WATER CONSUMPTION OF COMMON PLANTS IN THE SOUTHWEST U.S.

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Farmers and plant biologists make extensive use of evapotranspiration estimates to determine the amount of water needed for plant growth and survival. Hydrologists and water resource managers use such knowledge to estimate the amount of water lost from the soil, bodies of water, and vegetated areas through plant uptake. In the latter case, evapotranspiration (ET) is a measure of how much water is used by the plants for transpiration and tissue building. It is expressed as volume per unit area, or depth over a particular area. The total ET for a crop or plant is usually the total amount of water lost from the plant from the period of its planting to its harvesting time. Because such water is considered permanently lost by the plants, the process is also known as consumptive use. A good understanding of this process is important to determine the amount of water needed to grow a particular plant or to develop a large-scale agricultural project in a certain area. It also helps to ensure optimal water use—where it is most productive and needed—especially in the face of scarcity.

This paper provides a compendium of estimates of water consumed by various crops, grasses, fruit trees, shrubs, and some forest trees of the U.S. Southwest, as determined by various researchers. The most important factors contributing to the amount of consumptive use are identified, followed by a discussion of common wayw to estimate water consumption by plants. Although the data presented are for short periods of time, the information may be valuable for providing farmers, foresters, gardeners, and other water users and managers with a good estimate of the ET values of various plants. In the absence of such information, the different groups may also use the Blaney-Criddle method, which is discussed in some detail, to estimate the average ET value of a plant, or the consumptive use of water by plants.

STUDY AREA

Because evapotranspiration is highly influenced by both the climate and topographic characteristics of an area, it is appropriate to provide a description of the different aspects of climate and other factors that affect ET in the Southwest. The most important of these climatic characteristics are precipitation, temperature, relative humidity, wind speed, cloud cover, and solar radiation (Beschta 1976; Tecle 1990). Annual precipitation in the Southwest ranges from less than 15 cm in the deserts to more than 90 cm in the high mountains, and temperatures vary from less than −10° C during some winter nights on the mountains to as high as 50° C on summer days in the deserts. The Southwest is also characterized by low relative humidity, mostly clear skies, ample wind speed, and a good dose of solar radiation, all of which directly contribute to the high evapotranspiration rate in the area (Beschta 1976).

The information gathered for this study is from Arizona and neighboring areas in the Southwest. The climate of the study site is arid with an average annual rainfall of about 20 cm. The regional topography is highly variable, with plains in the lower elevations and along the coasts and rugged mountains along the Mogollon Rim, the western part of the Colorado Plateau, the Sierra Nevada Mountains, and the Coastal Ranges. These physical features have some influence on moisture availability and the rates of evapotranspiration. The consumptive use values for the different crops and other vegetation types presented in this paper represent these features and the climatic conditions in the region.

PURPOSE OF THE STUDY

Estimates of daily evapotranspiration values are used extensively to determine plant water requirements, and knowledge of the consumptive use of different plants is useful in determining plant water needs as well as designing the most appropriate irrigation-scheduling scheme. The latter, in

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turn, is important for establishing the right irrigation application rates for various crops or other vegetation types. Projection of the expected irrigation scheduling scheme for a plantation during a season requires estimation of periodic "expected evapotranspiration" for the different plants grown in the area. But most importantly, information on ET would help in adopting proper water resource management, especially where water is scarce such as in the U.S. Southwest.

The purpose of this paper is therefore mainly to present the estimated water consumptive use of various crops, vegetables, grasses, shrubs, fruit trees, and the most common deciduous and evergreen trees in the Southwest. This information also demonstrates that ET values for the same plants can differ both spatially and temporally. The variation is a function of an area's specific climatic and physiographic characteristics.

CONSUMPTIVE USE OF SOME COMMON PLANTS

Evapotranspiration (ET) or plant water consumptive use is a measure of the quantity of water used in the processes of plant transpiration and the building of plant tissues and the water evaporated from plant-intercepted precipitation during a specific period of time. The ET values gathered here are from different sources and provide results of studies made at different time periods. Table 1 shows the seasonal evapotranspiration values for various crops grown in Arizona and other similar places in neighboring states, and Table 2 gives the specific ET values for certain plants grown in the Owens Valley, CA (Duell 1990) as well as for a few grasses grown elsewhere in the Southwest (Todd 1970). The ET values in Table 1 are given for specific seasons in specific years.

An interesting point in the data of Table 2 is the large variation in the saltgrass ET values from one type of cover to another. For example, values vary from a low of 385 mm per year for desert sink scrub type vegetation to 989 mm per year for rush and sedge meadow cover types (Duell 1990). This means the ET value for any particular range plant depends on the type and severity of the prevailing climatic conditions in an area; the ET values of these range plants or any other plants in the U.S. Southwest should reflect such circumstances.

Table 3 provides the annual average ET values for certain hardwood plants and shrubs. However, it is important to note that these values were measured during just one year, 1960 (Todd 1970; Raymond and Rezin 1989).

FACTORS THAT INFLUENCE EVAPOTRANSPIRATION

Many factors or variables influence the amount and rate of ET in an area. The most important of these can be categorized as climatic, soil, plant, cultural, or a combination of these factors. The climatic factors that may affect the level of ET in an area include wind speed, land cover albedo, cloud cover, solar radiation, relative humidity, air and dew point temperatures, and precipitation, and these may be affected by an area's aspect, altitude, and latitudinal and longitudinal position (Doorenbos and Pruitt 1977).

Also the ways these factors occur have a direct bearing on the ET values. In the case of precipitation, for example, amount, duration, rate, frequency of occurrence, and the inter-arrival time between occurrences can affect the ET value of a plant in a particular place. The effects of such variables on ET can be through their influence on water availability and changes in temperature.

Soil conditions mainly affect plant ET values indirectly. The effects are usually a function of soil water availability, restriction in heat movement, and reduction in energy absorption. The effects of plants on ET, on the other hand, are more direct; the most influential factors are plant cover density, type of plant population, spacing and orientation in planting, plant height, rooting depth, stage of growth, shading, and the rate of water uptake by plants (Jensen et al. 1990). These factors may have either negative or positive effects on the water consumption of plants. For example, there may be more ET from a plant growing densely than from a sparsely spaced one, and shading may decrease the ET value from a plant while plant size increases it.

Cultural factors may also affect the amount and rate of ET. These factors are directly related to management activities or can be controlled easily to suit management needs. They include land preparation schemes, irrigation practices, tillage, weeding and harvesting methods, surface mulching and shading levels. Other influential factors may arise from the interaction or combination of the above factors. For example, ET reaches its maximum when uniformly dense vegetation is growing in water-saturated soils.

METHODS OF MEASURING ET

There are numerous methods of measuring and estimating ET (Shuttleworth 1993). Some require simple measurement such as using pan evaporation, while others are more complex and involve

Table 1. Seasonal evapotranspiration amounts (in mm) for well-watered, common crops in Arizona and other areas in the Southwest.

Crop	Location	Period	Years	ET Values	References
Field Crops					
Barley	Mesa, AZ	16 Dec–15 May	1952–53, 56	643	Erie et al. 1968
Cotton	Mesa & Tempe	1 Apr–15 Nov	1954–62	1046	Erie et al. 1968
Sugarbeet	Mesa, AZ	1 Oct–17 July	1965–66	1054	Erie and French 1965
Wheat	Mesa, AZ	15 Nov–15 May	1969–70	582	Erie et al. 1968
Safflower	Mesa, AZ	1 Jan–15 July	1958–60	1153	Erie et al. 1968
Soybean	Mesa, AZ	16 June–31 Oct	1944	564	Erie et al. 1968
Sorghum	Mesa, AZ	1 July–30 Oct	1955–58, 60	645	Erie et al. 1968
Flax	Mesa, AZ	1 Jan–30 June	1943–44	795	Erie et al. 1968
Corn	Davis, CA	15 May–20 Sept	1970–71	640	Erie et al. 1968
Corn, sweet	Mesa, AZ	16 Mar–15 June	1959, 61–62	498	Lourence & Pruitt 1971
Rice	Davis, CA	1 May–30 Sept	1968–69	920	Lourence & Pruitt 1971
Beans	Various areas		250–500	5	
Grain	Palo Verde, CA	12 months	1981–1982	579.12	Owen-Joyce & Kimsey 1987
Fruit Crops					
Grapefruit	Phoenix, AZ	12 months	1931–34	1217	Erie et al. 1968
Oranges	Phoenix, AZ	12 months	1931–34	993	Erie et al. 1968
Plumes	Arvin, CA	12 months	1962–63	1072	State of Calif. 1967, 1974
Vineyards	Different places	Seasonal	—	450–900	State of Calif. 1967, 1974
Vegetable Crops					
Broccolli	Mesa, AZ	1 Sep–14 Feb	1960–62	500	Erie et al. 1968
Cabbage	Mesa, AZ	1 Sept–15 Mar	1960–62	622	Erie et al. 1968
Cantaloupe	Mesa, AZ	1 Apr–15 July	1959–60	485	Erie et al. 1968
Carrots	Mesa, AZ	16 Sept–31 Mar	1960–62	422	Erie et al. 1968
Cauliflower	Mesa, AZ	16 Sept–31 Mar	1960–62	472	Erie et al. 1968
Lettuce	Mesa, AZ	16 Sept–31 Dec	1960–62	216	Erie et al. 1968
Onion, dry	Mesa, AZ	1 Nov–15 May	1961–62, 64	592	Erie et al. 1968
Onion green	Mesa, AZ	16 Sept–31 Jan	1960–62	445	Erie et al. 1968
Potatoes	Phoenix, AZ	15 Feb–15 June	1959–63	617	Erie et al. 1968
Tomatoes	—	Seasonal	—	300–600	Doorenbos & Pruitt 1977
Forage Crops					
Alfalfa	Mesa & Tempe	12 months	1946, 50, 62–63	1887	Erie et al. 1968
Alfalfa	Palo Verde Valley, CA	12 months	1981–1982	1615.44	Owen-Joyce & Kimsey 1987
Bermuda	Mesa, AZ	16 Apr–15 Oct	1959–60, 63–64	1105	Erie et al. 1968
Turf	Reno, NV	112 days	1965–67	554	Tovey et al. 1969
Grass	Arvin, CA	12 months	1960–65	1308	State of Calif. 1967, 1974

various activities. The latter type includes the soil depletion method, the use of lysimeters, and a method involving the Bowen ratio.

The soil water depletion method involves measuring the change in soil water to indicate the amount of water lost due to ET over a period of time. In an irrigation system, for example, soil is sampled 2–4 days after irrigation or rain and again 7–15 days later or just before the next irrigation period. The holes from which the soil cores are removed are usually filled with soil, and are marked to enable taking the next samples some 30–40 cm from the first core to minimize sampling error. In this way, the amount of moisture in the soil samples is measured.

Another method uses lysimeters, which are tanks filled with soil in which crops or other plants grow under natural conditions to measure the amount of water lost by evaporation and transpiration. This method provides a direct measurement of ET and is frequently used to study climatic effects on ET. This method assumes conditions inside the lysimeters to be essentially the same as those outside.

Table 2. Annual evapotranspiration values for range plants in Jan–Dec, 1984–1985 in the Owens Valley, CA (Duell 1990) and for other grasses in the Southwest (Todd 1970).

Type of Cover	Plant Type	ET Values (mm)	Sources
Alkali meadow	Alkali sacaton	828	Duell 1990
Rabbitbrush meadow	Saltgrass orrubber rabbitbrush	471	Duell 1990
Desert sink scrub	Rubber rabbitbrush, alkali sacaton or Mormon tea	606	Duell 1990
Desert sink scrub	Saltgrass greasewood	385	Duell 1990
Alkali meadow	Saltgrass, alkali sacaton, and rubber rabbitbrush	626	Duell 1990
Alkali meadow	Nevada saltbrush, alkali sacaton & rubber rabbitbrush	820	Duell 1990
Rush and sedge meadow	Saltgrass, alkali sacaton & Baltic rush	989	Duell 1990
Chaparral	Southern California chaparral	508	Todd 1970
Grass type	California woodland-grass	457	Todd 1970
Chaparral	Arizona chaparral	445	Todd 1970
Grass and shrub	Semiarid grass and shrub	269	Todd 1970

Table 3. Annual ET values in 1960 for some common trees and shrubs in the U.S. Southwest.

Plant Type	ET Values (mm)	Source
Lodgepole pine	483	Todd 1970
Engelmann spruce–fir	381	Todd 1970
White pine–larch–fir	559	Todd 1970
Mixed conifer	559	Todd 1970
True fir	610	Todd 1970
Aspen	584	Todd 1970
Pacific Douglas-fir–hemlock and redwood	762	Todd 1970
Interior ponderosa pine	432	Todd 1970
Interior Douglas-fir	533	Todd 1970
Pinion-juniper	368	Todd 1970
Saltcedar	1812.1	Raymond and Rezin 1989
Arrowweed	1628.2	Raymond and Rezin 1989
Mesquite	2585.3	Raymond and Rezin 1989
Cottonwood-willow	712.5	Raymond and Rezin 1989
Mixed stand	1396.8	Raymond and Rezin 1989

A third method is the energy balance method, which involves the Bowen ratio, which is the ratio of upward energy flux as sensible heat to the latent energy flux in the same direction. This method is used to determine hourly or shorter values of ET (Jensen et al. 1990.)

ESTIMATING EVAPOTRANSPIRATION

There are a number of methods for estimating reference evapotranspiration (ET). The methods differ from one another in terms of the main climatic characteristic(s) or variables they use. As noted above, the simplest method to determine the ET value of an area is to use an evaporation pan. The value so determined is then adjusted using an adjustment factor to estimate the actual ET values of specific plants. Other more complex methods used to estimate ET values include the radiation-based estimating method of Priestley and Taylor (1972), the temperature and radiation method of Jensen and Haise (1963), the Penman model, which is based on combined energy and mass transfer principles (Penman 1948), the temperature-based methods of Hargreaves and Samani (1982), the soil moisture depletion method (Bell et al. 1987), the lysimeter method (Aboukhaled et al. 1982), and numerous other techniques (Shuttleworth 1993).

One method that is commonly used around the world to estimate ET that is a little more involved than the pan evaporation method is the Blaney-Criddle method, described in Doorenbos and Pruitt (1977). This method is presented here because it is relatively simple and requires only a few variables to calculate the reference crop ET values. The variables, which are easy to measure, are mean daily temperature, daily minimum relative humidity, average daily sunshine hours, daytime wind speed, daily solar radiation, and monthly extraterrestrial radiation of an area. The primary equation for this method may be expressed as

$$ET_r = a + b*[p*(0.46*T + 8.0)] \quad [1]$$

where ET_r = reference crop ET in mm/day for a particular month; a and b = adjustment factors; p = mean daily percentage of total daylight hours for a given month and latitude; and T = mean daily temperature in °C.

The mean daily temperature used in the above equation for reference ET can be determined using the equation

$$T(°C) = [T_{max}(°C) + T_{min}(°C)]/2 \quad [2]$$

where T_{max} and T_{min} are, respectively, the maximum and minimum daily temperatures in an area.

The adjustment factor a, used in the Blaney-Criddle method for estimating ET_r, is determined using minimum relative humidity and daily sunshine hours as shown in the following relationship, developed for Arizona conditions (Yitayew 1990):

$$a = 0.0043*[(RH_{min}) - (n/N)] - 1.41 \quad [3]$$

where RH_{min} = daily minimum relative humidity at the place of interest and n/N = the ratio of actual to maximum daily sunshine hours.

In the absence of measured data, the value of n/N can be estimated using the equation (Yitayew 1990)

$$n/N = 2*(R_s/R_a) - 0.5 \quad [4]$$

where R_s = solar radiation in millimeters per day and R_a = extraterrestrial radiation in millimeters for the month and latitudinal location of the site under consideration.

The value for the other adjustment factor, b, in the Blaney-Criddle method also depends upon estimates of minimum relative humidity, average daily sunshine hours, and daytime wind speed, as described in Yitayew (1990) and Doorenbos and Pruitt (1977). The values for these variables can be obtained from tabular or graphical relationships like those developed in Doorenbos and Pruitt (1977).

Once ET_r is determined, the actual ET for a particular plant can be estimated using an appropriate adjustment value, k. Accordingly, the actual evapotranspiration (ET_a) for a particular plant can be estimated using:

$$ET_a = k*ET_r \quad [5]$$

The value of k in this equation represents the ratio of actual plant ET to reference ET. As such it is important that accurate k and reference ET values be eventually developed for the different plants grown in order to estimate their consumptive use. For the time being, general reference ET rates are developed for the study site by extrapolating information provided in Yitayew (1990).

The average daily reference ET values (in mm/day) for the 12 months of the year are given in Figure 1. Using the monthly average daily values, the annual total reference ET for the study site is estimated to be 1100 mm (or 43.3 inches; Blee 1988). Then, assuming a k value of 0.75 for the area, the annual average ET for the site is about 825 mm (or 32.5 inches).

CONCLUSIONS AND RECOMMENDATIONS

Knowledge of the rate and amount of evapotranspiration from crops and other agricultural plants is important for proper planning and management of water use by plants. Such knowledge is especially more useful in arid and semi-arid areas, which face the dual problems of water scarcity and high plant consumption of water. This information enables farmers and plantation managers to decide when and how much water to use in their projects. Also knowledge of the water consumptive use of plants helps farmers decide the kinds of crops to plant under uncertain water conditions. For example, farmers would plant crops that have lower water consumption values during drought periods or in arid environments compared to farmers in wetter climates.

A couple of cautionary notes are in order in using the ET values of the different crops, fruit trees, grasses, shrubs, and trees provided in this study. Because most of the ET values presented are based on single year or single season measurements, the amounts may depend on the particular climatic conditions prevailing at the time of measurement. Hence, long-term measurement of ET would provide more reliable data for the various crops and other plants listed in this study.

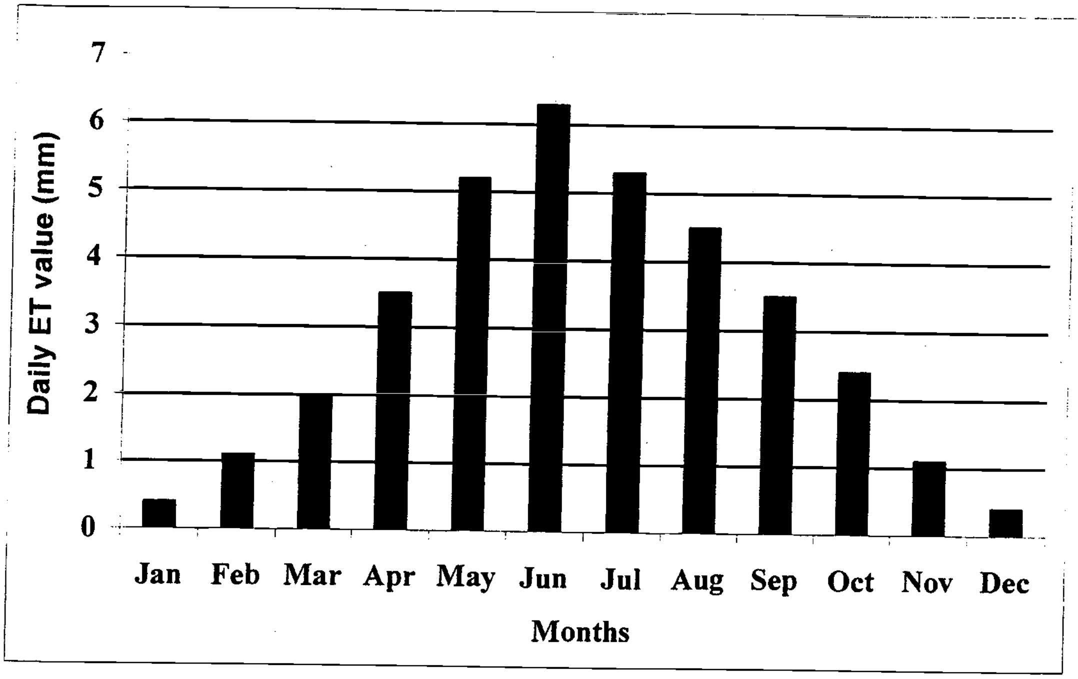

Figure 1. Monthly average reference evapotranspiration values for northern Arizona (the bars represent average daily values in mm).

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