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WATER BALANCE CALCULATIONS, WATER USE EFFICIENCY, AND ABOVEGROUND NET PRODUCTION

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Abstract

A discrete form of the water balance equation is used to illustrate the interaction among precipitation, runoff, percolation below the root zone, bare soil evaporation, plant transpiration, and plant available soil moisture. Under rangeland conditions, water availability is often the limiting factor in plant survival and growth. Therefore, the water balance equation is used, together with soils data and water use efficiency factors, to estimate annual aboveground net primary production of perennial vegetation.

INTRODUCTION

Arid and semiarid rangelands are extensive (e.g., Branson et al., 1981), and in these regions, water availability is most often the limiting factor in plant production. Water availability is also the most important environmental factor controlling survival of range plants (e.g., Brown, 1977). Therefore, water balance calculations are essential in soil-water-plant relationships studies. Plant water use, as a component of total evapotranspiration (ET), affects the water balance and soil moisture content, and thus, infiltration and runoff. As will be discussed later, soil moisture often limits the rate of ET so that consideration of feedback is necessary in water balance calculations.

If we assume no net subsurface water movement in the horizontal direction and a limited rooting depth well above the permanent water table, then a discrete form of the water balance equation in terms of unit area is:

$$\frac{\Delta S}{\Delta t} = P - Q - ET - L \quad (1)$$

where:

- S = soil water content (mm representing units of volume per unit area),
- Δt = time for the calculation period (e.g., hr, day, month, etc.)
- P = rainfall depth for the time interval (mm),
- Q = net runoff for the area (mm),
- ET = combined evaporation and plant transpiration (mm), and
- L = seepage or percolation below the root zone (mm).

The rate of ET in Eq. (1) depends upon atmospheric demand (a potential rate), soil texture, and vegetation characteristics (e.g., the leaf area index (LAI)) when soil moisture (SM) is nonlimiting, and upon soil water content, soil texture, atmospheric demand, and vegetation characteristics when water is limiting. Veihmeyer and Hendrickson (1955) suggested that the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET) stayed about constant as the soil moisture decreased from field capacity to near the wilting point. Thornthwaite and Mather (1955) suggested a linear relationship between the ratio AET/PET and available soil water. Other investigators have proposed nonlinear relationships, as summarized by Hanson (1973, Fig. 3, p. 16). This relationship can be expressed as:

$$AET = \begin{cases} PET & SM \geq SM_1 \\ f(SM, PET) & SM_0 < SM < SM_1 \\ 0 & SM \leq SM_0 \end{cases} \quad (2)$$

where SM_1 is a limiting soil water content (between wilting point and field capacity) where soil water content above SM_1 does not influence AET, and SM_0 is the permanent wilting point where plant available soil water is exhausted. The function f controls the ratio of AET to PET when soil moisture is between the limits SM_1 and SM_0 . The parameters SM_1 and SM_0 are often expressed in terms of the soil water content at -1/3 and -15 bars, respectively.

Leaf area index (LAI) is the leaf area per unit area of land surface (e.g., m^2/m^2), and is often used in models to relate evapotranspiration and plant growth (e.g., Chang, 1968; Stern, 1965; Penman, 1963; and Brougham, 1956). Hanson (1973, Fig. 2, p. 15) illustrates two relationships between LAI and AET/PET. For LAI = 0 (bare soil), the ratio AET/PET varied from zero to about 0.26, depending upon the

relationships assumed and on the potential rate, PET. For LAI = 1.0, the ratio was about 0.5, and for LAI > 2.5, the ratio approached 1.0. Therefore, LAI can be used to estimate the magnitude of AET and to partition total AET into bare soil evaporation, E, and plant transpiration, T (e.g., Parton et al., 1978; Ritchie, 1972; Ritchie and Burnett, 1971; Ritchie et al., 1976; and Smith and Williams, 1980).

Ritchie (1972) describes the two stages of bare soil evaporation: stage 1 (constant rate limited by supply of energy to the surface) and stage 2 (falling rate stage where water movement to evaporation sites at the surface depends upon soil properties). The volume of evaporation during stage 1, u, is:

$$u = a (c - b)^d \quad (3)$$

where u is in mm, a, b, and d are fitting coefficients (e.g., a = 9, b = 3, and d = 0.42 fit Ritchie's data), and c is a parameter dependent upon soil texture. Stage 2 evaporation rate is:

$$E_{s2} = 1/2 ct^{-1/2} \quad (4)$$

where E_{s2} is evaporation in mm/day, t is time in days since initiation of stage 2, and c is the soil texture parameter. The total soil evaporation during a drying period, t, can then be approximated as:

$$E_t = u + \int E_{s2} dt \quad (5)$$

which, as a first order approximation for a finite time period, can be represented as:

$$E_t = u + Au = (1 + A)u \quad (6)$$

where A is the ratio of stage 2 to stage 1 evaporation volume.

Now, if this volume is assumed to represent water extracted when soil moisture is between field capacity, FC, and wilting point, WP, then by continuity, we can write:

$$y(FC - WP) = (1 + A)u \quad (7)$$

where y is the effective depth influenced by bare soil evaporation. Values of c, in Eq. (3) and (4), are reported by Ritchie (1972) and by Jackson et al. (1976). The value of E_t , in Eq. (5), was compared with data from Ritchie (1972), Hillel (1976), and Jackson et al. (1976) to estimate the value of A in Eq. (6). Data presented by Jackson et al. (1973, Fig. 8) show the locus of the zero flux surface (vertical direction) in a soil profile (16 to 38 cm with a mean of about 20 cm) which provided experimental data to compare with y values calculated from Eq. (7). Finally, SCS (1982) presents additional data on values of c in Eq. (4) vs. soil texture.

Rawls et al. (1982) analyzed data from over 1300 soils in 32 states to generalize soil water properties as a function of textural class. Interpolated values from the texture triangle (from Rawls et al. (1982) and from SCS (1982)) were combined to produce the gross soil properties summarized in Tables 1 and 2. Table 1 lists 12 texture classes, representative proportions of clay, silt, and sand, mean rates of saturated hydraulic conductivity, and soil evaporation parameters. Notice that the data labeled "avg" represent a central, or representative, value for mean hydraulic conductivity and c in Table 1, and for mean water holding capacities in Table 2. The columns labeled "low" and "high" refer to low and high estimates on the mean, not to the maximum expected range for the given parameter. Moreover, the parameters in Tables 1 and 2 were derived predominately from agricultural soils, and probably do not represent desert soils with high gravel content.

Table 1.--Selected soil properties based on soil textural class.

Soil texture class	Representative composition			Saturated hydraulic conductivity (cm/hr)			Bare soil evaporation parameter c(mm/day 1/2)		
	Clay	Silt	Sand	Avg	Low	High	Avg	Low	High
Sand	3	7	90	23.	11.7	43.2	3.3	3.05	3.32
Loamy sand	5	15	80	6.1	3.6	11.7	3.3	3.05	3.32
Sandy loam	10	20	70	2.2	1.7	3.6	3.5	3.10	4.06
Loam	20	40	40	1.3	.91	1.7	4.5	3.20	4.57
Silt loam	15	65	20	.69	.46	.91	4.5	3.20	4.57
Silt	5	87	8	.51	.30	.61	4.0	3.15	4.40
Sandy clay loam	30	10	60	.30	.25	.46	3.8	3.15	4.32
Clay loam	35	35	30	.20	.19	.25	3.8	3.15	4.32
Silty clay loam	35	55	10	.18	.15	.19	3.8	3.15	4.32
Sandy clay	45	5	50	.13	.11	.15	3.4	3.10	3.56
Silty clay	45	50	5	.10	.09	.11	3.5	3.10	3.81
Clay	65	20	15	.08	.06	.09	3.4	3.10	3.56

Table 2.--Porosity and water holding capacity (water content in % by volume) based on soil textural class.

Soil texture class	Total porosity			-1/3 Bar Water holding capacity			-15 Bar Water holding capacity		
	Avg	Low	High	Avg	Low	High	Avg	Low	High
Sand	41	39	43	9	7	15	3	2	6
Loamy sand	43	39	45	12	10	20	6	4	8
Sandy loam	45	39	52	20	14	29	9	5	12
Loam	47	45	52	26	20	36	12	9	18
Silt loam	50	49	55	31	20	36	13	7	20
Silt	51	49	55	28	26	30	9	6	12
Sandy clay loam	42	38	45	27	17	34	17	11	21
Clay loam	47	40	51	34	29	38	20	16	24
Silty clay loam	47	46	51	36	33	40	21	18	24
Sandy clay	42	40	44	31	27	40	21	18	30
Silty clay	48	46	49	40	35	46	27	23	32
Clay	49	44	52	42	34	49	29	23	38

Smith and Williams (1980) describe the AET calculations used in the CREAMS model (Knisel, 1980). Their basic equations follow Ritchie's model, and were formulated as follows: Potential daily soil evaporation is adjusted for the plant canopy such that

$$E_{s0} = E_0 e^{-.4 \text{ LAI}} \quad (8)$$

where E_0 is the potential evaporation, and E_{s0} is the reduced potential soil evaporation which is then used to compute stage 1 and stage 2 evaporation rate, as described earlier. Plant transpiration is computed as:

$$T_0 = \begin{cases} (E_0)(\text{LAI}/3) & 0 \leq \text{LAI} \leq 3 \\ E_0 - E & \text{LAI} > 3 \end{cases} \quad (9)$$

where E is the actual soil evaporation. If soil water is limiting, then the reduced transpiration is computed as:

$$T = (T_0)(\text{SM})/(0.25 \text{ FC}) \quad (10)$$

where T_0 is computed from Eq. (9), SM is soil moisture $< 0.25 \text{ FC}$, and FC is field capacity of the soil. At each time step, the sum of soil evaporation, E from Eq. (3), (4), and (8), and transpiration, T from Eq. (9) and (10), cannot exceed E_0 calculated from temperature and radiation. Therefore, total AET is partitioned into soil evaporation and plant transpiration according to the value of LAI . This value of LAI varies throughout the season to reflect crop growth stage or plant phenological stages.

Therefore, to estimate AET and plant water use using a model such as Ritchie's equations in the CREAMS model, it is necessary to know soil properties (Tables 1 and 2), plant rooting depth, the seasonal LAI , and the other data used to solve the water balance equation. The CREAMS model is typical of many water balance-climate models in that it uses LAI to partition AET into E and T , and AET is limited by available soil moisture, as described by Eq. (2). More complex models (e.g., the ELM model, Innis (1978) and the EPIC model, Williams et al. (1982)) explicitly include plant growth components and direct feedback with the water balance components. In the absence of sufficient information to estimate the parameters of these complex models, or if the objective is to obtain first-order approximations for plant production when water is limiting, then simple water balance-plant production models (e.g., Wight and Hanks (1981) or Lane et al. (1983)) can be used to relate the water balance and plant production.

WATER USE EFFICIENCY

Water use efficiency (WUE) has been defined in many ways, but in each case, the intent was to relate a quantity of plant production to a quantity of water used for that production. Briggs and Shantz (1914), and others (e.g., Pendleton, 1966; Viets, 1966), have used the term water requirement to mean the amount of water required to produce a gram of aboveground dry matter. Others (e.g., Dwyer and DeGarmo, 1970) have used total dry matter production (roots, shoots, and fruits) as a measure of plant production in defining water use efficiency. Still others (e.g., Szarek, 1979; Tadmor et al., 1966) have used annual precipitation as a predictor for annual actual evapotranspiration, which in turn was used as a predictor of actual plant water use. McGinnies and Arnold (1939) illustrated seasonal influences on WUE, and Dwyer and DeGarmo (1970), among others, have illustrated the influence of soil moisture status on WUE. Unless we state otherwise, water use efficiency shall mean the ratio of the amount of aboveground dry matter production (g, g/m², kg, kg/ha) to the amount of water used in that production (g, kg, kg/m², mm) on an annual basis. The term water use excludes evaporation from bare soil and evaporation of intercepted

water from vegetation surfaces. Thus, production refers to aboveground only, and water use refers to plant water use. Finally, it is not known, explicitly, how WUE factors, measured under controlled conditions, apply to field conditions where water stress, competition, spatial variability in weather and soil characteristics, and related factors might affect water use efficiency.

Selected WUE data, from greenhouse or carefully controlled plot studies, are listed in Table 3. The first column of Table 3 lists the vegetation types, the second column lists WUE in units of g of aboveground dry matter production per kg of water use, which is the same as g d.w./m² over mm H₂O/m², or grams dry weight per square meter per mm of plant transpiration per square meter. The third column of Table 3 provides comments, and the fourth column lists the appropriate reference. The references were selected to be representative of results obtained from the literature for arid and semiarid rangelands. Data collected by McGinnies and Arnold (1939) were from 76-liter galvanized Witt cans filled with 125 to 145 kg of soil. Because of the rather large-sized soil containers and duration of the experiment (1932-1936), these data are probably among the most reliable of those shown in Table 3. These data represent annual means, with summer WUE being from near to one and a half times as large as the annual values. The mean annual WUE for the six desert grasses was 1.8 g d.w./kg H₂O and ranged from 1.7 to over 1.9. In contrast, the mean annual WUE for the desert shrubs and trees was 0.57 g d.w./kg H₂O and ranged from 0.42 to 1.30. Therefore, these data suggest that, on the average, the selected desert grasses have a WUE some three times higher than the selected trees and shrubs (the range of the ratio of WUE grass to WUE trees and shrubs was 1.3 to 4.6). Dwyer and DeGarmo (1970) used pots (18 cm diameter by 25 cm deep) to study the WUE of four desert grasses and four desert shrubs. Means for the desert grasses ranged from 1.0 to 1.09, with an overall mean of 1.03 g d.w./kg H₂O. The means for Dwyer and DeGarmo's four shrubs ranged from 0.23 to 0.57, with an overall mean of 0.28 g d.w./kg H₂O. These data suggest that, on the average, the desert grasses have a WUE some 3.7 times higher than the selected desert shrubs.

Table 3.--Selected water use efficiency data.

Vegetation (Type)	WUE (g d.w./kg H ₂ O)	Comments	References
Desert grasslands	1.70 - 1.92	Annual values for 6 species	McGinnies and Arnold (1939)
Plains grasslands	1.42 - 2.09	Annual values for 3 gramma grasses	McGinnies and Arnold (1939)
Southern tall grasss	1.41 - 2.12	Annual values for 3 species	McGinnies and Arnold (1939)
Desert shrubs and trees	0.42 - 1.30	Annual values for 6 species	McGinnies and Arnold (1939)
Desert grasses	1.00 - 1.09	Greenhouse study of 4 species, 120 days	Dwyer and DeGarmo (1970)
Desert shrubs	0.23 - 0.57	Greenhouse study of 4 species, 120 days	Dwyer and DeGarmo (1970)
Native and seeded within the pinyon-juniper type	-	Brief survey of values reported in the literature	Branson et al. (1981) from Gifford (1976)
Selected grasses	0.31 - 2.95	Brief survey of values reported in the literature	Teare (1977)

The ratio of mean WUE for the desert grasses, in McGinnies and Arnold's study to Dwyer and DeGarmo's, was 1.81/1.03 = 1.75, and, for the trees and shrubs, a similar ratio was 0.57/0.28 = 2.04. The reasons for these differences between the two experiments are not clear. One possible reason might be distortions due to root bound plants in the small pots. This situation, if it did in fact occur, would tend to lower the mean water use efficiency. Finally, Branson et al. (1981) and Teare (1977) present brief summaries of water use efficiency data selected from a variety of sources. Data, such as those presented in Table 3, may be used to estimate aboveground production. However, the magnitude of the variability in WUE values, as discussed above, should be kept in mind.

ANNUAL ABOVEGROUND NET PRIMARY PRODUCTION

Annual aboveground net primary production (ANPP) is the total aboveground dry weight (d.w.) biomass produced per unit area in a growing season. Net refers to the gross production minus respiration per unit time of an individual plant, and primary is the sum of the net productions of all individual plants in a unit area (Whittaker and Macks, 1975). Total above and below ground net primary production of general ecosystem types is summarized by Whittaker and Likens (1975). They suggest values for desert and semidesert scrub of 10 - 250 g/m²/yr, with a mean value of 90. Corresponding estimates for woodland and shrubland range from 250 - 1200, with a mean of 700, while values for temperate grassland vary from 200 - 1500, with a mean of 600. These values are for total annual net primary productivity so that the aboveground values would be significantly less, depending on the root-shoot ratios. Lieth (1975) lists similar estimates for selected climatic regions, and Murphey (1975) lists estimates for tropical terrestrial ecosystems. Webb et al. (1975) present productivity data, including grasslands and desert ecosystems,

and Szarek (1979) summarizes data for four North American deserts.

Generalized relationships relating annual actual evapotranspiration, AET, and annual aboveground net primary production, ANPP, have been developed by several investigators (e.g., Rosenzweig, 1968 and Webb et al., 1978). Data on ANPP and AET for three North American deserts (Szarek, 1979 and Lane et al. 1983) and for a site in the Tunisian steppes (Floret et al., 1982) are shown in Fig. 1. Notice that, for the data shown, Rosenzweig's equation tends to provide an upper limit on ANPP, and that the Webb et al. equation seems to fit the overall trend, but underestimates for low values of AET < 120 mm.

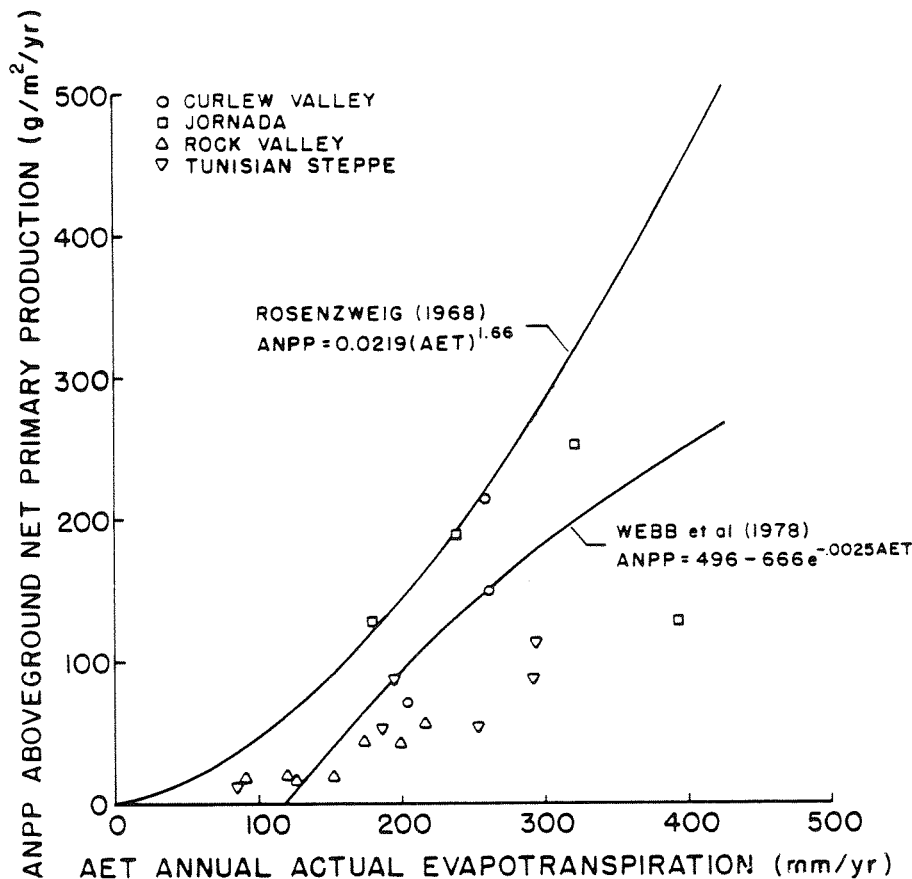


Figure 1.--Relation between AET and ANPP for selected data from desert and semidesert areas and proposed general relationships.

An expanded plot of the Rock Valley, Nevada data are shown in Fig. 2. The curve labeled 1 is the equation from Webb et al. (1978), and the curve labeled 2 is a linear regression between ANPP and AET. The least squares equation derived for this particular data set provides a better fit than the generalized equation which is intended for broader application over wider ranges of AET. For comparison, annual actual transpiration, AT, is plotted against ANPP, as shown in the left portion of Fig. 2, identified as curve 3. If seasonal estimates of transpiration from a continuous simulation model are used, then the unexplained variance in ANPP is further reduced ($R^2 = .90$), as described by Lane et al. (1983). The slope of the line relating AT and ANPP can be used as an approximate estimate of the water use efficiency, WUE, provided the intercept is near zero. From curve 3, in Fig. 2, the WUE for Rock Valley data is about 0.7, which is well within the range of values suggested in Table 3 (WUE values of 0.42 to 1.30).

If the product of AT and WUE provides a first order approximation of ANPP (curve 3 in Fig. 2), then relationships, such as curves 1 and 2 in Fig. 2 and the curves shown in Fig. 1, provide a somewhat coarser approximation using AET as an approximate predictor for actual plant water use, AT. The relationship between ANPP and AET is inherently weaker than the one between ANPP and AT, because AET includes bare soil evaporation, and is thus an imperfect predictor for AT or plant water use. However, less information is required to estimate AET than is required to estimate AT, so that the choice of approximating relationships depends upon the degree of accuracy required, the amount of information available, and the intended scale of application.

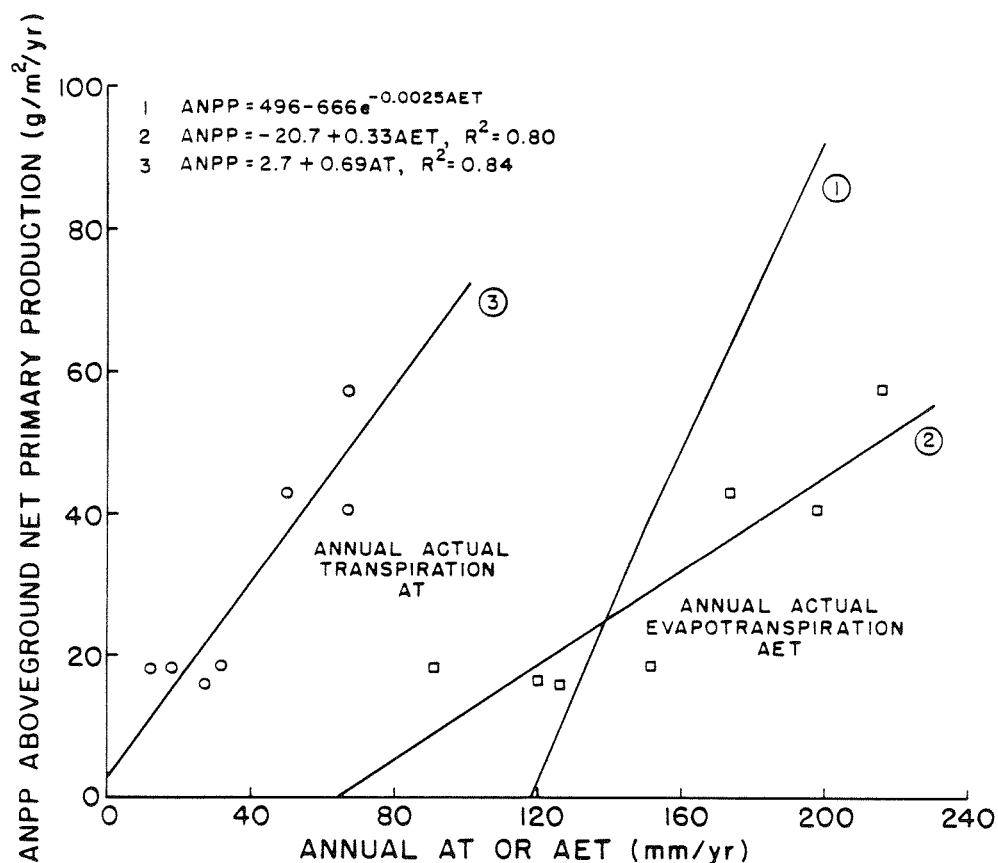


Figure 2.--Relation between annual AT, AET, and aboveground net primary production for Rock Valley, Nevada.

SUMMARY

Water balance calculations are important in soil-water-plant relationships studies and essential to predict net primary production when water availability is the limiting factor. These circumstances are often realized on arid and semiarid rangelands so that the water balance equation can be used together with soils data and water use efficiency factors to estimate net primary production. Equations (1) and (2) describe a simple water balance in a discrete form, selected soil properties are summarized in Tables 1 and 2, and water use efficiency factors are presented in Table 3. Figures 1 and 2 illustrate relationships between actual evapotranspiration, actual transpiration, and annual aboveground net primary production. Depending upon scale of application, available information, and desired accuracy, relationships such as these can be used to estimate annual aboveground net primary production of perennial vegetation.

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