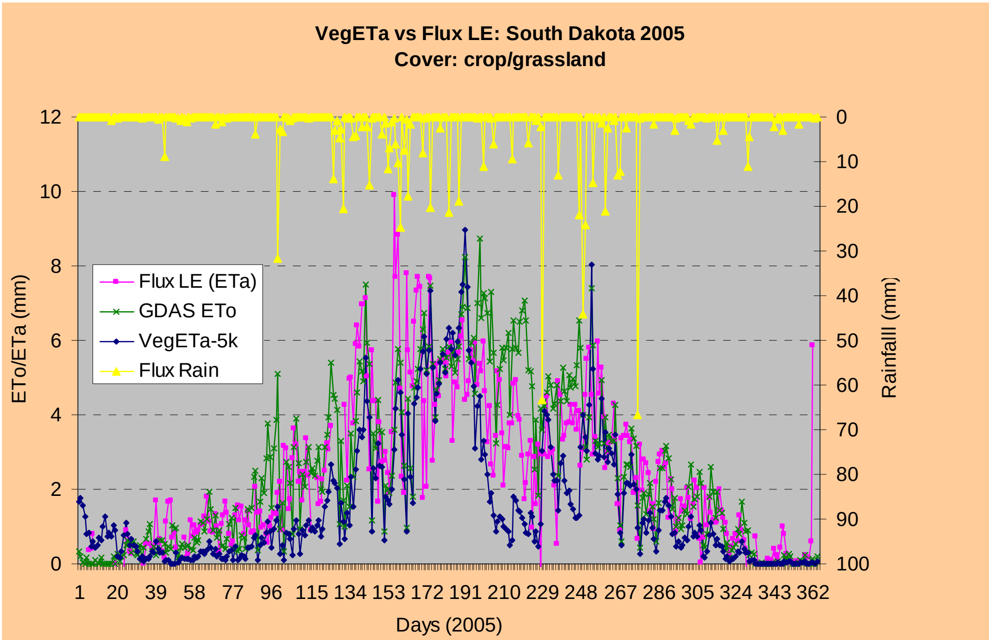


(a)

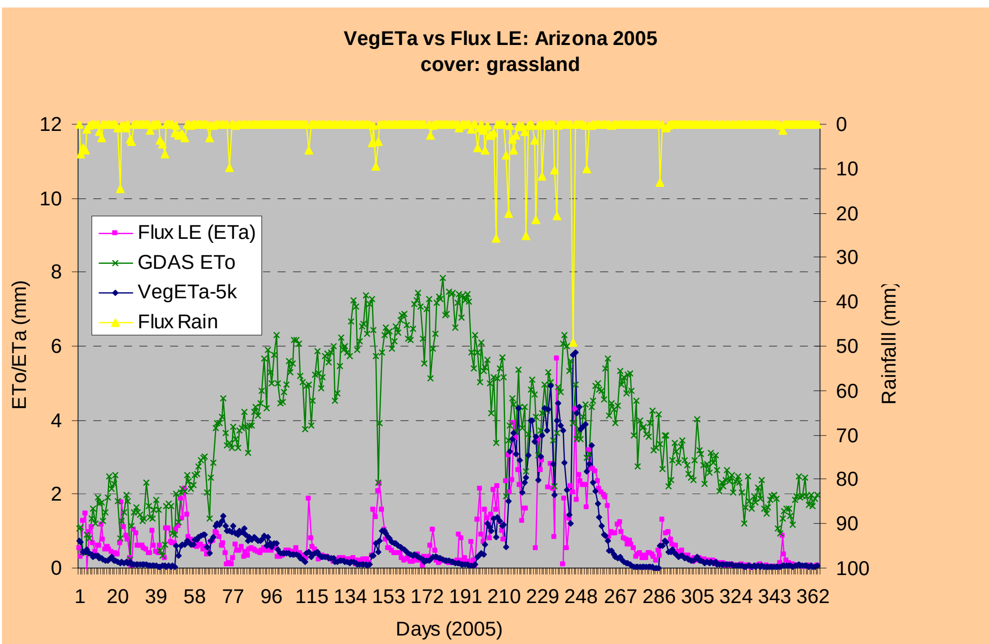


(b)

Figure 1: Seasonal ETa (May–September) maps for 2005 (a) and 2006 (b). Illinois appears drier (lower water use in the form of ET) in 2005 than 2006, whereas the southeastern United States and the Dakotas appear drier in 2006 than 2005.



(a)



(b)

Figure 2: Validation of VegET ETa using AmeriFlux data in cropland region, South Dakota (a) and grassland region (Arizona) using daily data from 2005. In South Dakota, both VegET ETa and flux tower latent heat (LE) flux track well close to the potential ETo. In Arizona (b), VegET and Tower (LE) track well but much lower than the "potential" GDAS ETo for much of the year, indicating a moisture limiting environment compared to an energy limiting condition in Figure 2a.

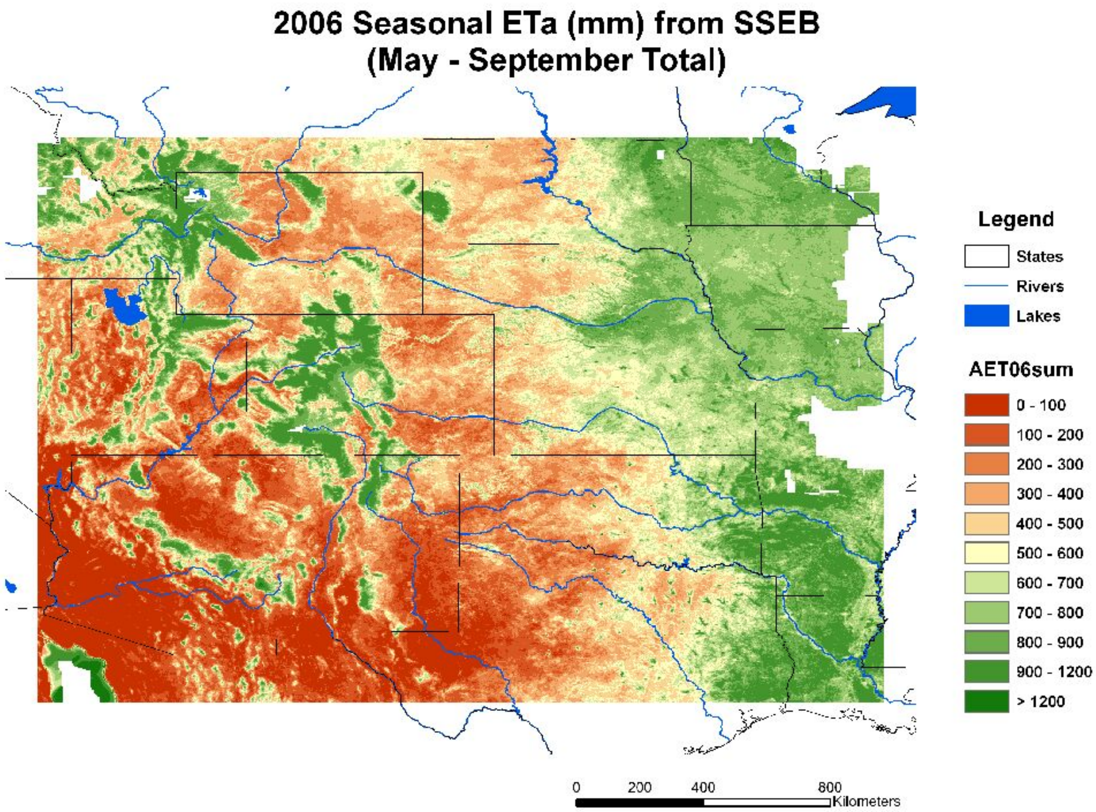


Figure 3: Seasonal ETa (May–Sep, 2006) in the Great Plains region of the United States at 1 km resolution, estimated using the SSEB model. Major crop growing regions, forested areas, and water bodies show higher season ETa values in excess of 600 mm while arid and semiarid regions show seasonal ETa values less than 300 mm.

Note that this model output does not include correction for elevation differences on the land surface temperature.

Null values (shown in white) are a result of missing data from any of the 8-day aggregation periods due to cloud cover or bad data in the MODIS thermal dataset.