ALFALFA: EFFICIENT OR INEFFICIENT USER OF WATER

R.S. Loomis[1] and J. Wallinga[2]

Abstract:

The efficiency of water use by alfalfa systems in production and conversion to human food is examined. The crop's efficiency is found to be as high or higher than several important alternative systems. Alfalfa does not appear to be a "water waster".

Keywords: evapotranspiration; water-use efficiency; food

INTRODUCTION

Alfalfa is viewed in the popular literature as a water-wasting crop. Whether that image is justified or not is an important question. Alfalfa is perennial and its annual use of water is of course large but its production is also large. To address the question, we need to examine the ratio of production to water use, i.e., the water use efficiency (WUE in kg dry forage ha^{-1} mm^{-1} water use) of the crop.

WATER USE BY VEGETATION

Plant cells conduct their chemistry in water and the dry atmosphere presents a serious challenge to the existence of plants. This challenge is met by epidermal layers on stems and leaves that are nearly impervious to water and water vapor. To grow, however, plants must exchange CO_2 and O_2 gases involved in photosynthesis and respiration with the outside air. This is accomplished through stomatal pores. The problem is that the walls and membranes of interior cells are freely permeable to water and the interior air spaces thus are saturated with water vapor. The strong gradient in vapor pressure between the interior space of a leaf and outside air causes a net flow of vapor from the leaf (transpiration) whenever the stomates are open. The flow is sustained by evaporation of water from the surfaces of the interior cells. The energy for evaporation comes from the leaf's radiation balance and from the surrounding warm air.

---

[1] Professor Emeritus, Agronomy & Range Science, University of California, Davis, CA 95616

[2] Graduate student, Theoretical Production Ecology, The Agricultural University, Wageningen, The Netherlands

In addition to transpiration, evaporation also occurs from soil surfaces, particularly when these are wet and unprotected by a canopy of leaves. The combination of transpiration + soil evaporation is termed evapotranspiration (ET, mm d^{-1}) and is a companion process of any vegetation. Where the seasonal evaporative demand (radiation load, atmospheric dryness, and wind) exceeds the amount of water available from rainfall and stored soil moisture, plants will be stressed, stomates will close, and plant productivity will decline. It is this limitation to production that we seek to eliminate for agriculture and landscape plantings in semiarid and arid environments through irrigation from developed water supplies.

ET varies strongly over the season due to variations in evaporative demand and to the type of cover presented by the crop. ET from lawn grass that completely covers the soil surface and is never short of water is taken as a standard, termed Reference ET (ET_o), against which other crops are compared. In Fig. 1, ET_o is compared with crop ET (ET_c) for sugarbeet, corn, dry bean, and barley at Davis. These crops differ from ET_o due to variations in duration of growth, degree of cover, color, and "roughness" (height and openness of the stand). Lawns are relatively smooth to wind and peak rates of ET_c for most types of vegetation, including the crops illustrated in Fig. 1, are greater than ET_o. Also evident are large differences among crops due to duration of cover and to growth during winter (barley) and summer (corn).

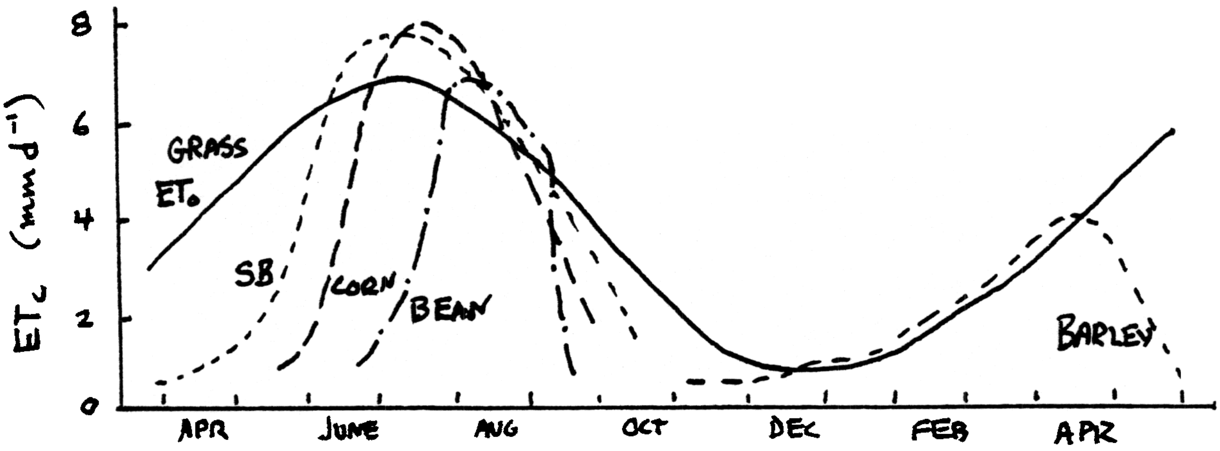

Fig. 1. Seasonal patterns of daily ET_c for various crops and ET_o of grass at Davis, CA. Redrawn from Pruitt et al. (1972).

With full cover, ET_c of alfalfa exceeds ET_o by about 20% but periodic harvesting results in extended periods of small cover when ET_c is much less than ET_o. This is illustrated in Fig. 2 with "crop coefficients" (K_c). For practical purposes, we can consider that low ET following harvest approximately balances the high ET at full cover, i.e., alfalfa $ET_c \approx ET_o$.

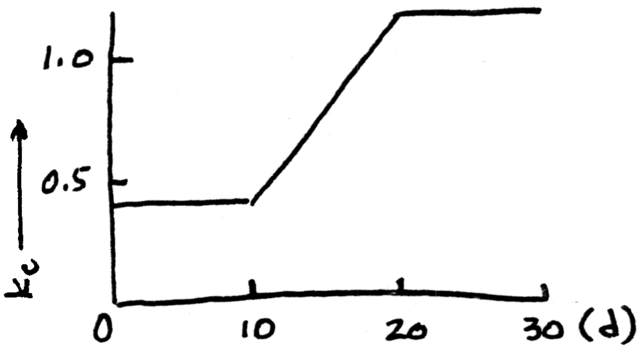

Fig. 2. Crop coefficients for alfalfa over the course of a cutting cycle.

ET_c can be measured as a component of the radiation and energy balances of a crop or from the crop's hydrologic balance:

$$P + I - R - D - S - ET_c = 0$$

where P is precipitation, I is irrigation, R is runoff, D is drainage, and S is change in soil storage. These rates are measured in mm d^{-1} or longer periods (1 in = 25.4 mm). To obtain the volume of water, multiply by rate by area to get m^3 (or ha mm or acre in). During a period without P or I (and thus little or no R and D), $ET_c = -S$ as measured from soil cores, neutron-gauge wells, or lysimeters. (Data for Fig. 1 were obtained with the large Davis weighing lysimeter.)

ET_o can also be estimated from weather variables with various forms of the "Penman-Monteith" equation. (The Pruitt form of the equation is used in California by CIMIS.)

WATER-USE EFFICIENCY

Since photosynthetic production and water loss both depend upon solar energy, leaf cover, and stomatal opening, we can expect a fairly close relationship between dry matter production and ET_c. Linear relationships are almost invariably found. Fig 3 is from D.W. Grimes' work at Parlier, CA.

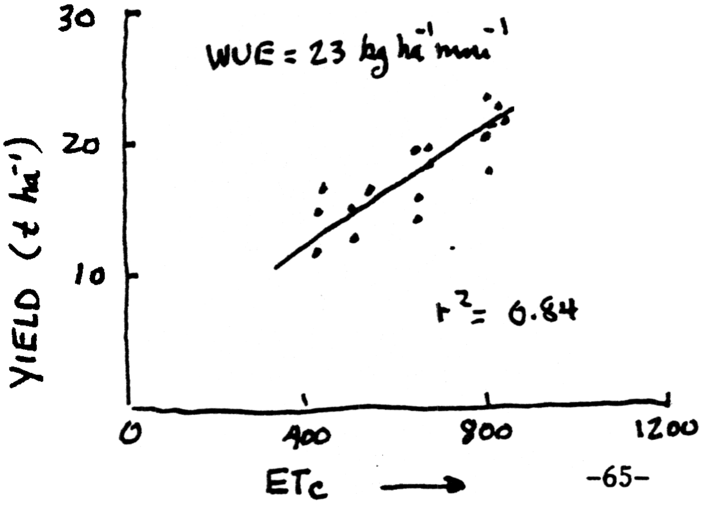

Fig. 3. Annual aboveground dry matter production by alfalfa as a function of season crop ET. Adapted from Grimes et al. (1992).

The slope of the line in Fig. 3 defines the WUE of that particular crop. The slope varies with factors that affect ET (weather) and with crop management (e.g., stand, disease, nutrient supply). Several observations of WUE by alfalfa in different environments are summarized in Table 1. For ready conversion to American units, 1 kg dry forage ha^{-1} mm^{-1} ET = 300 lb forage at 12% moisture acre^{-1} foot^{-1}.

Table 1. Observations of WUE for alfalfa.

Location	WUE (kg ha^{-1} mm^{-1}	Reference
New Mexico & Nevada	9-18	Sammis (1981)
North Dakota	15.9	Bauder et al. (1978)
Kimberley, ID	17.2	Wright (1988)
Lubbock, TX	17.4	Bolger & Matches (1990)
Cyprus	14.1-18.1	Metochis & Orphanos (1981
Logan, UT	14-22	Retta & Hanks (1980)
Parlier, CA	23.3	Grimes et al. (submitted)
Becker, MN	30.1	Carter and Shaeffer (1981

We are now able to simulate both production and water use by alfalfa with a sophisticated crop growth model (ALFALFA; Denison & Loomis 1989). The model has been validated against yield trials in various parts of the state and the simulations also agree well with ET$_c$ measurements of Grimes et al. (1992). At Davis, where the climate is particularly well suited to alfalfa, simulated WUE was near 25 kg ha^{-1} mm^{-1} during the summer period. The annual average at Davis, including the cold winter when alfalfa grows poorly, is near 19. Applied to Imperial Valley, the model predicts the seasonal pattern of WUE illustrated in Fig. 4

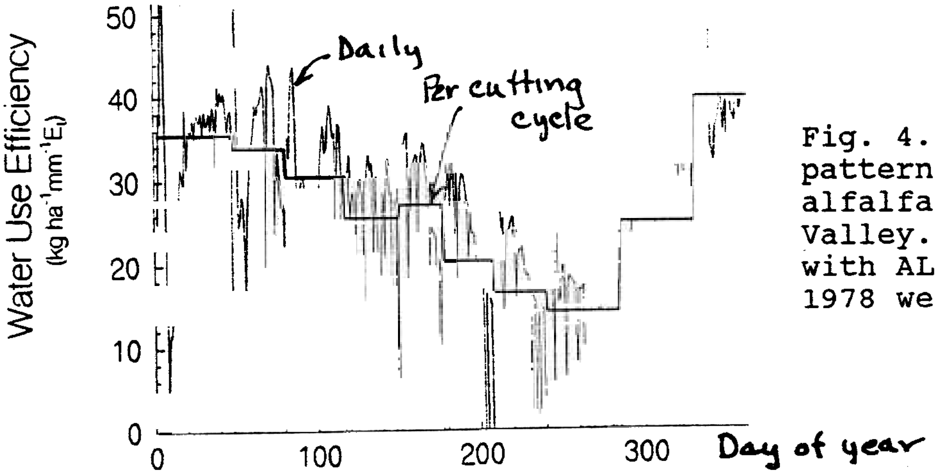

Fig. 4. Seasonal pattern of WUE by alfalfa in Imperial Valley. Simulated with ALFALFA 1.5 and 1978 weather data.

A strong climatic effect is clearly evident in Fig. 4 with high WUE in spring and fall and low values in late summer when crop ET is large and growth is poor. The annual average is 20 kg ha^{-1} mm^{-1}. Surprisingly, the effect of not irrigating during the summer period (to reduce water use) was the same as reducing acreage, i.e., annual WUE was not affected. Deficit irrigation, by contrast, lowered WUE.

We conclude from these simulations, and the data in Table 1, that California growers can expect ~20 kg ha^{-1} with good management. This is equivalent to 3 ton of 12% hay per acre foot.

COMPARISON WITH OTHER CROPS

Whether alfalfa is "water wasting" must be judged in relation to other crops. Such comparisons are complicated. Here, we will attempt a comparison on a food-value basis with the crops illustrated in Fig. 1. To do this, we need to have total biomass production (W), the harvest index (HI), and the food or feed → food value. For alfalfa, all of the aboveground forage is harvested but it then must be fed to a dairy or beef animal to arrive at food per unit water. Approximate nutritional efficiencies (E) of cattle and humans with particular feeds and foods were calculated from USDA and NRC handbooks following the approach presented in Loomis and Connor (1992). The basic scheme of calculation is:

$$WUE_b = \text{biomass } (W)/ET_c$$

$$WUE_h = WUE_b \times HI$$

$$WUE_f = WUE_b \times HI \times E$$

Results from the first two equations are given in Table 2 while those from the third equation appear in Table 3.

Table 2. Approximate WUE (kg ha^{-1} mm^{-1}) of various crops grown in the Davis environment compared on biomass and harvested yield bases. Corn, barley, and dry bean are taken as grains; sugarbeet as sucrose.

Crop	Season ET_c (mm)	Biomass (kg ha^{-1})	WUE_b	HI^1	WUE_h
Alfalfa	1330^2	25 000	18.8	1.00	18.8
Corn	710	22 000	32.6	0.50	16.3
Sugarbeet	780	26 000	30.6	0.45	14.0
Barley	390	10 000	25.6	0.45	11.5
Dry bean	570	6 000	10.5	0.40	4.2

[1] HI = harvest yield as a fraction of aboveground biomass.
[2] ET_c for alfalfa includes the winter period when no production occurs.

Alfalfa suffers in Table 2 through inclusion of winter ET_c (ca. 300 mm). Fallow ET for the other summer crops amounting to perhaps 50 mm was not included in the calculations. The superior WUE of "C4" type photosynthesis is evident in WUE_b of corn but sugarbeet and barley are nearly as effective because of their growth during cool weather.

Table 3. Approximate WUE_f (kg DM ha^{-1} mm^{-1}) of various crops expressed on the basis of human food produced in direct consumption or after conversion by animals. WUE_f is also given in human-edible energy (MJ ha^{-1} mm^{-1}) and protein (kg ha^{-1} mm^{-1}).

System	WUE_h	E^1	WUE_f	$WUE_{f\text{-Joule}}$	$WUE_{f\text{-protein}}$
Alfalfa→sprouts	1.1	0.40	0.5	9	0.10
Alfalfa→beef	18.8	0.03	0.6	18	0.24
Alfalfa→milk	18.8	0.15	2.7	63	0.73
Corn→beef	16.3	0.06	1.0	31	0.42
Corn→milk	16.3	0.25	4.1	96	1.10
Barley→beef	11.5	0.06	0.7	22	0.29
Barley→beer	11.5	0.31	3.6	81	0.14
Sugarbeet	14.0	1.00	14.0	220	0
Dry bean	4.2	0.70	2.9	50	0.73

[1] Conversion by cattle to dry edible meat and milk calculated on net energy basis for moderate rate of production (e.g., 0.8 kg live gain d^{-1}). E values also account for the fraction of human-edible material in the product and its digestibility by humans.
to milk:

While the calculations in Tables 2 and 3 should serve well as a first approximation, the numbers should be treated with caution. Production, water use, and conversion efficiency all vary with climate and management practice. Table 3 offers a number of important tentative conclusions. Sugarbeet, for example, is the winner over the other options on a digestible-energy basis and alfalfa sprouts, a popular "alternative" food, is very poor while beer is surprisingly good. The important point for our story is that alfalfa conversion to human-edible energy and protein per unit ET_c compares quite favorably with the grain systems and with a vegetarian diet of beans. WUE of the corn systems would about double, however, if the calculations were done for a silage system.

In a final analysis, dollar value is perhaps the most valid basis for comparison. The great bulk (ca. 80%) of California's alfalfa production goes to milk providing it with both value and efficient use of water. How do we compare that, however, with water use for urban lawns or with alfalfa fed to pleasure horses?

SUMMARY

The efficiency of water use by alfalfa systems is found to be as high or higher than several important alternative systems. Alfalfa does not appear to be a "water waster".

LITERATURE CITED

Bauder, J.W., A. Bauer, J.M. Ramirez, and D.K. Cassel. 1978. Alfalfa water use and production on dryland and irrigated sandy loam. Agron. J. 70:95-99.

Bolger, T.P. and A.G. Matches. 1990. Water-use efficiency and yield of sanfoin and alfalfa. Crop Sci. 30:143-148.

Carter, P.R. and C.C. Shaeffer. 1983. Alfalfa response to soil water deficits. I. Growth, forage quality, water use and water use efficiency. Crop Sci. 23:669-675.

Denison, R.F. and R.S. Loomis. 1989. An integrative physiological model of alfalfa growth and development. Publ. No. 1926. Div. Agric. Nat. Res., Univ. Calif., Oakland, California. 73 p.

Grimes, D.W., W.R. Sheesley, and P.L. Wiley. 1992. Alfalfa irrigation for hay/forage production: I. Yield, evapotranspiration, and crude protein. (In preparation.)

Loomis, R.S. and D.J. Connor. 1992. Crop ecology: productivity and management in agricultural systems. Cambridge University Press, Cambridge, U.K. (In press.)

Metochis, C. and P.I. Orphanos. 1981. Alfalfa yield and water use when forced into dormancy by withholding water during the summer. Agron. J. 73:1048-1050.

Pruitt, W.O., F.J. Lourence, and S. von Oettingen. 1972. Water use by crops as affected by climate and plant factors. Calif. Agric. 26(10):10-14.

Sammis, T.W. 1981. Yield of alfalfa and cotton as influenced by irrigation. Agron. J. 73:323-329.

Wright, J.L. 1988. Daily and seasonal evapotranspiration and yield of irrigated alfalfa in southern Idaho. Agron. J. 80:662-669.