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DEVELOPMENT OF A CLIMATE-BASED FORAGE GROWTH MODEL FOR A PEACE RIVER COMMUNITY PASTURE

by

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ABSTRACT

Based on periodic clipping of a fertilized pasture plot in the Peace River region in 1977 and 1979, accumulated dry matter production of a timothy, red fescue and alsike clover mix was found to be linearly related to accumulated transpiration during the active growing season, with a growth/transpiration ratio of 0.026 t ha^{-1}/(mm H_2O). The effect of fertilizer level and cutting management on dry matter production is discussed.

Energy balance/Bowen ratio measurements of evapotranspiration (E) in 1977, 1978 and 1979 showed that daytime E can be calculated for energy limiting conditions using the Priestley-Taylor formula with $\alpha = 1.26 \pm 0.05$. Daytime net radiation required in this formula was estimated to within 15%, using the Idso-Jackson longwave radiation equation and daily solar radiation data from a regional climate station 50 km away. During water supply limiting conditions E was found to be linearly related to root zone water storage. Root zone drainage was found to be negligible in this soil, which has a high bulk density subsoil.

A simple model for calculating the course of pasture growth during the growing season at Sunset Prairie Community Pasture is described. The model is composed of a single-layer root zone water balance submodel and a relationship between dry matter production and transpiration. The water balance submodel estimates daily transpiration and requires daily values of rainfall, solar radiation and maximum and minimum air temperature. It also requires crop albedo and an estimate of the initial root zone water storage. Estimates of root zone water storage during the three growing seasons agreed well with gravimetric and neutron moisture probe measurements. The model, using the above growth/transpiration ratio, was found to estimate hay growth during the droughty growing season in 1978 to within 15% of measured values. An effective growth/transpiration ratio of 0.013 t ha^{-1}/mm was required to account for the growth of pasture subjected to a simulated monthly grazing rotation.

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LIST OF SYMBOLS

a,b,c	Empirical coefficients
B	Jury-Tanner soil evaporation coefficient (Chapter II equation 8)
c_p	Specific heat of air
D	Drainage rate
e_a	Vapour pressure
e*	Saturated vapour pressure
E	Evapotranspiration rate
E_{eq}	Equilibrium evapotranspiration rate
E_{max}	Energy limited evapotranspiration rate
E_o	Evaporation rate from free water surface
E_s	Soil limited evapotranspiration rate
E_{soil}	Evaporation rate from bare soil
E_t	Transpiration rate
G	Forage growth (above ground dry matter)
I	Interception (daily)
$K\downarrow$, $K\uparrow$	Incoming and outgoing shortwave radiation flux density, respectively
$K\downarrow_{clear}$	Incoming shortwave radiation flux density on cloudless day
L	Latent heat of vapourization of water
$L\downarrow$, $L\uparrow$	Incoming and outgoing longwave radiation
LAI	Leaf area index
m	Growth/transpiration ratio
N	Days from start of growing season
P	Precipitation rate

Q^*	Net radiation flux density
Q^*_G	Net radiation flux density at soil surface
Q_E	Latent heat flux density
Q_G	Soil heat flux density
Q_H	Sensible heat flux density
r	Albedo (shortwave reflectivity)
r_c	Canopy resistance
r_a	Aerodynamic resistance
R	Runoff rate
s	Slope of saturation vapour pressure vs temperature curve
t	Time
T_a	Mean screen-height air temperature
ΔT, ΔT_w	Dry and wet-bulb temperature difference over vertical distance above crop canopy
W	Rootzone water storage
W_{min}	Value of W at which transpiration is approximately zero
W_{max}	Saturated capacity of rootzone
Δz	Thickness of soil layer
α	Priestley-Taylor coefficient
α_s	Priestley-Taylor coefficient for bare soil
β	Bowen ratio
γ	Psychrometric constant
ε_a, ε_s	Atmospheric and surface emissivities
σ	Stefan-Boltzman constant
ρ_B	Soil bulk density
θ_g, θ_v	Gravimetric (dry weight basis) and volumetric soil water content
θ_e	Extractable root zone water content

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I would like to thank the Kirtzinger family of Sunset Prairie for making us feel welcome in their home and in the community; all of us who worked on the project enjoyed their fellowship and gained a better perception of agriculture in the area through our association. Finally, I would like to thank the members of my family and my friends, especially Jane Watson, for their continual support and love.

CHAPTER I. INTRODUCTION

Large tracts of land in the Peace River region are being considered for potential agricultural use, but there are limitations to their development. In addition to the economic problems of location, there are climatic limitations to crop growth. Regional land-evaluation techniques such as that demonstrated by Williams *et al.* (1980) require verification, preferably including locally derived yield-climate relationships. In order to be useful on the scale of the region (18,000 km^2) the relationships should be based on easily obtainable data.

Many models have been developed to relate plant yield to climatic factors. Recently, models have been oriented towards extremely short time scales, of the order of single hydrologic events, or plant physiological processes. This level of detail is useful in research applications, but for regional studies simpler models are required.

In 1977, the B.C. Ministry of Environment began a project to study the relationship between pasture productivity and climate in the Peace River region. A study site was established in the Sunset Prairie Community Pasture, near Fort St. John, B.C. (Figure 1). During the first year of the study, micrometeorological instrumentation was operated

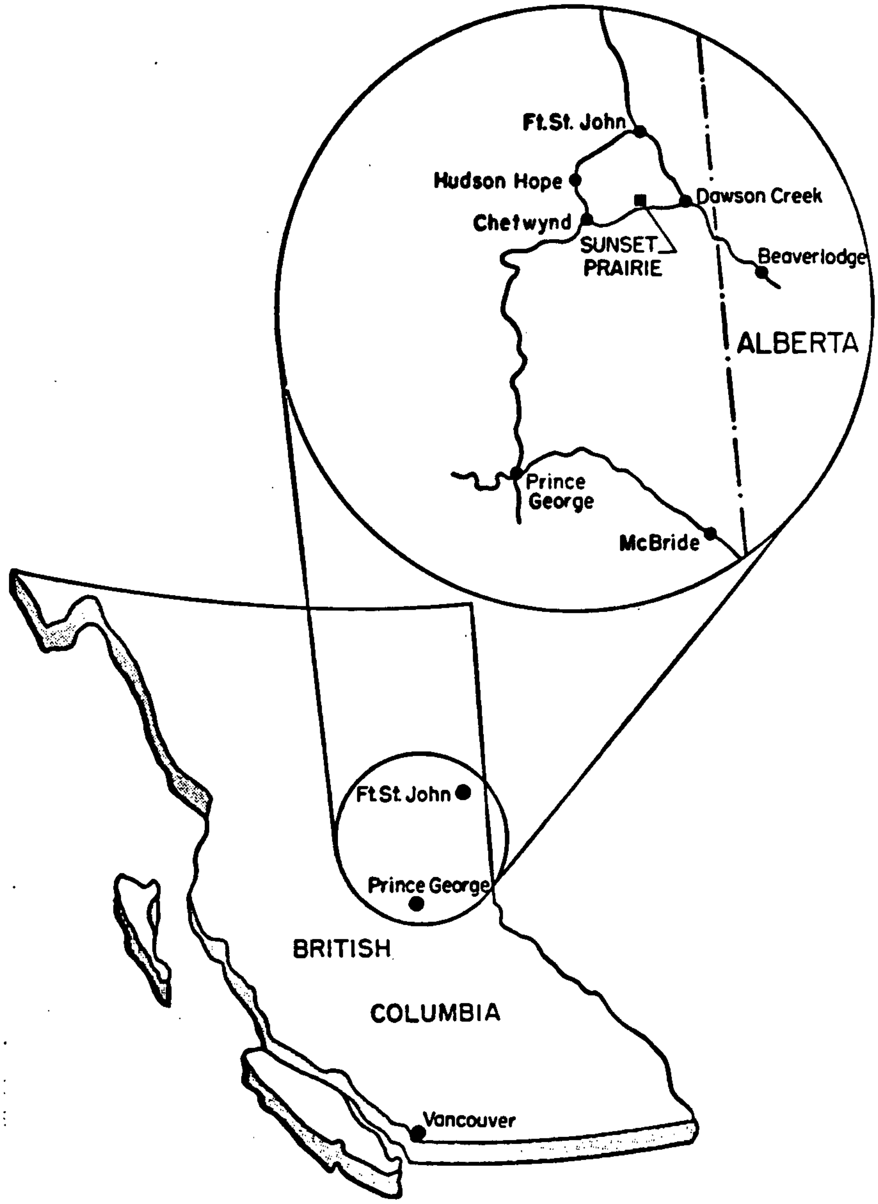

Figure 1. Outline map of British Columbia with inset showing Peace River region and location of Sunset Prairie Pasture (From Davis, 1978).

during the growing season, and plant production was measured. The study continued in 1978, with intermittent micrometeorological measurements supplementing basic climate and productivity data. In 1979, the study was extended to six auxiliary sites in order to assess variations within the pasture. During 1980 investigations were continued at two other community pastures to test the relationships found at Sunset Prairie.

This thesis constitutes a portion of the research carried out under Agriculture Canada contract #OSU 78-00211, and seeks to address the following objectives:

1. To determine whether relationships exist between pasture productivity and evapotranspiration under various growing conditions.

2. To determine whether these relationships can be used to develop a model of pasture production that requires data obtainable by land managers.

3. To test the relationships and the model for a variety of conditions and locations.

The first objective is addressed in Chapter II, where a linear relationship between above-ground dry matter production and transpiration is presented, based on data for two years when there was ample soil moisture. The relationship for a simulated monthly grazing rotation is compared with that for hay growth. The sensitivity of the relationship to fertility is also examined.

The second, and third objectives are addressed in Chapter III, in which a model is presented for estimating pasture production using routinely available data. The model consists of a growth/transpiration relationship, and a simple root zone water budget which is used to account for soil moisture limitations.

CHAPTER II. TRANSPIRATION AND GROWTH RELATIONSHIPS AT SUNSET PRAIRIE PASTURE

A. INTRODUCTION

In the Peace River region of British Columbia and Alberta, crop yields are susceptible to both moisture and temperature limitations (Williams et al., 1980). Grain cannot be grown to maturity in much of the region, so hay and pasture production are extensive. New land is being brought into production, and assessment of its potential is needed to help regional planners and managers. Crop productivity models developed in more southerly locations often require data which are not available in northern agricultural areas, so simpler procedures are desirable.

Much of the variation of crop yield in the Canadian Prairies is due to weather (Williams, 1970). Williams found regions where a factor, such as rainfall, was positively correlated with yield in dry years, and negatively correlated in wet years. This could occur if yield was water limited in dry years, and energy limited in wet years. The Peace River region is such a region, in which application of simple statistical techniques to yield prediction is unlikely to be successful. Statistical techniques are generally most useful in predicting final yields, but because they do not often rely on understanding growth processes, they are not generally used to predict the course of yield through the growing season. Models which are developed to simulate crop growth frequently incorporate water limitations, but may not emphasize temperature or energy limitations. Selirio and Brown (1979), in their model of forage yield, relate growth to growing degree days, and apply water limitation as a reduction factor. Their approach is quite successful, but it represents the integration of many years of research in Ontario, much of which has not been done in the Peace River region.

It is practical to try to relate growth to a single variable which describes both water and energy limitations. Evapotranspiration depends on the availability of water and energy to the crop, and has been used with considerable success as a yield predictor (Briggs and Shantz, 1913; Staple and Lehane, 1954; DeWit, 1958; Arkley, 1963; Rose *et al.*, 1972; Hanks, 1974; van Keulen, 1975). DeWit (1958) discussed the concept of an average growing season relationship between plant growth and transpiration expressed as:

$$G = m \int E_t dt \qquad (1)$$

where G is the aboveground dry matter growth, E_t is the transpiration rate, dt is a time increment, and m is the growth/transpiration ratio for the growing season. In predicting grain yields it has been recognized that susceptibility to water limitation varies with the stage of plant maturity (Biscoe et al., 1975; Morgan et al., 1980), and the concept of a single transpiration ratio has been modified to allow for weighting of critical periods (Hanks and Ashcroft, 1977). Modelling hay productivity is simpler, since vegetative growth is not so subject to critical periods as grain yield. Several workers have successfully related pasture growth to evapotranspiration under conditions of ample moisture supply (Stanhill, 1960; Penman, 1962; Rose et al., 1972; Davis, 1978). Rose et al. (1972) show how fertilizer level affects this relationship for Townsville Stylo in Australia and incorporate this in a simple model. It is also known that periodic cutting or grazing can reduce growth (Brougham, 1956; Younger and Nudge, 1976; Johns and Lazenby, 1973).

The objectives of this chapter are (i) to determine the relationship between crop growth and E_t during two growing seasons, 1977 and 1979, when growth was not limited by soil moisture, (ii) to find the dependence of the relationship on fertility, and (iii) to compare yields of uncut forage (hay growth) with yields of forage subjected to periodic cutting (simulated grazing).

B. BACKGROUND

1. Calculating Evapotranspiration

The evapotranspiration rate (E) of a crop is given by the Penman-Monteith equation as follows (Monteith, 1965):

$$E = \frac{[s/(s+\gamma)][(Q^*-Q_G)+\rho c_p [e^*(T_a)-e_a]/(s+\gamma)\ r_a]}{(1+[\gamma\ /(s+\gamma)]\ \ r_c/r_a)L} \qquad (2)$$

where s is the slope of the saturation vapour pressure curve, γ is the psychrometric constant, Q^* is the net radiation flux density, Q_G is the soil heat flux density, ρ is the density of air, c_p is the specific heat of air, $e^*(T_a)$ is the saturation vapour pressure at air temperature, e_a is the vapour pressure of the air, r_a is the aerodynamic resistance, r_c is the canopy resistance, and L is the latent heat of vapourization.

Since evaluation of r_c and r_a on a routine basis is difficult, evapotranspiration will be calculated as described in the following sections.

a) Energy-limited evapotranspiration (E_{max})

Priestley and Taylor (1972) found that for extensive wet surfaces and vegetated surfaces well-supplied with water, the evaporation rate under these conditions (E_{max}) could be related to the first term of (2) as follows:

$$E_{max} = \alpha \ (s/(s+\gamma))(Q^*-Q_G)/L \qquad (3)$$

where α is an experimentally determined coefficient, and the remainder of the right-hand side is referred to as the equilibrium evaporation rate (Slatyer and McIlroy, 1961). Priestley and Taylor (1972) found that α was 1.28 on a 24-hour basis for data sets from several parts of the world. Many studies have since reported 24-hour α values of 1.25 $\pm$0.05 (Tanner and Jury, 1976; Stewart and Rouse, 1977; DeBruin and Keijman, 1979; Mukammal and Neuman, 1977). Davis (1978) reported a daytime value of 1.28 for Sunset Prairie in 1977. Tanner and Jury (1976) showed that α values calculated on a daytime basis are smaller than those calculated on a 24-hour basis, since Q^*-Q_G is smaller for 24 hours than for the daytime period.

McNaughton *et al*. (1979) suggested that the limits of α in an environment free of local advection are:

$$1 < \alpha < (s+\gamma)/s \qquad (4)$$

The lower limit corresponds to evaporation at the equilibrium rate, while the upper limit implies that all available energy (Q^*-Q_G) is used for evaporation. Clearly, evaporation at the higher rate cannot be sustained, since atmospheric convection would cease in the absence of a sensible heat flux. The upper bound in (4) ranges from 1.18 at 40°C to 2.46 at 0°C. Several studies have suggested that there may be a seasonal trend in values of α , and have reported higher values in months with lower temperatures (deBruin and Keijman, 1979; Jackson et al., 1975). For most studies, however, the value seems to be nearly constant throughout the growing season.

The Priestley and Taylor method has drawn criticism on theoretical grounds (McNaughton, 1976; Monteith, 1978; Shuttleworth and Calder, 1979) but there seems to be considerable evidence of its usefulness.

b) Soil-limited evapotranspiration (E_s)

Under conditions of low soil moisture, transpiration becomes limited by the ability of the soil to supply moisture to the plant. Priestley and Taylor (1972) refer to this as the drying phase, and show E/E_{eq} as a linear function of the root zone water storage (W). Ritchie (1972) plotted E/E_o as a function of the fraction of extractable water in the root zone (θ_e), defined as follows:

$$\theta_e = (W - W_{min})/(W_{max} - W_{min}) \qquad (5)$$

where E_o is the free water evaporation rate, W_{max} is the root zone storage at saturation, and W_{min} is the value of root zone storage at which transpiration virtually ceases. Tanner and Ritchie (1974) analyzed 15 experiments and showed that such a relationship was a reasonable description of the results. Black (1979) showed that evapotranspiration at two different forest sites with similar soils could be described using the same function of extractable root zone water. Based on comments by McNaughton _et al_. (1979), Black and Spittlehouse (1981) used

$$E_s = b\ \Theta_e \qquad (6)$$

where b is an experimentally determined coefficient.

2. Estimating Transpiration (E_t)

Before the plant canopy is fully developed, evaporation from the soil represents a significant fraction of evapotranspiration. Since the evaporative flux is not associated with growth, it is desirable to find a method of separating evaporation and transpiration. Several methods based on the leaf area index (LAI), of the crop have been proposed (Ritchie, 1972; Tanner and Jury, 1976).

Tanner and Jury suggested that the two components could be expressed in terms of the proportion of net radiation incident on soil and leaves as follows:

$$E_{soil} = \alpha_s (s/(s+\gamma))(Q^*_G - Q_G) \quad (7a)$$

$$E_{max} = \alpha (s/(s+\gamma))(Q^* - Q_G) \quad (7b)$$

where E_{soil} is the evaporation rate from bare soil, α_s is the Priestley-Taylor coefficient for soil, and Q^*_G is the net radiation flux density at the soil surface. Transpiration is calculated as the difference between (7a) and (7b).

Tanner and Jury stated that α_s was initially the same as that for the crop canopy, and that it gradually approached unity as the canopy approached complete cover. They also presented relationships linking LAI to standing dry matter (G), and percent cover. Their relationship for calculating E_{soil} is:

$$E_{soil} = E_{max} [\exp(-B \cdot LAI)] \quad (8)$$

where B is an empirical constant. Their relationship LAI = 0.02 (% cover) is consistent with Johns and Lazenby (1973), who reported that full cover corresponded to LAI $\geq$ 2 for pasture. In this chapter a relationship based on standing dry matter is presented.

3. Relationship Between Growth and Evapotranspiration

a) Physiological basis for the relationship

The relationship between transpiration and dry matter production is indirect, since the water lost by transpiration is not a photosynthetic product. The most direct measure of net assimilation is net carbon dioxide (CO_2) uptake. CO_2 and water vapour fluxes share a common pathway, via the stomata, which control the rate of diffusion of these gases. Since the diffusion coefficients of the two entities are similar, the ratio of the two fluxes is closely related to the ratio of their concentration gradients across the stomatal pores.

Species differences in mesophyll resistance to CO_2 would affect the value of the ratio (Monteith, 1966). Since the ratio of the concentration differences will change with atmospheric humidity, the growth/transpiration ratio should also change (Bierhuizen and Slatyer, 1965). The photosynthetic process becomes light saturated, but transpiration rates have been observed to increase almost linearly with solar irradiance, if water is adequately supplied (Monteith, 1966). It is therefore likely that the growth/transpiration ratio will be higher under conditions of low irradiance. If these hypotheses are correct, care must be exercised in comparing growth/transpiration ratios derived under differing levels of irradiance or atmospheric humidity.

It should also be considered that transpiration often ceases at night, while respiration continues; however, night-time respiration activity appears to be positively correlated with daytime photosynthetic activity (Biscoe *et al.*, 1975; Rosenberg *et al.*, 1974). A nocturnal temperature that is 10°C lower than daytime temperature results in a respiration rate about half that in the daytime (Biscoe *et al.*, 1975). The relatively small magnitude of night-time respiration losses, and their correlation with daytime activity will help to preserve the relationship between transpiration and crop growth, especially for short cool nights, such as are often experienced in northern regions.

b) Experimental support for the relationship

Briggs and Shantz (1913) found that dry matter production was linearly related to transpiration, and that the ratio varied between species. DeWit (1958) confirmed these findings in field studies, and noted that the growth/transpiration ratio was lower in more arid regions. Staple and Lehane (1954) found a nearly linear relationship for wheat yields in Saskatchewan, even under conditions of moisture limitation. Stanhill (1960) showed linear relationships for well watered grass at seven locations ranging from Trinidad to Denmark, with the most efficient use of water occurring at high latitudes. Monteith (1966) confirmed these observations, stating that a given species is likely to produce more dry matter per unit of transpiration in a cloudy, humid climate than in a sunny, arid climate.

Several methods have been proposed to account for atmospheric humidity levels. DeWit (1958) suggested that a modified transpiration ratio be calculated by dividing a species' dry matter production rate (in kg $ha^{-1}d^{-1}$) by the free-water evaporation rate (E_o, in mm d^{-1}). This approach, and that of Bierhuizen and Slatyer (1965), in which they substituted vapour pressure deficit for E_o, help to account for different humidity levels, although van Keulen (1975) reported that the latter method did not properly account for variations between seasons. These methods will not account for differences between latitudes, except as the latter are reflected in the daily evaporation rate. For instance, the daily radiation total at 56^{o}N is the same as that at 40^{o}N in the summer (Carder, 1956), yet the growth/transpiration ratio is higher at the more northerly latitude, due to the more favourable distribution of radiation (longer daylength) and cooler temperatures.

Van Keulen (1975) developed a method for calculating growth/transpiration ratios for different latitudes and prevailing climates. His tests for Israel show promising results but it remains to be shown if his model is generally applicable.

Most of the literature reports non-limiting nutrient levels, but Rose et al. (1972) proposed that a family of linear relationships existed for different fertility levels. Walker (1978) proposed a nutrient status factor, which he suggested would vary, depending on interactions between nutrient status and water availability.

Although the growth/transpiration ratio concept is useful in establishing variations between species, climates, and latitudes, it is not yet possible to calculate such ratios from basic environmental and physiological data. Even so, the concept presents a useful basis for a climatically based growth index. By using a linear relationship, data can be used for periods ranging from days to weeks.

It is possible that stomatal control of transpiration may help to preserve the constancy of the relationship (Monteith, 1966), especially under water-limiting conditions (Stanhill, 1960). Growth calculations over short time intervals (e.g. 1 hour) should be avoided, since the concept represents an average relationship between non-linear, interacting processes.

C. EXPERIMENTAL PROCEDURE

1. Experimental Site

The field measurements were made at the Sunset Prairie Community Pasture (55°56'N, 120°45'W), approximately 50 km south of Fort St. John, B.C. The main site was described by Davis (1978), and consists of a 160 m x 40 m enclosure at the downwind end of a 45 ha grazed pasture, at an elevation of 800 m. The pasture was seeded in 1968 with a mixture of timothy (Phleum pratense), red fescue (Festuca rubra), and alsike clover (Trifolium repens), fertilized in May 1977 and in May and October 1978 with 100 kg ha^{-1} of 30-0-0 (Nitrogen-Phosphorus-Potassium). The enclosure contained field instrumentation, soil and plant sampling areas, and a trailer and a 3kW Onan diesel generator near the downwind end.

In the direction of the prevailing southwest wind, fetch was approximately 500 m, and in no direction was the fetch less than 250 m. The pasture is situated near the margin of the cultivated agricultural portion of the region and is part of a 250 ha area of tame pasture on gently rolling terrain, with cleared fields to the south and east, and deciduous forests to the west (mainly aspen). Until 1977 the 45 ha pasture was a single unit, but since that time it has been used as a three-paddock rotational grazing system, with a 4 ha reserve.

In 1979, six additional sites were established, as shown in Figure 1. Each 0.1 ha site was fenced, and 4 or 5 neutron tubes were installed as well as a storage raingauge, recording thermograph, and maximum and minimum thermometers, located in a Stevenson screen at 1.5 m. Half of sites 4 and 6 were fertilized in May 1979 with 100 kg ha^{-1} of 40-20-0, and plots for forage growth sampling were established at all sites. Soil profile descriptions were completed at each site, and textural analysis showed all sites to be clay loam. Sites 2 and 4 were classified as Alcan series, and the others as Codesa, with a scattered pebble layer at 30 cm being the distinguishing feature (A. Green, Personal Communication). Both soils belong to the Gray Luvisol soil great group.

Soil bulk density (ρ_B) measurements have been made by Davis (unpublished), and during the 1978 survey of the auxiliary sites and the 1979 field season (Hertzman, 1981). The mean values have been summarized in Table 1.

Laboratory soil water retention data for the main site were collected by Davis (unpublished) and Hertzman <u>et al</u>. (1981). Davis' values were obtained from 2.5 cm diameter cores using ceramic extraction plates. The data in Hertzman <u>et al</u>. were obtained using the hanging column method for a slab 15x30x5 cm. Hertzman <u>et al</u>. report good agreement between the data from both analyses. Values for the 30 cm depth are

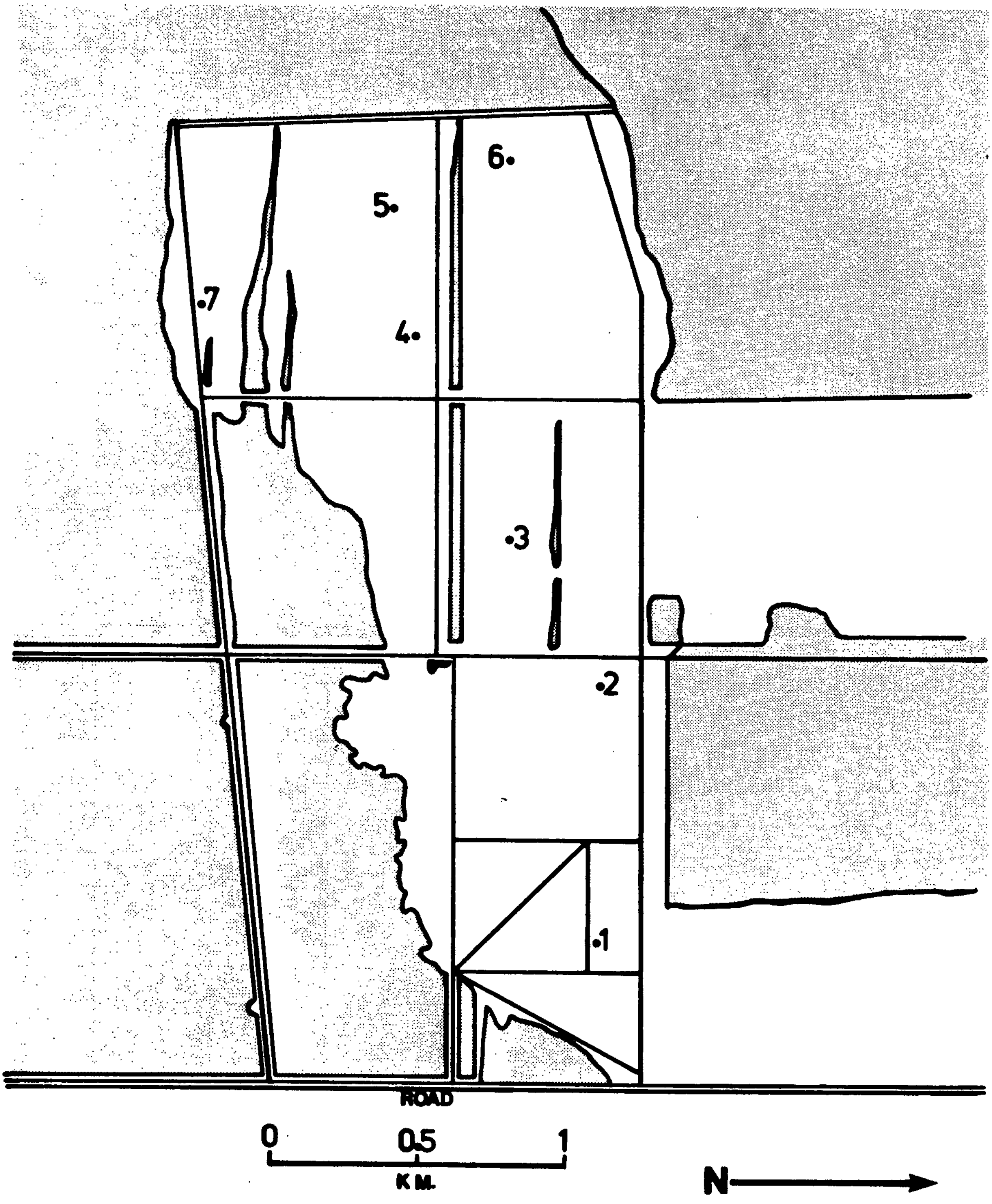

Figure 1. Experimental area at Sunset Prairie showing locations of seven 0.1 ha sites. Shaded areas are treed with 5 to 10 m high deciduous trees.

Table 1. Variation of soil bulk density with depth at Sunset Prairie for Codesa soil. ($Mg\ m^{-3}$)

Depth (cm)	5	15	25	35	45	55	80	100
Hertzman (1981)	1.2	1.35	1.5	1.55	1.6	1.6	1.6	1.6
Davis (1978)			1.52			1.75		

Table 2. Soil water retention characteristics for Codesa soil at Sunset Prairie.

Soil Matric Potential (M Pa)	Soil Water Content	
	(kgH_2O/kg soil)	(m^3H_2O/m^3 soil)
-0.001	0.35±0.04	0.53±0.06
-0.01	0.28±0.02	0.43±0.03
-0.1	0.23±0.02	0.35±0.03
-1.5	0.16±0.03	0.24±0.05

given in Table 2. These values indicated a total storage capacity of ~ 0.19 kg H_2O/kg soil (0.001 to 1.5 MPa), which corresponds to a volumetric capacity of 0.29 m^3 H_2O/ m^3 soil.

2. Measurements

a) General program

1978: The field measurement program began May 28, and continued until August 16. During this period eight sets of soil moisture and plant productivity determinations were made. Energy balance/Bowen ratio data were collected intermittently in four periods totalling 38 days.

1979: The field measurement program began May 20 and continued until August 24, with Bowen ratio data being collected on 94 out of 96 days. Soil moisture was measured at least weekly, and forage growth samples were taken every two weeks.

b) Forage growth

Forage growth was measured by clipping above ground dry matter from one square meter plots. Standing live vegetation was harvested and dried at 80°C for 24 hours. In 1978, hay growth plots were cut from within a 10 m by

15 m area of fairly uniform vegetation. A monthly mowing program was established in 1979 to simulate the grazing rotation in the surrounding pasture. To measure pasture growth, three samples were cut monthly at each site, including the fertilized and unfertilized halves of sites 4 and 6. In order to provide continuity with the 1977 and 1978 field seasons, samples of dry matter were taken from uncut areas at sites 1 and 7. Due to cattle break-ins, the data sets at sites 3 and 6 were not complete.

Root production was estimated by taking 7.5 cm diameter cores to a depth of 60 cm, which represented the estimated extent of the root zone. Because of the extensive analysis required, generally no more than four cores were taken every two weeks. Leaf area index measurements were made on samples which were separated according to species. The projected leaf area was measured using a Hayashi Denko Model AA-5 automatic photoelectric leaf area meter.

c) <u>Soil moisture</u>

In 1978, gravimetric moisture samples were taken to a depth of 1.5 m at the main site. Samples were taken from within a 0.5 m radius of five marked locations. Six samples were taken between 0 and 10 cm each day for estimating soil heat capacity.

In 1979, a Troxler Model 1257 neutron meter was used to make weekly soil moisture measurements to a depth of 1.5 m at 4 or 5 locations at all seven sites. Gravimetric samples were collected from the 0 to 10 cm layer within a radius of 0.5 m from each access tube.

The values of gravimetric water content were converted to volumetric content (θ_v) using bulk densities from Hertzman _et_ _al_. given in Table 1. The neutron meter was calibrated four times during the growing season by taking gravimetric profiles of soil water content near an access tube for which readings had been made. Based on the limited range of moisture conditions experienced in 1979, the calibration curve drawn relating θ_v to neutron meter count was considered valid for $0.5 > \theta_v > 0.23$ (Hertzman _et_ _al_., 1981). Root zone storage was calculated using $W = \sum_{i=1}^{n} (\Delta z_i \theta_{vi})$ for root zone layer thickness Δz.

d) Radiation

Solar radiation measurements were made with a Kipp and Zonen pyranometer mounted 1.5 m above ground level. A pair of Lintronic pyranometers were mounted back-to-back at 1.0 m, and used to determine albedo. Net radiation was measured with a Swissteco S1 pyrradiometer, purged with dry air. The radiometer signal was electronically integrated for fifteen minute periods, and the pyranometers were read every fifteen minutes. The Swissteco and Kipp and Zonen instruments were calibrated by the National Radiation Centre of Environment Canada in 1978, prior to the field season. The Lintronic pyranometers were checked against a local standard.

e) Soil heat flux

Surface soil heat flux was determined using two soil heat flux plates installed at a depth of 5 cm, approximately 1 m apart, and correcting for the rate of heat storage in the 0-5 cm layer. The latter was measured using two integrating thermometers, each consisting of five diodes in series, set into a 10 cm long epoxy rod. In 1978, germanium (1 N 2326) diodes were used, but in 1979 they were replaced with silicon (FD 300) diodes.

The soil heat capacity was determined by weighting the heat capacities of the water, mineral and organic matter by their volume fractions and summing (de Vries, 1963). The volume fractions of mineral and organic matter in the surface layer were reported by Davis (1978) to be 0.567 and 0.014, respectively. The volume fraction of water was obtained by gravimetric sampling and bulk density measurement, with values interpolated for days between samples.

f) Bowen ratio

The calculation of the Bowen ratio and evapotranspiration are discussed in section (i). The following section describes only the instrumentation used. The psychrometric apparatus and data recording system used to measure the wet and dry bulb temperature gradients were used by Davis and described by Black and McNaughton (1971) and Tang (1976). The system consisted of two sensing heads, each housing a wet and dry-bulb temperature sensitive germanium (1 N 2326) diode. The wet-bulb sensors were supplied with distilled water via a cotton shoelace wick which feeds from a reservoir located on the side of the housing. The heads were thermally insulated with polyurethane, and radiatively shielded by wrapping with aluminized mylar, and the sensors were aspirated at a rate > $3\ m\ s^{-1}$ by a vacuum pump. The heads were located at 1.0 and 2.0 m above the soil surface, and rotated automatically every fifteen minutes to eliminate systematic errors in the temperature difference measurement.

The diodes had a sensitivity of 2.3 $mV\ {}^{o}C^{-1}$ and their signal was integrated for ten minutes, after a five minute equilibration period following rotation. The sensors were calibrated at seven temperatures over the range $7^{o}C$ to $35^{o}C$ prior to the 1978 field season. They were recalibrated at five temperatures prior to the 1979 field season, following circuitry modifications and repair work.

g) Data recording

Operating periods were generally from 0500 until 2200 hours MST, except during rainfall or maintenance periods. Periodically, operations were continued overnight, but this was not done routinely because of increased generator servicing requirements.

All electronic signals were transmitted using shielded signal cable to the data logging system located in a trailer 50 m east of the main site. Power was provided by the grounded Onan diesel generator. The trailer temperature was maintained above 10°C at night, but since no cooling was available the data logging equipment was occasionally subjected to temperatures of 35 to 40°C during the daytime.

The wet and dry bulb difference signals and the net radiation signal were integrated by electronic integrators as described by Tang (1976). Pulses from the integrators, produced at a rate proportional to the input voltage, were recorded by Sodeco counters which printed every fifteen minutes. All diode temperatures, pyranometer signals and the soil heat flux signals were logged on a 20 channel Esterline-Angus recorder which printed simultaneously with the Sodeco counters.

h) Other meteorological measurements

A Belfort (Model 5780) weighing raingauge with its orifice 90 cm above ground was used to obtain daily rainfall amounts at the main site. A storage gauge with its orifice 30 cm above ground was located several meters away. In 1979, weekly precipitation amounts were obtained for all sites using storage gauges.

At the main site, a Stevenson screen containing a recording thermograph calibrated to B.C. Ministry of Environment network standards was maintained throughout the growing season. In 1979, similar thermographs were installed at the auxiliary sites.

Barometric pressure measurements were obtained from the Atmospheric Environment Service station at Fort St. John Airport 50 km north of Sunset Prairie.

i) Calculation of evapotranspiration

The energy balance of a vegetated surface can be written:

$$Q^* = Q_H + Q_E + Q_G \qquad (9)$$

where Q_H and Q_E are the sensible and latent heat flux densities, respectively, if it is assumed that horizontal flux divergence and canopy energy storage rates are negligible. The first assumption is usually considered to be valid if the fetch exceeds100 times the measurement height. The second assumption is considered reasonable for short crops, such as grasses (Thom,1975).

The Bowen ratio (β) is defined as the ratio of the sensible heat flux density to that of the latent heat flux density. i.e. $\beta = Q_H/Q_E$. By substituting this equation into (9), rearranging, and dividing by L, the evapotranspiration rate can be expressed as:

$$E = (Q^* - Q_G)/ \quad (1 + \beta\ ) L \qquad (10)$$

The Bowen ratio can be calculated using (Fuchs and Tanner, 1970):

$$\beta = [(s/\gamma + 1) (\Delta T_w / \Delta T) - 1]^{-1} \qquad (11)$$

where ΔT_w and ΔT are the wet and dry-bulb temperature differences, respectively, over a vertical distance within the constant flux layer. The psychrometric constant was evaluated at air temperature for the half hour period, and corrected using the barometric pressure measured at Fort St. John airport.

When Bowen ratios are near -1, large errors in the flux estimates can result, since the denominator of equation 10 approaches 0. Following McNaughton and Black (1973) and Davis (1978), fluxes were interpolated by eye for periods when $-1.5 < \beta < -0.5$. Such periods occurred briefly in the early morning and late afternoon when the profiles changed from inversion to lapse, and back, contributing little error to the evaporation totals reported, since the fluxes were small at these times.

In order to obtain evapotranspiration totals, values were interpolated for missing periods, using Priestley and Taylor estimates when radiation data were available. When the Priestley and Taylor formula was used, values of α were chosen by comparison with the nearest times for which values were available.

Davis (1978) compared evapotranspiration rates measured by the Atmospheric Environment Service lysimeter at Woodbridge, Ontario, with measurements made with the Bowen ratio system used in this study. He found good agreement with standard error of 30 W m^{-2} for half-hourly values, stating that estimates of E were within $\pm 8\%$ for daily totals. Complete error analysis for Bowen ratio calculations of evapotranspiration rate are available (Fuchs & Tanner, 1970; Bailey, 1978; Spittlehouse, 1981).

D. RESULTS AND DISCUSSION

1. Pasture Evapotranspiration

a) Energy balance

Typical energy balance results for wet and dry soil conditions are shown in Figures 2 and 3, respectively. Appendix 1 shows daytime energy balance components for 1978 and 1979. In 1979, daytime Bowen ratios ($\Sigma\ Q_H / \Sigma\ Q_E$, both summed over the period $Q^* > 0$) ranged from 0.05 to 0.75, with a seasonal average value ($\Sigma\ Q_H / \Sigma\ Q_E$, both summed over the season) of 0.39. In 1978, daytime Bowen ratios as high as 1.24 were measured, but the seasonal average was only 0.41. These values compare with a range of 0.09 to 0.73, and mean of 0.32 for 1977 (Davis, 1978). Early in 1979, values of Bowen ratio were fairly high, despite cool conditions, possibly because measurements began before E_t was significant, and E_{soil} was limited by surface drying.

The daily soil heat flux declined from 20% to 7% of the net radiation flux as the season progressed, because of the insulation of the soil surface by the developing canopy. In both 1978 and 1979 the seasonal average value of the ratio Q_G/Q^* was 0.12, compared to Davis' reported value of 0.09 in 1977. This difference is reasonable, because the canopy was denser in 1977, than in the two following years.

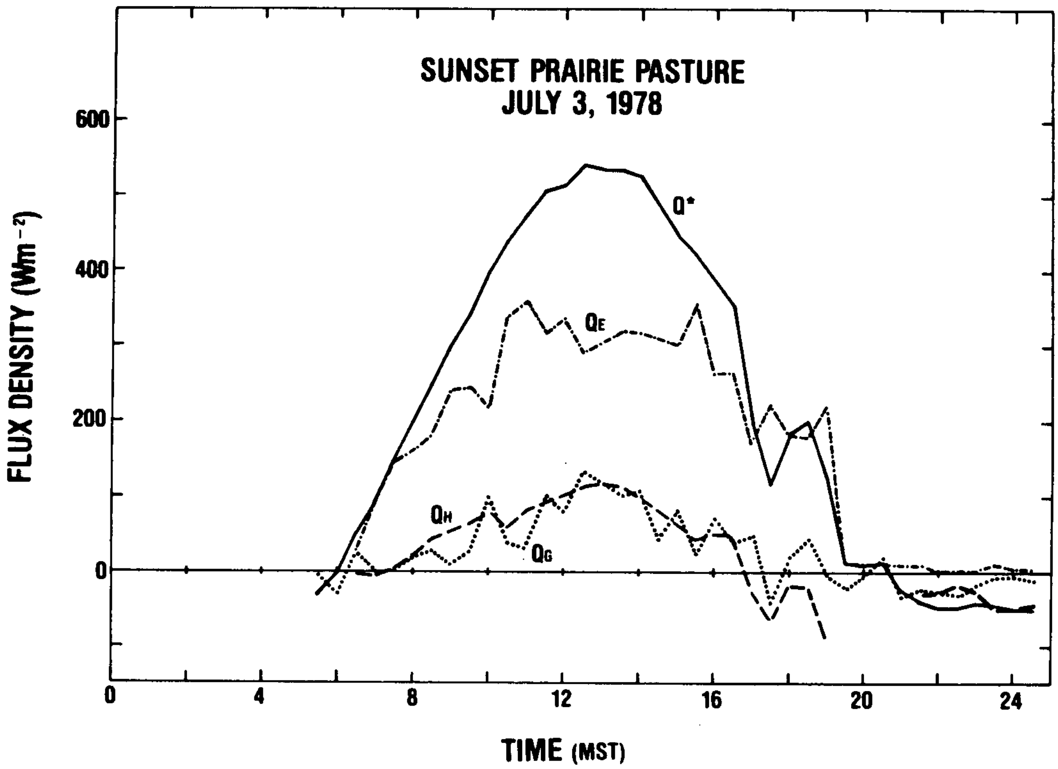

Figure 2. Energy balance components for July 3, 1978 under conditions of ample soil moisture. Daytime Bowen ratio is 0.16.

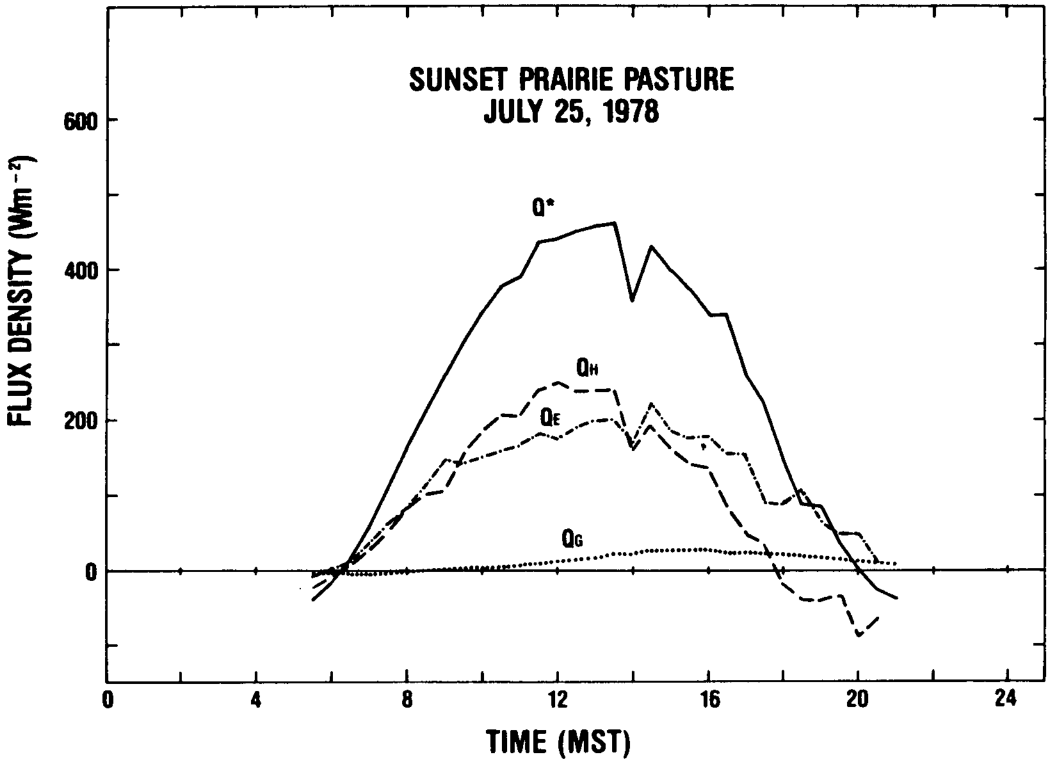

Figure 3. Energy balance components for July 25, 1978 under soil-limited conditions. Daytime Bowen ratio is 1.05.

b) <u>Energy-limited evapotranspiration</u> (E_{max})

Daytime evapotranspiration data for 1978 and 1979 are plotted against root zone storage (W) in Figure 4. All values of E for $W > 75$ mm are considered to be limited only by available energy, although a few of the values for $W \ll 75$ mm and low E_{max} could be included in this category. A regression of daytime E versus daytime E_{eq} was calculated for all days with $W \gg 75$ mm, with the following result, shown in Figure 5:

$$E_{max} = 1.26\ E_{eq} - 0.01 \text{ mm d}^{-1} \qquad r^2 = 0.95 \qquad (12)$$

Davis (1978) found a slope of 1.28 in 1977 at Sunset Prairie. Similar values were found for well-watered vegetation by Tanner and Jury (1976), Stewart and Rouse (1977), Mukammal and Neumann (1977). DeBruin and Keijman (1979) found a value of 1.26 for the ratio E/E_{eq} for Lake Flevo, but calculated a regression slope of only 1.17, with a positive intercept of 0.2 mm d^{-1}. Although they considered this intercept significant, they offered no explanation for its existence.

The value of 1.26 for α has been used to draw the horizontal lines representing E_{max} for different values of E_{eq}. The data are stratified according to ranges of E_{eq}. Since the data generally fall within the horizontal lines

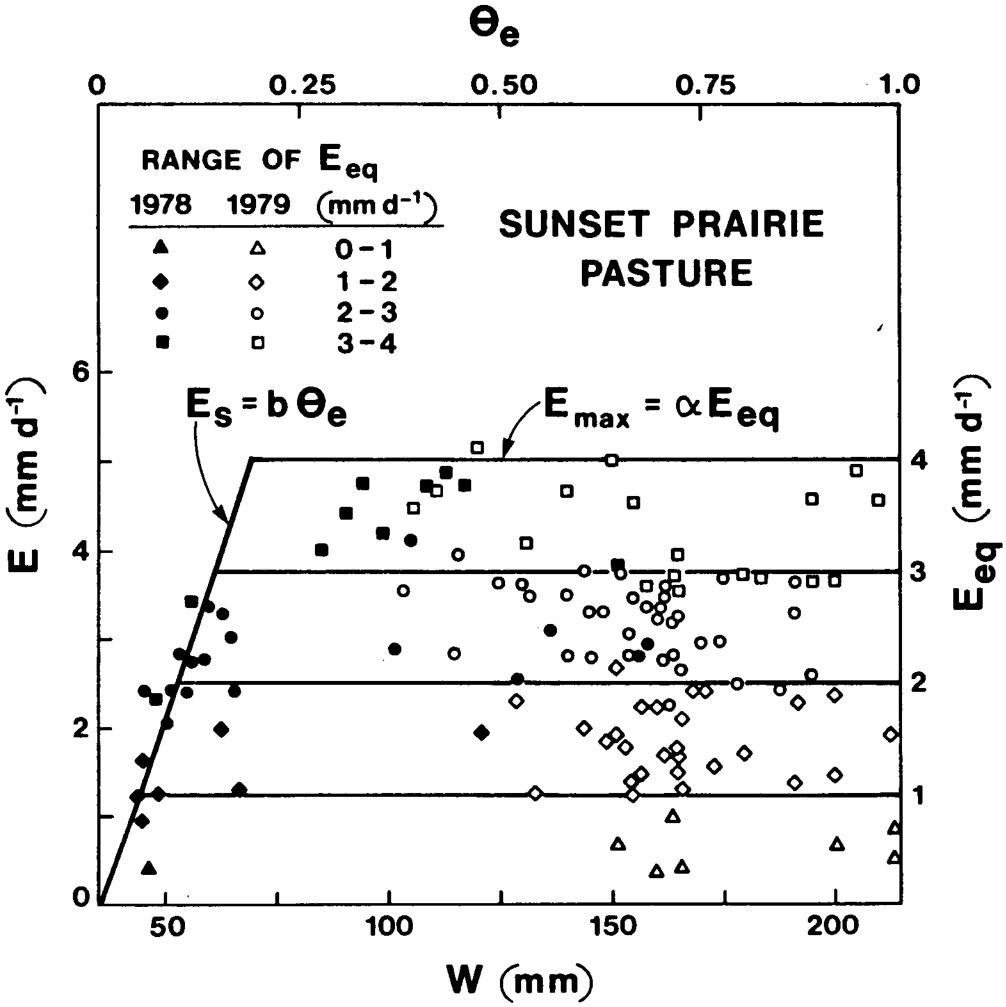

Figure 4. Daytime evapotranspiration for 1978 and 1979 versus rootzone storage. Horizontal lines represent values of E_{max} with $\alpha = 1.26$. Data points are stratified by ranges of E_{eq}. Soil limited line, $E_s = b\theta_e$, uses $b = 27$ mmd^{-1}.

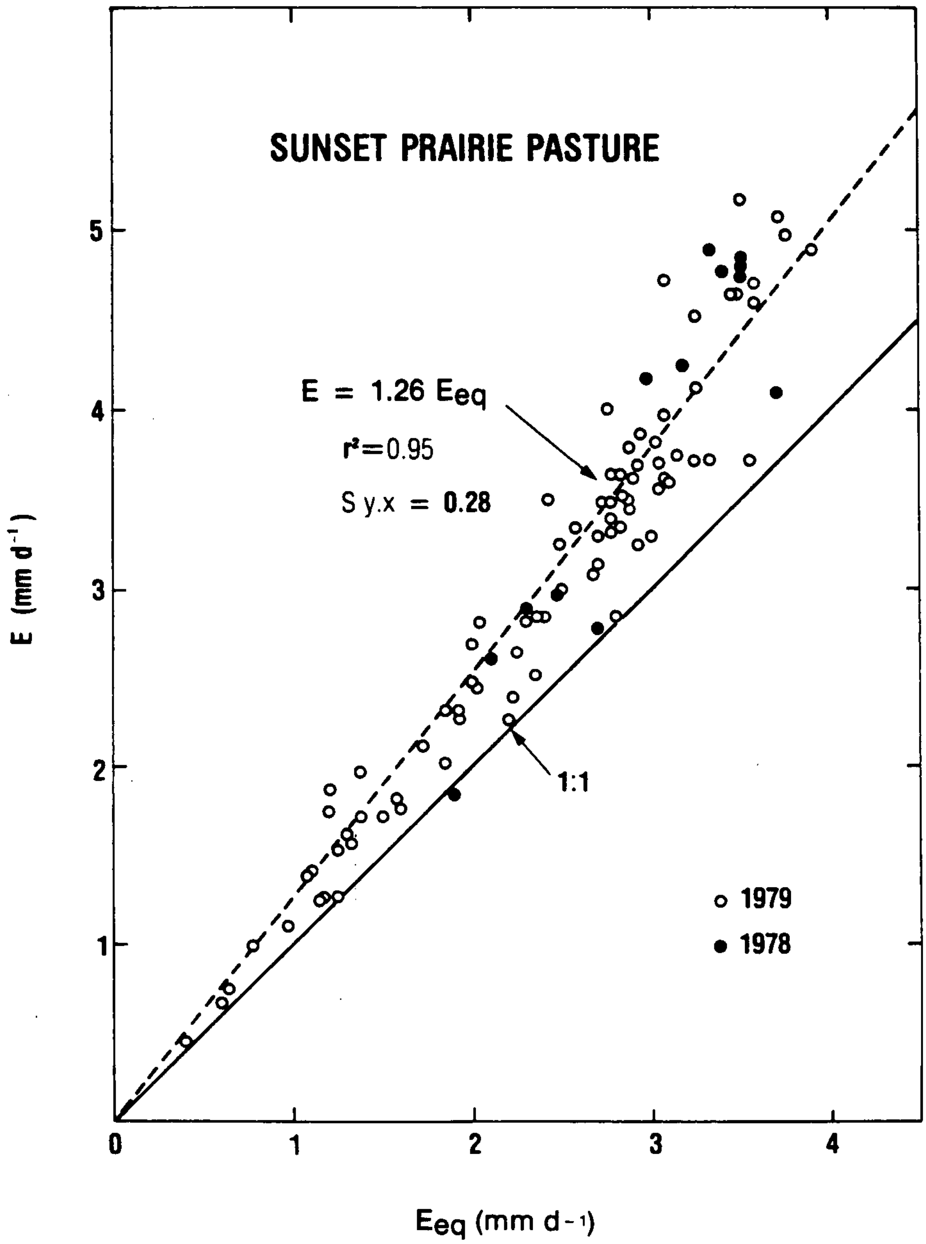

Figure 5. Measured E versus E_{eq} for 1978 and 1979 data showing regression and 1:1 lines.

bracketing their respective range, it can be concluded that E_{max} is well estimated using 1.26 as the value of α.

c) Soil-limited evapotranspiration (E_s)

During the 1978 growing season E began at the potential rate (i.e. $E = E_{max}$), but declined significantly after July 20. Values of E/E_{eq} declined from 1.34 for 10 days in early June to 1.07 for 12 days in late July, and 0.95 for 6 days in mid-August. Values of E for low soil moisture conditions are shown in Figure 4. A line was fitted by eye to the points representing soil-limited evapotranspiration as follows:

$$E_s = 6.7\ (W - 35) = 27\ \Theta_e \qquad (13)$$

In the figure, W_{min} is found to be 35 mm ($\Theta_v = 8\%$). No soil moisture limitation is evident until Θ_e falls below 25%, which compares with values of 80% and 40% used by Selirio and Brown (1979) and Black and Spittlehouse (1980), respectively, for coarser soils.

d) Estimation of evapotranspiration

From the previous two sections, it can be seen that (12) and (13) describe energy and soil limited E. To estimate E, the lesser of the values generated by (12) and (13) must be used. Hence, a procedure by which root zone water storage could be calculated would be useful in estimating E. This procedure will be discussed further in Chapter 3. The partitioning of E into evaporation and transpiration is discussed in Section D.3.

2. Dry Matter Production

a) Variation between years

Cumulative hay growth at the main site for 1977, 1978, and 1979 are shown in Figure 6. Productivity was higher in 1977 than in either 1978 or 1979, possibly because of an earlier start. This explanation cannot be supported by data from the site, since the climate record began on May 14, 1977, but growth was evident by May 7, 1977, and had probably started at least a week earlier.

The 1978 growing season appears to have started later than in 1977. Growth rates in 1978 paralleled those of 1977 until early July, after which they were much slower

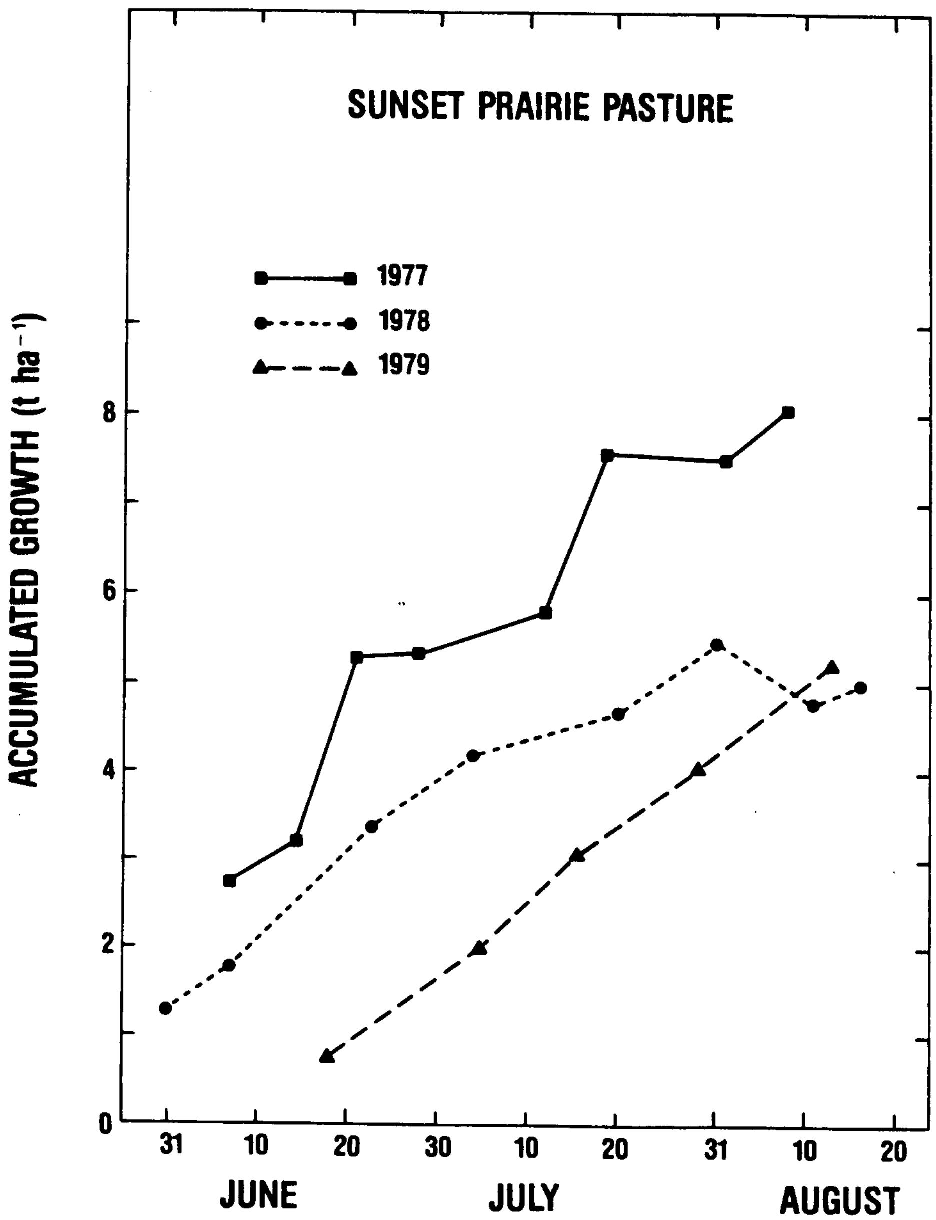

Figure 6. Accumulated hay growth at site 1 for 1977, 1978 and 1979 growing seasons.

probably due to soil moisture limitation. In 1979 growth began about one month later than in 1977, with no new growth appearing until after May 20. Growth proceeded at approximately the same rate as in 1977, and matched 1978 production by mid-August, despite having been only half as productive by early July.

The apparent variability in 1977 growth rates is chiefly due to the natural variations in the pasture, which have been reduced in 1978 and 1979 by continued fertilizer application. In 1979, the pasture was still growing actively by August 20, under conditions of ample soil moisture, while senescence was observable in 1978 under dry conditions.

b) <u>Results of grazing simulation</u>

Figure 7 compares the accumulated growth of the simulated monthly grazing with accumulated hay growth for sites 1 and 7 (a naturally fertile site) in 1979. Over the period May 25 to August 13, the cutting reduced growth by about one-third. Most of this reduction occurred during the period between the first and second cuts. Growth of the cut forage was only 40% of that of the uncut forage during this period, despite adequate soil moisture and insolation. The reduction in growth has several possible causes. Firstly, mowing causes mechanical damage, and removal of the actively

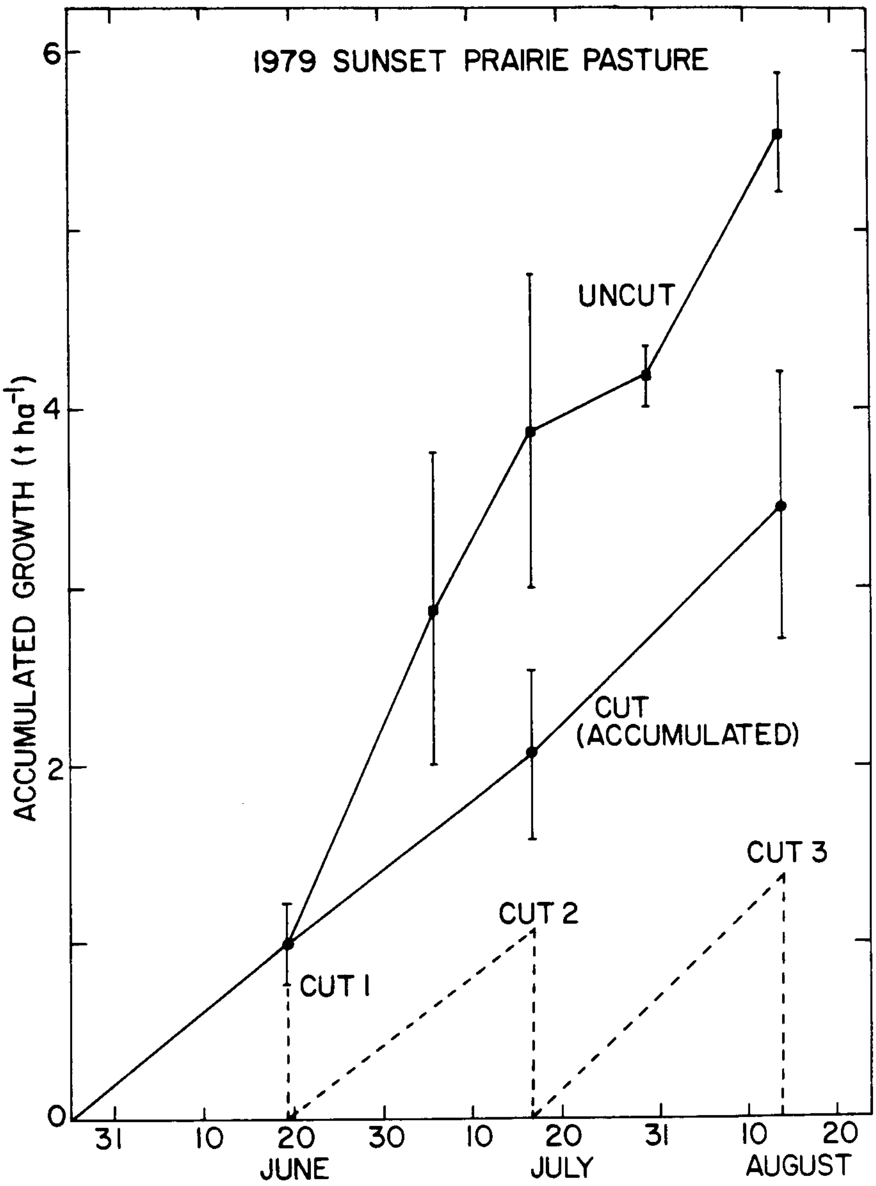

Figure 7. Comparison of accumulated growth of uncut (hay) and cut (simulated pasture) forage. Values are averages of measurements at sites 1 and 7 with range bars shown.

growing portion of the plant, exposing chlorophyll-poor shade leaves. Secondly, leaf area may be reduced below that necessary for complete interception of available light. The evapotranspiration measurements suggest that the first explanation is more likely since no reduction of E was observed over the pasture after cutting and extensive grazing. Brougham (1956) found that pasture cut to 7.5 cm suffered productivity reduction for several weeks afterward. At lower latitudes, several workers have observed that similar cutting regimes resulted in an increase in productivity compared with uncut plots. This may be due to the higher levels of maintenance respiration in the uncut stands (McCree, 1970), which substantially reduce net productivity.

Although total productivity is reduced by harvesting, the foliage is younger and therefore likely to be more palatable and of higher quality. The interaction of yield and quality will not be discussed but it will certainly affect decisions in grazing management. Harvesting resulted in visible changes in species dominance, since the mower removed the greatest proportion of the tallest species. Since this selection process is different from that exerted by cattle grazing, sustained cutting could affect the species composition of the experimental plots, but this was not considered to be a serious problem within a single growing season.

c) Spatial variation and effects of fertility

The spatial variation in unfertilized growth, shown in Figure 8 for 1979, was not great for most sites, however, site 7 growth was comparable to that of the fertilized portions of sites 4 and 6. This difference was easily observed by eye in the field. The variations in temperature and rainfall were small, and water was not considered limiting in 1979. It is possible that site 7 has a more favourable nutrient regime than the other sites. The site is located 0.5 km from the ridge top, on a 5^{o} southerly slope, but the difference in radiation from a level site is only of the order of 5% (Hay, 1979), while productivity was virtually double that of the other sites. Site 6 was on a similar slope facing north, but suffered no apparent productivity loss compared with other sites.

Fertilizer applied at sites 4 and 6 resulted in almost 100% increases in yield. The single application of 40-20-0 at sites 4 and 6 produced about 50% higher yield than the three applications of 30-0-0 at site 1. At site 1, the last application was in the fall of 1978, and, unlike sites 4 and 6, was subject to losses through the winter. Since the response to phosphorus is not great for this soil series, the differences are thought to be mainly due to the time of application (J. Dobb, personal communication).

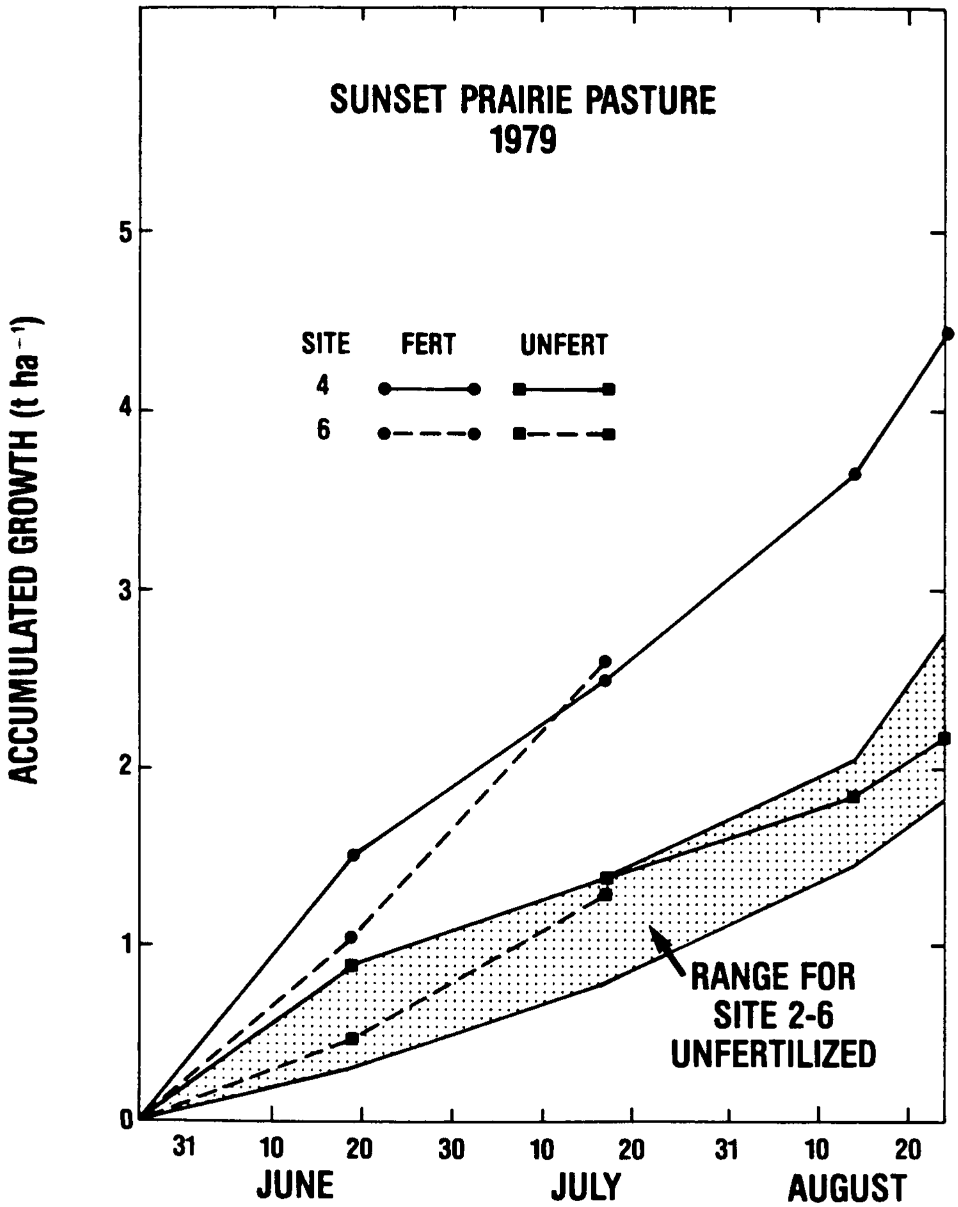

Figure 8. Comparison of accumulated growth of fertilized and unfertilized cut (simulated pasture) forage. Measurements are the average of three replicates at sites 4 and 6. Shaded area shows range of accumulated growth of cut, unfertilized forage growth at sites 2 to 6.

3. Relationship Between Growth and Transpiration

a) Relationship with evapotranspiration

Figure 9 shows accumulated hay growth plotted against evapotranspiration for 1977 and 1979. Davis (1978) represented the smoothed 1977 data by a power function: $G = 126\ E^{0.713} + 2740$ kg ha^{-1} (where E is the daily evaporation total in mm). Further analysis indicated that both years can be satisfactorily represented by linear equations. A regression was calculated for 1977 as follows:

$$G = 26.2\ E\ (\text{mm}) + 3180\ (\text{kg ha}^{-1}) \quad r^2 = 0.821\ (14)$$

If the summation of E was started at the beginning of the growing season, a small negative value of the intercept would be expected (Walker, 1978), since bare soil evaporation must be subtracted. If E were accumulated from May 1, rather than June 7, at an average rate of 3 mm d^{-1}, the intercept would be 192 kg ha^{-1} rather than 3180. This change is represented by the dashed line in Figure 9, and supports the supposition that growth began prior to May 1, in 1977. Since the energy balance data are incomplete for 1978, the relationship cannot be verified for conditions of water limitation until a satisfactory model is developed to estimate E. This objective will be addressed in the next chapter.

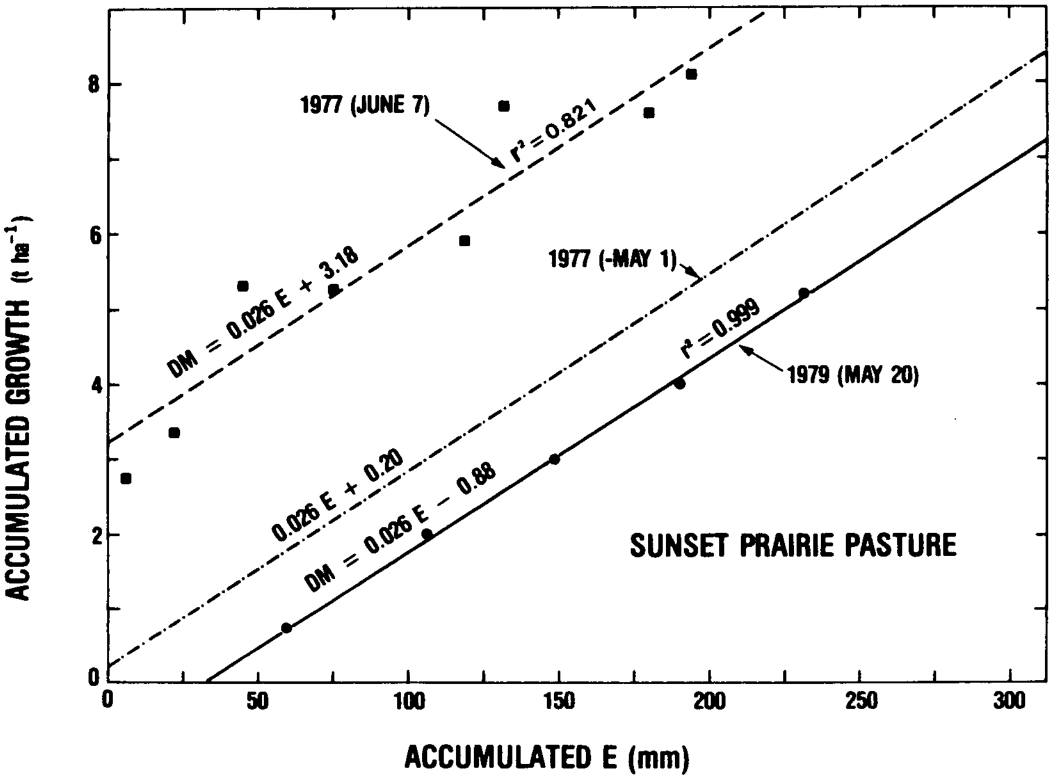

Figure 9. Accumulated hay growth versus accumulated E for 1977 and 1979, showing starting dates for summation of E. Line showing May 1 starting date assumes average E of 3 mm d^{-1} from May 1 to June 7.

When hay growth was plotted against accumulated E for 1979, a strong linear relationship was evident, with a calculated regression as follows:

$$G = 26.2\ E\ (\mathrm{mm}) - 878\ (\mathrm{kg\ ha}^{-1}) \qquad r^2 = 0.999 \qquad (15)$$

A negative intercept is observed, as expected, since energy balance measurements began before the first green leaves emerged, and significant evaporation from the soil occurred prior to canopy closure.

b) <u>Correction for bare soil evaporation</u>

The data from 1979 suggest that full cover was reached at a standing dry matter weight of 1 t ha^{-1}, which conforms to a relationship suggesting LAI = 2 G (t ha^{-1}) (Brougham, 1956).

A value of B = 1.5 was used in (8) to correct for soil evaporation which is higher than the range of values given by Tanner and Jury (1976) for row crops (0.4-0.7). It seems reasonable, though, that grasses would provide much more uniform cover than row crops, and more effectively suppress soil evaporation. When such a correction was made the relationship between G and transpiration was found to be linear, with a greatly reduced intercept, lending strong support to deWit's (1958) concept of an average growth/transpiration ratio which applies during active growth. This will be used, and discussed further in Chapter III. Such a relationship does not account for senescence of the vegetation, and could therefore not be applied for the full duration of the growing season. No attempt has been made to separate the contributions of different species, so that if growth patterns differ significantly, adjustments may be needed to account for species composition. Data from the forage nursery at Sunset Prairie may be useful in making such adjustments.

c) Comparison with other studies

If it is assumed that soil evaporation is negligible after canopy closure, then the slope of the regression line calculated in (14) corresponds to deWit's growth/transpiration ratio. Any overestimate of the transpiration rate because of the inclusion of evaporated dew or rainfall will lead to a proportionate underestimate in the transpiration ratio.

The value of 26 kg ha^{-1} per millimetre of water transpired for Sunset Prairie, compares with values of 22 found for England (Penman, 1962) and 19 for Denmark (Stanhill, 1960), both of which are located at similar latitudes to that of Sunset Prairie. Rose *et al*. (1972) reported 8 and 14 kg

$ha^{-1}/mm\ H_2O$ for different stages of growth of Townsville Stylo at 14.5^oS in Australia, which differs substantially from Stanhill's (1960) value of 5.5 kg $ha^{-1}/mm\ H_2O$ for grasses in Israel.

E. CONCLUSIONS

Energy limited evapotranspiration can be estimated from the equilibrium potential method using $\alpha = 1.26$. Soil limited evapotranspiration can be estimated as a function of root zone water storage. Transpiration can be calculated as the lesser of (1) and (2) by correcting for the effects of bare soil evaporation. A strong linear relationship between hay growth and evapotranspiration was observed. When a correction was made for soil evaporation a linear relationship with a much smaller intercept was found. Simulated monthly grazing results in half the production of hay growth, and also shows a linear relationship with evapotranspiration. Fertilizer application consistent with local practice doubles natural productivity.

CHAPTER III. A SIMPLE MODEL FOR FORAGE GROWTH IN THE PEACE RIVER REGION

A. INTRODUCTION

Simple agroclimatic procedures for estimating pasture and hay growth rates are important in evaluating the agricultural potential of remote areas. Models such as that of Selirio and Brown (1979), which rely on an extensive data base are not easily applied in areas where soil, climate, and crop response data are scarce. A model is required which needs only standard soil and climate data, and which can be used easily by regional land managers.

In order to estimate growth, the availability of water and energy to the crop must be assessed. Solar irradiance measurements are made relatively easily, and can be extrapolated over fairly large distances. Assessing the soil water supply throughout the growing season is difficult since it depends on the variability of precipitation and soil water storage characteristics in the area of interest.

Growth can be related directly to water storage in conditions of soil water supply limitation (Williams, 1970), or to solar irradiance in conditions of energy supply limitation (Brouwer, 1956). Transpiration has been found to be well correlated with growth and to incorporate both the effects of water and energy supply limitation (Rose *et al.*, 1972). In modelling evapotranspiration, several workers have used soil water content to establish water availability to plant roots (Rose *et al.*, 1972; Rasmussen and Hanks, 1977; Feddes *et al.*, 1978; van Keulen, 1975; Russell, 1980). Selirio and Brown (1978), and Walker (1978) used modified versions of the Versatile Soil Moisture Budget (Baier *et al.*, 1979) in their simulation models. In view of the difficulty of assigning the parameters required to operate these multiple layer models, it was decided to use a simpler scheme based on a simple one-layer model developed by Black *et al.* (1970) for calculating changes in root zone water storage during the growing season.

In this chapter a simple model which uses standard daily climate data is developed and evaluated for calculating crop growth during the growing season using a growth/transpiration ratio. Evapotranspiration is calculated using solar radiation and air temperature data, and a one-layer root zone water balance to account for water supply limitation. Transpiration is calculated by subtracting evaporation losses from the soil and foliage from the calculated evapotranspiration. The validity of using solar radiation, measured at a regional climate station, for calculating evapotranspiration at the study site is tested.

B. THEORETICAL BASIS OF THE MODEL

1. Estimating Transpiration

The evapotranspiration rate (E) is calculated as the lesser of the energy and soil limited rates. The energy limited rate (E_{max}) is calculated using the Priestley and Taylor (1972) approach on a daytime basis, as follows:

$$E_{max} = \alpha [s/(s + \gamma)] \quad (Q^* - Q_G)/L \qquad (1)$$

where s, γ and L are the slope of the saturation vapour pressure curve, the psychrometric constant, and the latent heat of vapourization, respectively, at the daily mean air temperature, Q^* is the net radiation flux density, Q_G is the soil heat flux density ($\simeq 0.1 Q^*$) and α is determined experimentally. Analysis of energy balance/Bowen ratio data for 1978 and 1979 indicated a daytime value of 1.26 (see Chapter II), which will be used in the evapotranspiration model.

In soil limited conditions E is often related to root zone water content (Rasmussen and Hanks, 1977; Feddes *et al.*, 1978). It was shown in Chapter II that the soil limited evapotranspiration rate (E_s) could be expressed as follows:

$$E_s = b\theta_e \tag{2}$$

where θ_e is the fraction of extractable water in the root zone and b is an experimentally determined coefficient. θ_e is calculated as follows:

$$\theta_e = (W - W_{min})/(W_{max} - W_{min}) \tag{3}$$

where W is the root zone water storage, W_{max} is the root zone storage at saturation, and W_{min} is the root zone storage at which evapotranspiration virtually ceases. On the basis of data from 1978, the coefficient b was taken to be 27 mm d^{-1} (see Chapter II). The value of b corresponds to PEMAX in the model of Selirio and Brown (1979), and is the theoretical maximum water supply rate for soil and vegetation when storage equals W_{max}.

Under soil limited conditions, the transpiration rate (E_t) is assumed to be approximated by E_s, since the soil surface is usually dry under these conditions and E_{soil} approaches zero. Under energy limited conditions E_t is calculated using a procedure from Tanner and Jury (1976) (see Chapter II) in which (8) is subtracted from E_{max} to give:

$$E_t = E_{max} \left[1 - \exp(-B \cdot LAI) \right] \tag{4}$$

where B is an empirical coefficient and LAI is the leaf area index. Equation 4 is based on the assumption that the ratio of evaporation from the soil (E_{soil}) to E is proportional to the ratio of the net radiation exchange at the soil surface to that above the canopy. It will tend to underestimate E_t somewhat as the soil dries and evaporation from the soil becomes soil-limited. Values of B reported in the literature vary from 0.47 for wheat (Denmead, 1973) to 0.69 for potatoes (Tanner and Jury, 1976). The value chosen here was 1.5 to account for the dense grass canopy containing the broad-leaf alsike clover. LAI of the crop was found to be well approximated as 2.0 G where G is the accumulated forage growth (in tonnes per hectare).

Evapotranspiration rate is assumed not to be significantly affected by the presence of intercepted rainfall, due to the low aerodynamic roughness of the crop (Rutter, 1977). However, an estimate of interception is necessary to estimate E_t. Interception is calculated using a function given by Feddes et al. (1978) as:

$$I = 0.55\ P^{(0.53\ -\ 0.0085\ (P\ -\ 5))} \qquad (5)$$

where P is precipitation in millimetres. This function approaches a maximum value of 1.85 mm. Intercepted rainfall is assumed to evaporate directly from the foliage at the energy-limited rate before further transpiration occurs. Transpiration for the day following rainfall is therefore estimated as the lesser of E_{max} minus interception, and E_s.

2. Estimating Net Radiation

The net radiation exchange above the canopy can be expressed as follows:

$$Q^* = (1 - r)\ K\downarrow\ + L\downarrow\ - L\uparrow \tag{6}$$

where r is the crop reflection coefficient or albedo, $K\downarrow$ is the incoming solar radiation flux density and $L\downarrow$ and $L\uparrow$ are the incoming and outgoing longwave flux densities respectively. On the basis of measurements made over three growing seasons, the daily average albedo was found to be approximately 0.25. The effect of clipping on the albedo was negligible.

The daily value of $L\downarrow - L\uparrow$ was determined using the semi-empirical approach proposed by Linacre (1968) and modified by Jury and Tanner (1975). This approach used estimates of $L\downarrow$ and $L\uparrow$ based on daily average screen height air temperature (T_a), and a correction for the effect of clouds. Several empirical methods have been developed to calculate incoming longwave radiation (Brunt, 1932; Swinbank, 1963; Brutsaert, 1975; Idso and Jackson, 1969; Satterlund, 1979). The equation developed by Idso and Jackson was used since it has been found to compare favourably with other methods over a wide range of temperatures (Aase and Idso, 1978; Satterlund, 1979). The equation gives L↓ under clear skies as $L\downarrow = \varepsilon_a \alpha T_a^4$ where σ is the Stefan-Boltzman constant and ε_a is the clear sky atmospheric emissivity as follows:

$$\varepsilon_a = 1 - 0.261 \exp(-7.77 \times 10^4 T_a^2) (T_a \text{ in } ^\circ C) \quad (7)$$

Idso (1980) notes that the equation over-estimates incoming longwave radiation in coastal and oceanic environments, and suggests that this may be due to lower dust loads than in the desert environment for which the equation was developed.

The outgoing longwave radiation flux under clear sky conditions was estimated using $L\uparrow = \varepsilon_s \sigma T_a^4$ where ε_s is the crop surface emissivity, assumed to be 0.95 in this study. The factor used to multiply the clear-sky estimate of $L\downarrow - L\uparrow$ to give an estimate for cloudy conditions is as follows (Linacre, 1968; Jury and Tanner, 1975):

$$c = a + b\,(K\downarrow / K\downarrow_{clear}) \quad (8)$$

where $K\downarrow_{clear}$ is the expected clear day value of incoming solar radiation. The values of a and b were found to be

0.1 and 0.9 respectively, within the range quoted by Linacre (1968). In summary, the daily value of net radiation was calculated as follows:

$$Q^* = K\downarrow \ (1-r) + (\varepsilon_a - \varepsilon_s)\bar{\sigma} T_a^4 \ [\ 0.1 + 0.9 (K\downarrow / K\downarrow_{clear})\ ] \quad (9)$$

where $r = 0.25$, $\varepsilon_s = 0.95$ and ε_a is calculated using (7).

3. Soil Water Balance

A soil water balance procedure was necessary to estimate daily values of root zone water storage during the growing season, in order to calculate daily evapotranspiration rate. Root zone water storage at the end of ith day (W_i) was estimated as follows:

$$W_i = W_{i-1} + (P_i - E_i - D_i - R_i)\,\Delta t \quad (10)$$

where W_{i-1} is the storage of the end of the previous day, P_i, E_i, D_i and R_i are the rates of rainfall, evapotranspiration, drainage and runoff, respectively, on day i, and Δt is the time interval one day.

E_i is determined by (i) calculating E_{max} from (1), (7) and (9); (ii) calculating E_s from (2) and (3) with W_{i-1}, and (iii) taking the lesser of E_{max} and E_s. In this one-layer model, water is assumed to be equally available to the crop regardless of its distribution within the root zone. Based on root density data (Hertzman et al., 1981) a single root zone depth of 450 mm was used for the entire growing season. Profiles of root zone water content for the 1978 growing season are shown in Figure 1, indicating that the majority of water extracting is from the top 600 mm.

Rain is assumed to fall at the end of the day, after evapotranspiration has occurred. Since the majority of summer rainfall events are convective, this will often be reasonable, and it does not affect the model output seriously. Daily rainfall amounts from the recording raingauge were used, with a 10% enhancement based on the totals from the two storage gauges.

Runoff can be generated in two ways. If the rainfall rate exceeds the infiltration rate, the excess is considered to be Horton runoff. If the calculated soil water storage exceeds W_{max}, the excess is considered to be Dunne runoff. W_{max} was calculated from bulk density measurements to be 48% by volume, or 216 mm of water storage in the root zone. An infiltration rate of 4 mm h^{-1} obtained by Hertzman (personal communication) was used. Rainfall is separated into amounts greater and less than 10 mm, with lesser amounts being considered convective, and greater amounts frontal. Convective rains have an assumed duration of 2 hours, and frontal rains a duration of 8 hours. Using an infiltration rate of 4 mm h^{-1}, Horton runoff was seldom generated. Dunne

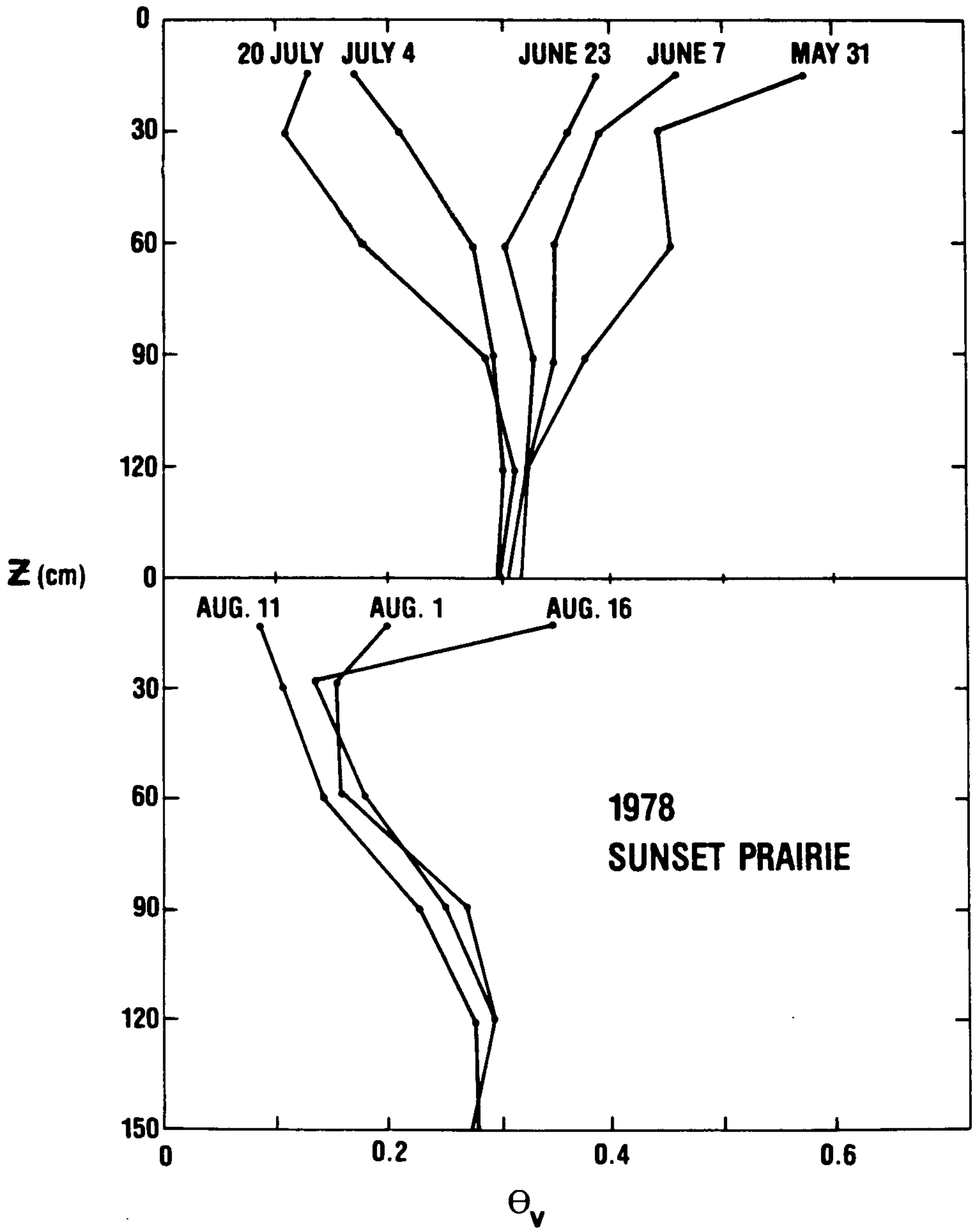

Figure 1. Profiles of volumetric soil moisture with depth at site 1 during the 1978 growing season.

runoff was generated less frequently than in a layered model which would permit the use of lower drainage rates for deeper zones, allowing runoff to occur.

Based on work by Carder and Hennig (1966) on a soil of similar physical characteristics at Beaverlodge, Alberta, it was suspected that drainage and capillary rise were negligible during the growing season. This is reasonable, since the bulk density of the subzone is 1.8 Mg m^{-3} implying low values of saturated conductivity.

The initial soil water content is generated iteratively, by running the model from saturation at the starting date to the date of the first storage measurement, and adjusting the initial content by the amount of the difference between the model output and the measurement. A complete listing of the FORTRAN program used to calculate the water balance is given in Appendix 2.

4. Relationship Between Growth and Transpiration

The model uses the growth/transpiration ratio concept (deWit, 1958) to calculate growth as follows:

$$G = \sum_{i=1}^{n} m \, E_{t_i} \qquad (11)$$

where n is the number of days from the start of the growing season, and m is the growth/transpiration ratio. Rose et al. (1972) used two values of m during the growing season for Townsville Stylo. Van Keulen (1975) calculated the ratio daily in his plant physiological model, but in this chapter an average value is used, similar to van Keulen's simpler model.

Initiation of growth is difficult to specify, since growth had already begun prior to the 1977 and 1978 field seasons. In this study, it was assumed, following Selirio and Brown (1979), that growth began on the first day following five consecutive days for which the mean screen-height temperature exceeded $5^{\circ}C$. Hertzman et al. (1981) have found this criterion inadequate under some conditions, but it is a reasonable first approximation.

In summary, the model calculates E throughout the season, using the lesser of the water and energy-limited values. Transpiration is calculated by correcting for evaporation from the bare soil and foliage, and (11) is used to calculate dry matter as a function of time.

C. EXPERIMENTAL SITE AND MEASUREMENTS

Field work was conducted at the Sunset Prairie Community Pasture, 50 km south of Fort St. John. The pasture is described in detail in Chapter III. Seven 0.1 ha plots in a grazed 250 ha tame pasture were used to test the water balance model. Growth measured at Site 1 was used to test the growth model. Since the measurement program is described in Chapter II, only a brief summary of measurements used in developing and testing the model is presented here.

Both net and solar radiation were measured at the main site during the 1978 and 1979 field seasons. Albedo measurements were made with upward and downward facing Lintronic pyranometers. In 1978, a Kipp solarimeter and integrating data logger were installed at the Fort St. John airport, making hourly totals of solar radiation available on a routine basis.

Daytime measurements were made using the instrumentation described in Chapter II, and by Davis (1978). The operating periods were from sunrise to sunset on an intermittent basis in 1978, and daily from May 20 to August 25 in 1979.

Soil moisture measurements were made every 5 to 10 days, and following major rainfall events in both 1978 and

1979. In 1978 gravimetric methods were used to obtain storage estimates for five locations at the main study site. In 1979, the study included six additional sites in an area of approximately 250 ha, and the neutron method was used to obtain measurements from 4 or 5 access tubes at each site, with gravimetric samples being used for surface layers.

Forage growth was measured by hand clipping the standing forage to a height of approximately 50 mm in 1 m^2 sample plots. In 1979, three replicate samples were taken from areas mowed monthly. Hay growth was measured in a fairly uniform 10 m x 15 m uncut area in 1978 and 1979.

D. RESULTS AND DISCUSSION

1. Estimating Net Radiation

Net radiation values for 1979 calculated by (9) for daylight periods were on average 4% higher than measured values. Idso (1980) reports similar overestimates for atmospheric conditions cleaner than the site for which (7) was developed. Subtracting 0.03 from the calculated atmospheric emissivity eliminated the overestimate for 1979 data and this procedure was adopted for the model.

Table 1 shows the results of using (9) to estimate Q* with solar radiation measured on-site and at Fort St. John in 1979, as well as the results of a regression between $K\downarrow$ and Q*. These results are for daytime totals of net radiation. The standard error of the predictions from (9) with reduced ε_a was 0.65 MJ m^{-2} d^{-1}, which is slightly lower than that for the regression between net and solar radiation measured at the main site on 67 days in 1979 as follows:

$$Q^* = 0.565\ K\downarrow\ - 0.27\ \mathrm{MJ\ m^{-2}\ d^{-1}} \qquad r^2 = 0.97 \qquad (12)$$

Equation (9) would provide better Q* estimates than (12) for sites with different albedos, and for temperatures beyond the range for which the regression was developed. Tanner and Jury (1975) reported Sy.x = 0.92 MJ m^{-2} d^{-1} using (9) for 24 hour periods without adjusting ε_a.

Using solar radiation from Fort St. John in (9) with r = 0.25 and ε_s = 0.95 resulted in an error of 1.72 MJ m^{-2} d^{-1}. Figure 2 shows Q* estimates using Sunset Prairie and Fort St. John solar radiation measurements in (9) plotted against Q* values measured at Sunset Prairie. It is evident that agreement is generally good using Fort St. John solar radiation, with only six days having errors greater than 2.0 MJ m^{-2} d^{-1}. A regression calculated between

Table 1. Comparison of standard errors of net radiation estimates using the Idso-Jackson formula, and a regression equation.

Estimation Method	Intercept ($MJm^{-2}d^{-1}$)	Slope	r^2	$S_{y:x}$ ($MJm^{-2}d^{-1}$)
K↓ Sunset Prairie				
Idso-Jackson, with ε_a corrected	0.30	0.973	0.978	0.57
Regression of Q* on K↓	0.27	0.979	0.971	0.66
K↓ Fort St. John				
Idso-Jackson, ε_a corrected	1.69	0.834	0.825	1.52
Regression of Q* on K↓	2.04	0.767	0.790	1.69

Q* (estimated) = a + b Q* (measured)

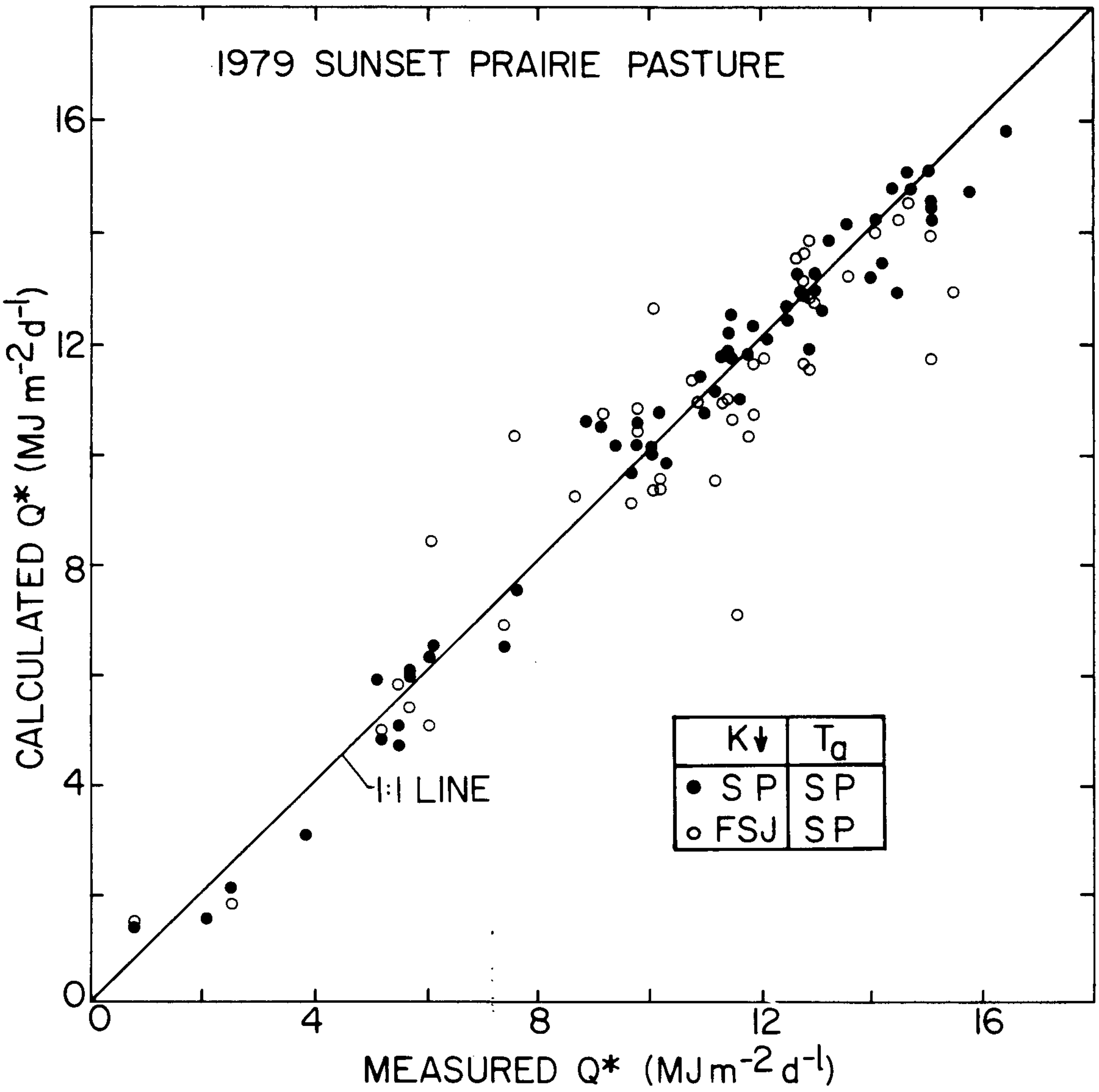

Figure 2. Calculated versus measured Q* using T_a measured on-site and K↓ measured on-site (SP) and at Fort St. John (FSJ).

solar radiation measured at Fort St. John (FSJ) and at Sunset Prairie (SP) for 54 daily totals in 1979 yielded

$$K{\downarrow}(SP) = 0.88K{\downarrow}(FSJ) + 1.48 \text{ MJ m}^{-2}\text{d}^{-1} \qquad r^2 = 0.86 \qquad (13)$$

Using this regression to calculate values of solar radiation from Fort St. John data only reduced the error from 1.72 to 1.50 MJ m^{-2} d^{-1}, which implies that the differences between the two sites are mainly random, and that the developed inter-site correlation does little to improve prediction accuracy. It appears that solar radiation is spatially well-correlated in the region, as would be expected (Suckling and Hay, 1976), and that the data from Fort St. John could be useful in estimating Q* at other locations.

Analysis of the 1978 data showed that for the 35 days of measurement, Q* estimates were better than those for 1979. In 1979, 47% of all estimates using (9) and (13) were accurate to within 10%, while in 1978, 62% were within 10%. Davis (1978) reported that his cloud layer model over-predicted net radiation by 7%, and that 41% of his daytime estimates agreed to within 10%. Subsequent recalibration of the pyranometer used in 1977 suggested that the over-estimate was less than 2% (Davis, personal communication). Measured and modelled net radiation values for 1978 and 1979 are given in Appendix 4.

2. Root Zone Water Balance

a) Seasonal root zone storage estimates

The values of root zone water storage calculated for the 1978 and 1979 growing seasons using the water balance model with W_{max} = 215 mm are compared with measured values in Figures 3 and 4. (Appendix 3 shows model estimates of the water balance terms and root zone storage.) The possible error in the storage measurement was estimated to be approximately $\pm$ 5 mm. On the basis of this figure, the maximum discrepancy of the model values was approximately 10 mm, and 75% of the estimates were found to be within the possible error range of the measurement. This close agreement lends support to the assumption that drainage during most of the growing season in this soil is negligible compared to other water balance terms. In several cases the calculated storage values are several days out of phase with measurements. This is possibly due to the use of a time step of one day instead of a smaller interval, or to the assumption that redistribution occurs instantaneously following heavy rains.

In a wet year, such as 1979, the calculation is sensitive to the value of saturated water storage capacity of the root zone (W_{max}). A decrease of 4% in soil porosity

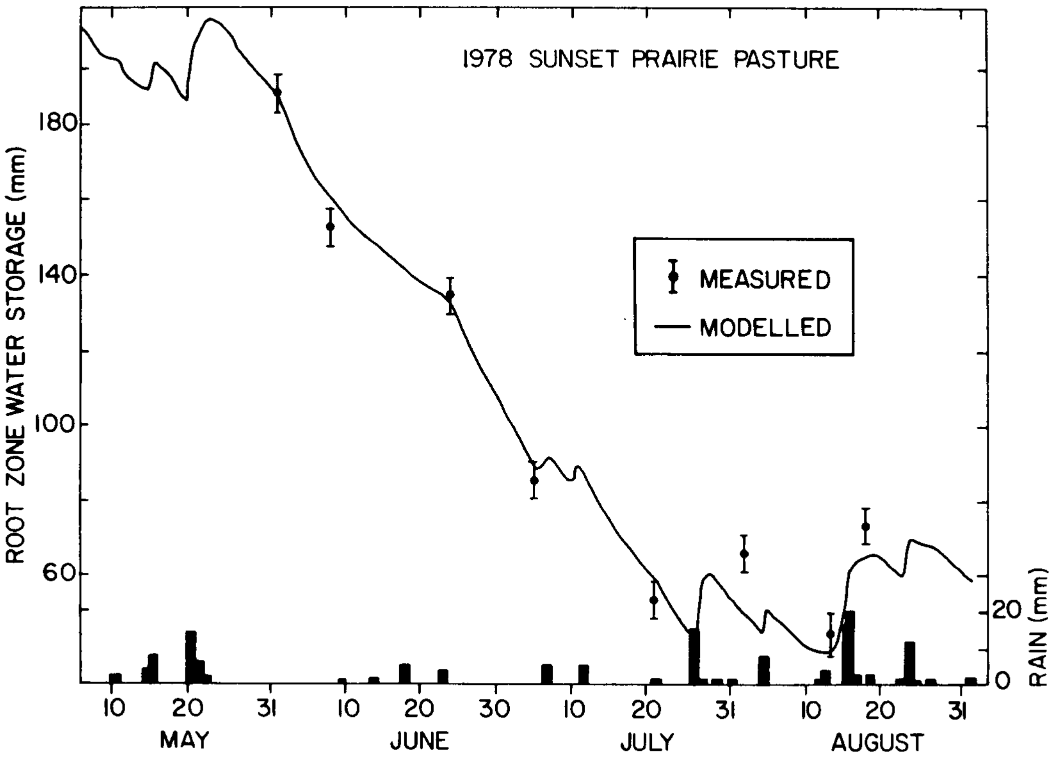

Figure 3. Modelled rootzone water storage compared with measured values in 1978.

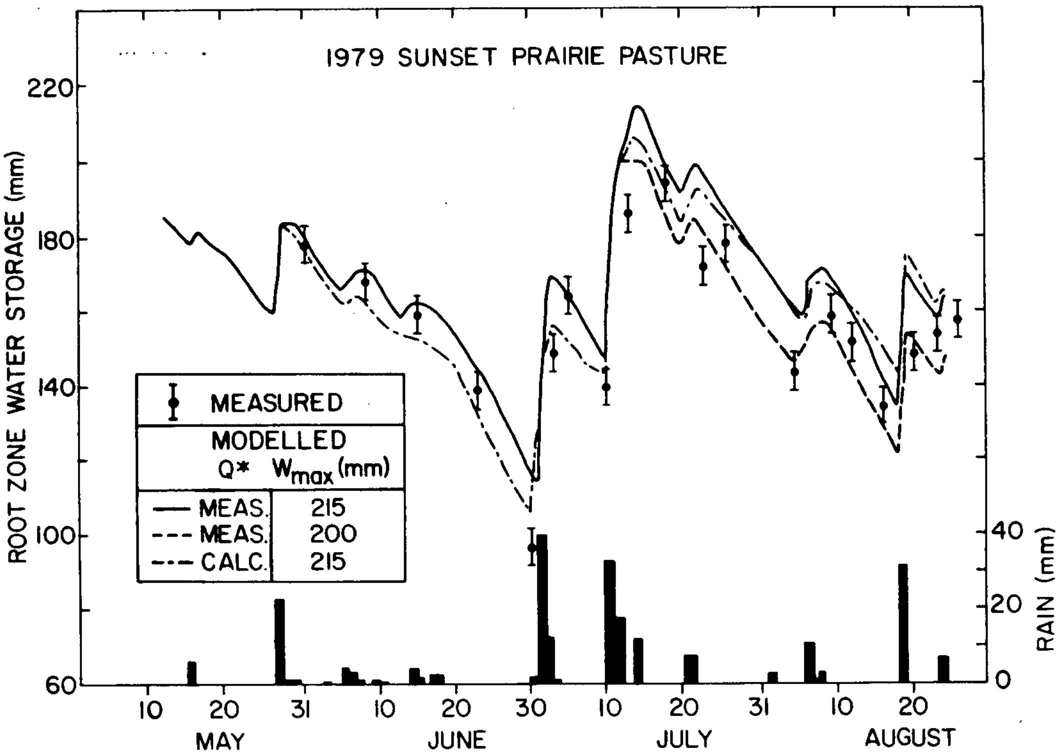

Figure 4. Modelled rootzone water storage compared with measured values in 1979. Effects of using measured and modelled Q*, and two values of maximum water storage (W_{max}) are shown.

results in a decrease of 15 mm in W_{max}. Figure 4 shows that the course of soil water storage, using a value of W_{max} of 200 mm, is between 4 and 15 mm less than that using a value of W_{max} of 215 mm. This appears to give better agreement with the data during the latter part of the growing season.

The spatial variability of measured root zone storage over the pasture is shown in Figure 5 and in Table 2. The figure shows the course of seasonal values of storage at the six auxiliary sites on the pasture, during the 1979 growing season. Measured water storage varies from 160 to 220 mm when the soil is wet, to 80 to 160 mm after significant drying. Sites 2, 3 and 4 are located on high ground, whereas 5, 6 and 7 are on lower ground. The high values for site 5 are somewhat surprising, but may be due to runon from upslope areas near site 4.

Also shown in Figure 5 are the courses of water storage calculated using the model with the initial water storages equal to the values for June 1 at sites 7, 2 and 4 corresponding to the upper, middle and lower lines respectively. These courses are parallel, because the same rainfall is used (see Chapter II), and evaporation is not soil limited at any of the sites, so extraction proceeds at the same rate.

Table 2. Rootzone storage data for 1978 and 1979. (values in mm are the mean of 4 or 5 replicates).

1978		1979								
Sample Date	Site 1	Sample Date	Site 1	2	3	4	5	6	7
May 31	188	May 30	178	177	164	150	199	166	197
June 7	152	June 7	168	168	158	136	---	---	---
		14	159	164	152	125	187	162	170
23	134	22	139	146	137	112	171	143	154
		29	98	122	108	84	163	119	128
		July 2	149	---	---	115	---	---	---
July 4	85	4	164	154	146	138	186	161	200
		9	140	---	---	110	---	---	---
		12	186	---	---	---	---	---	---
		17	194	191	176	173	---	---	---
20	52	22	172	175	169	158	202	175	197
		25	178	---	---	139	---	---	---
		28	163	161	156	129	182	153	164
Aug. 1	65	Aug. 3	144	---	---	114	161	134	145
		8	159	---	---	130	---	---	---
12	43	11	152	141	137	114	173	139	154
		15	135	---	---	95	---	---	---
17	82	19	149	139	136	118	163	142	141
		22	154	---	---	107	---	---	---
		25	157	148	145	109	---	---	---

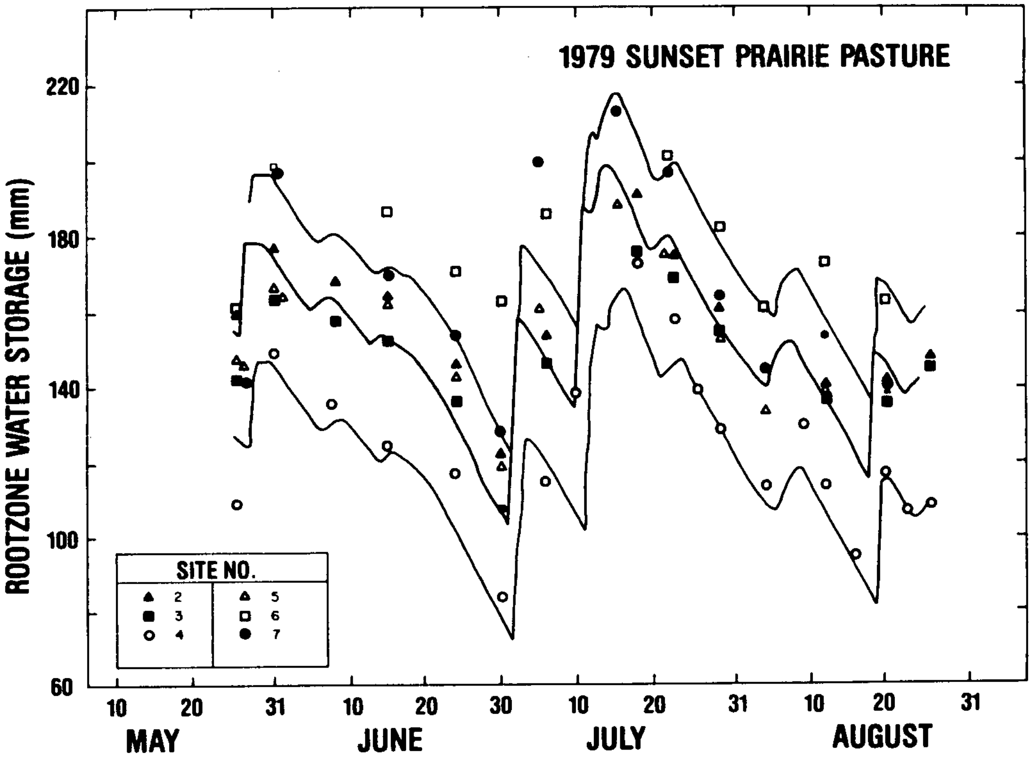

Figure 5. Spatial variation in measured and modelled rootzone water storage in 1979. The upper, middle, and lower lines represent model runs using initial values on June 1 from sites 7, 2, and 4 respectively.

In general, the model gives a good indication of the changes in soil water storage during the growing season, with exception of site 5 during the first drying period. It appears that knowledge of the range of initial moisture conditions leads to reasonable predictions of the subsequent course of root zone storage. Although this would not be true in areas of more extreme topography, it is probably applicable to much of the land utilized for tame pasture and hay in the region.

The soil moisture model is probably accurate for most of the growing season, although the value of α might be higher for cooler autumn conditions (DeBruin and Keijman, 1979). If the model is used as a site index it is probably more practical to obtain an initial moisture content measurement than to attempt to simulate the processes of snowdrifting and snowmelt in order to model early spring conditions.

b) <u>Estimating evapotranspiration and transpiration</u>

The general agreement between measured and modelled values of W in Figures 3, 4 and 5 indicates that the evapotranspiration model is acceptably accurate. Agreement during periods when drainage is known to be small gives strong support to the evapotranspiration model.

There was no test of the estimates of crop transpiration from (4) using LAI and evapotranspiration. Over the first three weeks of the 1979 growing season when total E was 70 mm, E_t was calculated to be 32 mm. While the accuracy of the latter estimate is not high, considerable error would result if transpiration was assumed equal to evapotranspiration. Similarly, in the first week following cutting as much as 10 mm of evaporation from the soil could occur. However, for much of the time (when LAI $>$ 1.5) $E_t \simeq E$.

Rainfall on dry soil results in an uneven distribution of water within the profile which cannot be simulated in a slab model. The interception function provides a degree of realism, since intercepted water is evaporated at the energy limited rate before further demand is placed on the soil. These problems could be alleviated, but at the expense of the model's simplicity. Currently the model can be operated using a hand-held calculator, but for some applications further sophistication may be necessary.

3. Estimating Growth From Evapotranspiration

Figure 6 shows the measured and calculated values of accumulated hay growth at the main site for 1978 and 1979, based on a growth/transpiration ratio of 0.026 t ha^{-1}/

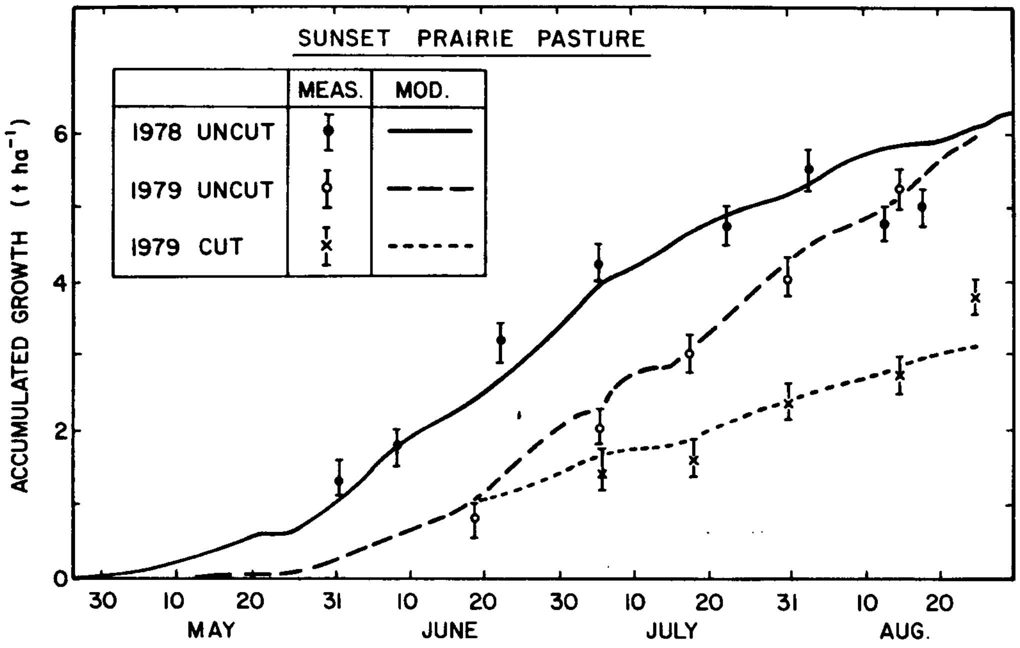

Figure 6. Modelled accumulated growth compared with measured values at site 1. Growth/transpiration ratios used in calculating uncut (hay) and cut (simulated pasture) growth were 0.026 and 0.013 t $ha^{-1}mm^{-1}$ respectively.

mm H_2O. Measurement error is estimated to be ±0.25 t ha^{-1}. and calculated values generally fall within this range. If evapotranspiration had been used instead of transpiration in the growth relationship, growth of hay or pasture would be overestimated by more than 100% in the first three weeks of the growing season.

It was found that a growth/transpiration ratio of 0.013 t ha^{-1}/mm was required to calculate accumulated growth of fertilized pasture (mowed monthly) at site 1 (Figure 5). This ratio is an average, and may be a result of a lower growth/transpiration ratio in the first week following mowing, with a gradual recovery to the higher ratio for hay growth. The yields of the unfertilized simulated pasture sites (2-5), which represent the majority of the pasture, were best predicted by a growth/transpiration ratio of 0.008 t ha^{-1}/mm.

In 1978, early senescence reduced productivity below the level predicted for August. This weakness of the model restricts its usefulness to periods of active growth. The decrease of productivity which occurs during senescence has been well documented (e.g. Biscoe et al., 1975; Byrne and Tognetti, 1969) but simple climatological criteria for its onset have not. The growing degree-day function used by Selirio and Brown (1979) in their model did not account for this early senescence. They used a sigmoid growth curve which approached a maximum yield of 12 t ha^{-1} (in Southern Ontario). Their model, based on accumulated growing degree days above 5°C predicted that the crop was closer to senescence in 1979 than in 1978, which is contrary to measurements and visual observations. Doyle and Fisher (1979) incorporated the effect of soil limited water uptake by wheat in a simple equation for the transpiration ratio:

$$m = a\ t^2 - b(E_s/E_{max}) \tag{15}$$

where t is the time from a critical growth stage. The use of such an equation would help to account for the reduction in growth observed in 1978, but the equation does not account for the irreversible reduction in growth rate which accompanies senescence.

E. CONCLUSIONS

The seasonal course of root zone water storage at Sunset Prairie Pasture can be calculated using a single slab water balance model which requires only soil retention characteristics, initial root zone water content and regional climate data. Evapotranspiration from dry or wet pasture can be estimated well using the Priestley-

Taylor (1972) approach with a daytime α of 1.26. Transpiration can be estimated from E and pasture growth (Tanner and Jury, 1976). Net radiation, required for estimation of E can be modelled to within $\pm$ 15% using on-site albedo and air temperature data, and solar radiation measured at Fort St. John. The course of accumulated hay and pasture growth can be estimated using the growth/transpiration ratio approach (Rose *et al.*, 1972). The ratio is affected by fertility, and the value used for pasture is half that for hay.

CHAPTER IV. SUMMARY AND CONCLUSIONS

Based on relationships developed from research conducted during three growing seasons, a simple climate-based model is proposed to describe forage growth at the Sunset Prairie Community Pasture in the Peace River region of British Columbia. The model, which is based on a linear relationship between growth and transpiration, describes the course of forage growth under limitations of temperature, evaporative demand and water availability.

In the model, growth is initiated after five consecutive days with mean air temperature exceeding $5^{o}C$. This criterion is generally accurate to within one week, and can be calculated using data from existing climate stations in the region.

Evapotranspiration used in the growth model is calculated as the lesser of energy and soil limited rates. The calculation of the energy limited rate (E_{max}) requires knowledge of the available energy, the air temperature, and α, the ratio of E_{max} to the equilibrium evaporation rate. Because of its high spatial correlation in the region, solar radiation measured at Fort St. John can be used to calculate net radiation at the Sunset Prairie Community Pasture. Temperature data required in this calculation are available for the community pastures in the region. Since α and the albedo are conservative for areas of similar vegetation, the calculation of E_{max} is well suited to a large homogeneous area such as the Peace River region.

The calculation of the soil limited evapotranspiration rate (E_s) requires more site specific data than does the calculation of E_{max}. The relationship between E_s and root zone water content depends on the vegetation characteristics and on the water retention properties of the soil. The model requires specification of the parameter b, which is the ratio of E_s to the fraction of extractable water in the root zone (Θ_e). Calculation of Θ_e requires knowledge of the upper and lower limits of root zone water storage (W_{max} and W_{min}, respectively).

The daily root zone water budget, which is used to determine the degree and duration of soil water limitation, requires knowledge of root zone water storage at the beginning of the growing season, the value of W_{max}, the infiltration rate, and daily total rainfall and E_{max}. In many models the initial water storage is assumed to equal W_{max}, but this assumption may seriously reduce the accuracy of model predictions in years with light snowpack or dry spring conditions. If a regional forage growth model were to be implemented, consideration should be given to measuring soil water storage on a weekly or monthly basis during the growing season. The arbitrary separation of rainfall into convective and frontal events contributes as much to the calculated runoff as does the infiltration rate specified. Any work to improve this portion of the model should therefore examine both rainfall climatology and soil characteristics.

Evaporation from bare soil and from foliage is separated from transpiration using empirical relationships which have not been verified for the region. Tests of the model suggest that the form of these relations is not critical, but that their functions contribute significantly to the accuracy of the growth calculations. Since the parameters in these relationships represent characteristics of the vegetation, they are probably applicable on a regional basis.

The growth/transpiration ratios obtained at Sunset Prairie apply to the forage mixture and fertilizer levels present. Since the other community pastures in the region are seeded with similar mixtures, the model can be applied if the fertilizer response is accounted for. Alternatively, the model can be used to calculate forage growth under the climate conditions prevailing at another pasture, using the growth/transpiration relationship developed for Sunset Prairie. This allows direct comparison of the climatic potential at several sites, exclusive of the effects of forage mixture, fertility level, and soil tillage.

The use of a senescence function based on crop aging and water limitation would significantly extend the period for which the model could be realistically applied. Because of the lack of field data late in the growing season, no general function was developed in this thesis. However, use of the simple function described in Chapter III significantly improved the model predictions during August 1978, when water limitations initiated early senescence.

In general, model estimates of evapotranspiration, soil water storage, and forage growth are good, considering the limited data required for their calculation. Currently, the model is quite realistic, in that the major physical processes which affect the plant are described. A number of improvements could be made to the model, in particular (i) characterization of soils and crops in the region is required to implement the model, (ii) improvement of the criterion used to initiate growth, (iii) quantitative description of fertilizer response. In addition, the interaction of grazing frequency and intensity is extremely complex, and merits further investigation. Preliminary work using an empirical multiplier to account for the reduction of forage growth from monthly cutting is promising, but it is not known whether different cutting heights and frequencies can be modelled. Further work on this problem should incorporate the quality of the forage, which is extremely important in pasture management. Modelling such interactions requires detailed knowledge of the physiology of the plants, and considerably more data than could be collected in this project (e.g. rates of photosynthesis and respiration,partitioning of photosynthetic products). Any attempt to improve the modelling of the effects of different environmental conditions and management practices must be judged both in terms of the accuracy and representativeness of the model estimates.

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APPENDIX 1.

Daily Energy Balance Components
for 1978 and 1979.

1 9 7 8 D A I L Y E N E R G Y B A L A N C E C O M P O N E N T S

THE FOLLOWING IS A SUMMARY OF DAILY TOTAL AND AVERAGE VALUES AS FOLLOWS:

DAY: THE JULIAN CALENDAR DAY NUMBER
QSTAR: THE NET RADIATION FLUX DENSITY
GZERO: THE SOIL HEAT FLUX DENSITY AT THE SURFACE
QHEAT: THE SENSIBLE HEAT FLUX DENSITY
QEVAP: THE LATENT HEAT FLUX DENSITY
BOWEN: THE DAILY BOWEN RATIO(QHEAT/QEVAP)
ALPHA: THE RATIO OF EVAPORATION/ EQUILIBRIUM EVAPORATION
P & T: THE CALCULATED PRIESTLEY-TAYLOR EVAPORATION WITH ALPHA = 1.26
WATER: THE FRACTIONAL VOLUMETRIC WATER CONTENT OF THE 0 TO 10 CM LAYER
SUMQE: THE SUM OF QEVAP FOR THE PERIOD
SUMQ*: THE SUM OF QSTAR FOR THE PERIOD
SUMPT: THE SUM OF P & T FOR THE PERIOD
SUMKD: THE SUM OF KDOWN FOR THE PERIOD
KDOWN: THE SHORTWAVE RADIATION FLUX DENSITY
ABDO: THE SURFACE ALBEDO
TDBAR: THE AVERAGE DAYTIME DRY BULB TEMPERATURE
TSBAR: THE AVERAGE SOIL TEMPERATURE IN THE 0 TO 5 CM LAYER
DLTD: THE AVERAGE DRY BULB TEMPERATURE OVER 1 METER
DLTW: THE AVERAGE WET BULB TEMPERATURE DIFFERENCE OVER 1 METER

THE FLUX DENSITIES ARE IN UNITS OF MJ M-2 D-1 AND TEMPERATURES ARE IN DEGREES CELCIUS

DAY	QSTAR	GZERO	QHEAT	QEVAP	BOWEN	ALPHA	P & T	% W	SUMQE	SUMQ*	SUMPT	SUMKD	KDOWN	ABDO	TDBAR	TSBAR	DLTD	DLTW
158	13.07	2.93	2.84	7.30	0.39	1.20	7.65	0.45	7.3	13.1	7.7	-0.0	-0.00	0.0	18.9	10.7	0.19	0.17
159	13.43	1.53	5.04	6.86	0.74	1.03	8.36	0.58	14.2	26.5	16.0	-0.0	-0.00	0.0	14.4	9.9	0.16	0.14
160	10.20	1.60	4.01	4.58	0.88	0.98	5.89	0.53	18.7	36.7	21.9	-0.0	-0.00	0.0	11.3	9.0	0.17	0.17
SUM	36.70	6.07	11.90	18.74	0.63	1.08	21.90	0.53	18.7	36.7	21.9	-0.0	-0.00	3.00	14.9	9.9	0.17	0.16

DAY	QSTAR	GZERO	QHEAT	QEVAP	BOWEN	ALPHA	P & T	% W	SUMQE	SUMQ*	SUMPT	SUMKD	KDOWN	ABDO	TDBAR	TSBAR	DLTD	DLTW
174	11.30	2.25	2.63	6.42	0.41	1.24	6.54	0.38	6.4	11.3	6.5	-0.0	-0.00	0.0	13.5	12.8	0.15	0.20
176	6.58	1.12	0.62	4.84	0.13	1.44	4.23	0.39	11.3	17.9	10.8	14.5	14.53	0.26	20.0	17.0	0.11	0.28
177	15.98	2.14	2.11	11.76	0.18	1.41	10.52	0.34	23.0	33.9	21.3	37.8	23.29	0.26	18.3	15.7	0.13	0.20
178	15.42	1.92	1.60	12.03	0.13	1.47	10.30	0.41	35.1	49.3	31.6	62.1	24.31	0.27	18.3	15.9	0.10	0.12
179	16.17	2.36	2.09	11.72	0.18	1.36	10.86	0.26	46.8	65.4	42.4	87.8	25.65	0.26	20.6	16.9	0.09	0.29
180	13.60	2.09	1.25	10.26	0.12	1.40	9.25	0.34	57.0	79.0	51.7	108.5	20.75	0.25	21.5	17.2	0.15	0.23
181	10.15	1.22	1.80	7.13	0.25	1.26	7.15	0.24	64.2	89.2	58.8	123.2	14.70	0.25	16.8	16.6	0.14	0.13
182	15.25	1.27	3.54	10.42	0.34	1.33	9.87	0.27	74.6	104.4	68.7	148.3	25.12	0.27	15.6	15.5	0.17	0.19
183	16.16	1.81	2.52	11.84	0.21	1.38	10.82	0.21	86.4	120.6	79.5	173.7	25.37	0.27	19.1	16.1	0.13	0.30
184	15.83	2.03	1.88	11.93	0.16	1.38	10.91	0.18	98.3	136.4	90.4	198.0	24.34	0.26	21.0	17.5	0.15	0.18
185	16.03	1.97	3.98	10.08	0.40	1.11	11.44	0.17	108.4	152.5	101.9	221.7	23.71	0.25	20.5	18.5	0.19	0.21
SUM	*****	20.18	24.03	*****	0.22	1.34	*****	0.17	108.4	152.5	101.9	221.7	*****	0.26	18.7	16.3	0.14	0.21

DAY	QSTAR	GZERO	QHEAT	QEVAP	BOWEN	ALPHA	P & T	% W	SUMQE	SUMQ*	SUMPT	SUMKD	KDOWN	ABDO	TDBAR	TSBAR	DLTD	DLTW
200	7.06	0.60	1.47	4.99	0.29	1.25	5.03	0.12	5.0	7.1	5.0	11.2	11.25	0.25	19.1	17.6	0.14	0.24
201	10.08	1.75	1.52	6.85	0.22	1.29	6.68	0.12	11.8	17.1	11.7	27.8	16.59	0.24	18.7	16.5	0.11	0.23
202	13.86	1.74	3.78	8.44	0.45	1.07	9.95	0.07	20.3	31.0	21.7	51.3	23.43	0.24	21.4	18.5	0.20	0.27
203	12.07	1.75	3.36	7.02	0.48	1.02	8.65	0.09	27.3	43.1	30.3	71.7	20.40	0.25	23.2	18.5	0.24	0.20
204	10.05	0.97	3.03	6.05	0.50	1.05	7.27	0.10	33.4	53.1	37.6	89.6	17.98	0.27	21.3	17.7	0.14	0.16
205	9.74	1.01	3.61	5.12	0.70	0.95	6.78	0.08	38.5	62.9	44.4	108.0	18.33	0.27	18.9	17.0	0.23	0.18
206	13.51	1.55	6.12	5.84	1.05	0.78	9.43	0.11	44.3	76.4	53.8	129.4	21.39	0.24	21.0	17.9	0.31	0.25
207	12.16	1.31	4.83	5.98	0.81	0.85	8.83	0.09	50.3	88.5	62.6	147.4	18.08	0.24	20.1	18.2	0.27	0.21
208	5.75	0.82	1.62	3.31	0.49	1.07	3.90	0.28	53.6	94.3	66.5	156.2	8.77	0.24	14.8	16.7	0.14	0.14
209	11.68	1.12	2.98	7.57	0.39	1.19	8.03	0.23	61.2	106.0	74.6	175.1	18.87	0.25	16.7	16.6	0.17	0.23
210	13.04	1.50	3.38	8.15	0.42	1.15	8.90	0.24	69.3	119.0	83.4	195.5	20.40	0.24	17.7	17.7	0.20	0.29
211	12.85	1.45	2.96	8.43	0.35	1.20	8.84	0.25	77.7	131.8	92.3	216.4	20.93	0.24	17.8	17.5	0.28	0.21
212	11.55	1.24	3.42	6.89	0.50	1.08	8.01	0.14	84.6	143.4	100.3	236.4	19.97	0.25	17.7	17.6	0.18	0.19
213	12.05	1.04	4.19	6.83	0.61	1.11	7.75	0.20	91.5	155.4	108.1	257.8	21.41	0.25	13.4	17.0	0.24	0.24
SUM	*****	17.85	46.29	91.47	0.51	1.07	*****	0.20	91.5	155.4	108.1	257.8	*****	0.25	18.7	17.5	0.20	0.22

DAY	QSTAR	GZERO	QHEAT	QEVAP	BOWEN	ALPHA	P & T	% W	SUMQE	SUMQ*	SUMPT	SUMKD	KDOWN	ABDO	TDBAR	TSBAR	DLTD	DLTW
222	6.15	0.64	2.24	3.27	0.68	0.96	4.28	0.15	3.3	6.1	4.3	10.2	10.18	0.25	17.9	17.1	0.15	0.15
223	5.56	0.37	2.89	2.33	1.24	0.78	3.79	0.08	5.6	11.7	8.1	22.2	12.06	0.24	11.7	15.2	0.17	0.13
224	1.87	0.10	0.73	1.03	0.71	1.08	1.21	0.13	6.6	13.6	9.3	24.7	2.51	0.22	8.2	13.6	0.10	0.12
225	11.41	1.21	4.14	6.05	0.68	0.99	7.67	0.11	12.7	25.0	17.0	43.0	18.27	0.25	15.0	13.9	0.22	0.22
226	8.30	0.69	3.54	4.08	0.87	0.90	5.69	0.07	16.8	33.3	22.6	57.8	14.75	0.25	16.1	15.3	0.18	0.16
227	5.13	0.21	1.84	3.08	0.60	1.08	3.59	0.15	19.9	38.4	26.2	66.0	8.26	0.23	12.0	13.8	0.14	0.12
SUM	38.42	3.22	15.38	19.85	0.77	0.95	26.23	0.15	19.9	38.4	26.2	66.0	66.02	0.25	13.5	14.8	0.16	0.15

1 9 7 9 D A I L Y E N E R G Y B A L A N C E C O M P O N E N T S

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P & T: THE CALCULATED PRIESTLEY-TAYLOR EVAPORATION WITH ALPHA = 1.26
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DLTD: THE AVERAGE DRY BULB TEMPERATURE OVER 1 METER
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THE FLUX DENSITIES ARE IN UNITS OF MJ M-2 D-1 AND TEMPERATURES ARE IN DEGREES CELCIUS

DAY	QSTAR	GZERO	QHEAT	QEVAP	BOWEN	ALPHA	P & T	WATER	SUMQE	SUMQ*	SUMPT	SUMKD	KDOWN	ABDO	TDBAR	TSBAR	DLTD	DLTW
139	5.16	0.41	3.61	1.09	3.30	0.46	2.97	0.49	1.1	5.2	3.0	-0.0	-0.00	0.0	10.3	5.7	0.23	0.15
140	1.76	0.52	0.10	1.08	0.09	2.04	0.67	0.49	2.2	6.9	3.6	-0.0	-0.00	0.0	8.0	5.3	0.01	0.01
141	5.23	-0.63	4.22	1.65	2.56	0.55	3.79	0.49	3.8	12.1	7.4	-0.0	-0.00	0.0	12.1	6.8	0.25	0.16
142	10.20	2.01	4.28	3.91	1.09	0.81	6.11	0.49	7.7	22.4	13.5	-0.0	-0.00	0.0	19.6	9.4	0.25	0.19
143	6.62	1.23	2.70	2.69	1.00	0.85	3.97	0.49	10.4	29.0	17.5	-0.0	-0.00	0.0	16.8	8.6	0.10	0.10
145	10.57	1.51	5.37	3.69	1.46	0.72	6.43	0.49	14.1	39.5	23.9	17.1	17.10	0.28	15.4	9.7	0.21	0.14
146	6.61	1.20	2.24	3.16	0.71	1.03	3.87	0.49	17.3	46.1	27.8	28.2	11.14	0.28	13.5	8.9	0.09	0.10
148	10.81	1.03	4.08	5.70	0.71	1.26	5.72	0.49	23.0	57.0	33.5	48.5	20.31	0.40	7.1	5.3	0.12	0.15
149	6.34	1.06	1.90	3.45	0.55	1.30	3.35	0.49	26.4	63.3	36.9	60.3	11.78	0.27	6.6	6.0	0.07	0.09
150	12.97	2.73	4.02	6.22	0.65	1.08	7.29	0.49	32.7	76.3	44.2	83.3	23.00	0.30	14.7	9.3	0.17	0.18
151	11.94	2.05	2.87	7.40	0.39	1.21	7.68	0.49	40.1	88.2	51.8	103.0	19.72	0.29	14.4	11.1	0.07	0.14
152	10.17	1.83	2.28	6.09	0.37	1.24	6.19	0.49	46.1	98.4	58.0	119.8	16.81	0.29	15.9	11.6	0.13	0.11
153	10.06	1.58	2.41	6.06	0.40	1.22	6.24	0.49	52.2	108.4	64.3	135.4	15.59	0.29	15.7	10.8	0.09	0.12
154	13.68	1.95	3.63	8.11	0.45	1.22	8.35	0.49	60.3	122.1	72.6	158.7	23.23	0.29	15.7	11.7	0.15	0.19
155	10.09	1.49	3.02	5.58	0.54	1.18	5.96	0.49	65.9	132.2	78.6	174.9	16.28	0.29	14.3	10.9	0.12	0.15
156	2.67	0.19	-0.69	3.17	-0.22	2.33	1.71	0.48	69.1	134.9	80.3	178.3	3.38	0.27	10.7	10.5	-.20	0.38
157	8.93	1.29	4.35	3.29	1.32	0.84	4.92	0.48	72.3	143.8	85.2	195.8	17.46	0.27	10.0	10.6	0.14	0.12
158	6.54	1.63	1.19	4.01	0.30	1.26	4.01	0.47	76.4	150.3	89.2	215.4	19.63	0.29	12.1	10.3	0.0	0.0
159	14.77	1.82	4.38	8.58	0.51	1.26	8.59	0.46	84.9	165.1	97.8	238.8	23.42	0.28	12.3	11.4	0.17	0.24

DAY	QSTAR	GZERO	QHEAT	QEVAP	BOWEN	ALPHA	P & T	WATER	SUMQE	SUMQ*	SUMPT	SUMKD	KDOWN	ABDO	TDBAR	TSBAR	DLTD	DLTW
160	7.73	1.02	2.47	4.24	0.58	1.16	4.59	0.46	89.2	172.8	102.4	250.1	11.25	0.26	10.3	10.0	0.12	0.15
161	9.90	-0.06	4.35	5.60	0.78	1.04	6.81	0.45	94.8	182.7	109.2	266.1	16.04	0.27	10.3	10.5	0.15	0.17
162	13.94	1.80	8.17	3.97	2.06	0.58	8.58	0.45	98.7	196.7	117.8	287.6	21.48	0.27	14.6	12.9	0.25	0.11
163	14.70	1.76	3.40	9.55	0.36	1.32	9.11	0.44	108.3	211.4	126.9	311.8	24.23	0.28	15.0	12.1	0.14	0.22
164	5.82	0.72	1.57	3.53	0.45	1.29	3.45	0.44	111.8	217.2	130.4	321.0	9.20	0.26	9.5	10.0	0.07	0.11
165	0.06	0.01	0.03	0.02	1.13	0.86	0.03	0.44	111.8	217.3	130.4	321.3	0.29	0.28	11.3	12.9	0.18	0.15
166	10.92	1.76	2.22	6.94	0.32	1.38	6.35	0.44	118.8	228.2	136.7	338.9	17.60	0.27	13.1	11.6	0.11	0.15
167	6.09	0.98	2.02	3.09	0.65	1.09	3.58	0.44	121.9	234.3	140.3	349.4	10.46	0.27	11.0	11.7	0.13	0.14
168	9.81	1.57	1.59	6.62	0.24	1.35	6.16	0.44	128.5	244.1	146.5	362.8	13.42	0.25	17.7	14.9	0.22	0.28
170	11.18	1.33	2.91	6.95	0.42	1.23	7.10	0.44	135.4	255.3	153.6	377.5	14.74	0.25	12.2	12.8	0.11	0.14
171	9.46	1.36	3.10	5.00	0.62	1.10	5.75	0.43	140.4	264.7	159.3	392.4	14.86	0.27	12.0	12.9	0.12	0.15
172	14.08	1.60	3.85	8.67	0.44	1.24	8.83	0.43	149.1	278.8	168.2	415.3	22.96	0.26	14.2	13.2	0.13	0.19
173	14.24	1.72	8.61	3.91	2.20	0.55	8.91	0.43	153.0	293.1	177.1	437.5	22.17	0.26	15.5	12.9	0.23	0.12
174	16.16	1.13	4.86	10.17	0.48	1.27	10.13	0.39	163.2	309.2	187.2	462.9	25.43	0.28	13.3	12.8	0.15	0.16
175	9.41	0.63	2.85	5.73	0.50	1.20	6.04	0.37	168.9	318.6	193.2	478.4	15.52	0.30	12.1	11.7	0.08	0.13
176	13.21	1.46	2.78	8.97	0.31	1.31	8.63	0.33	177.9	331.8	201.9	498.9	20.43	0.27	17.0	12.8	0.12	0.20
177	16.36	1.61	2.04	12.71	0.16	1.47	10.90	0.31	190.6	348.2	212.8	525.1	26.26	0.27	19.4	13.6	0.07	0.22
178	12.94	1.39	1.69	9.86	0.17	1.45	8.59	0.29	200.4	361.1	221.3	544.8	19.71	0.28	18.2	13.2	0.04	0.18
179	14.34	1.58	1.12	11.64	0.10	1.54	9.52	0.26	212.1	375.5	230.9	567.9	23.11	0.27	20.1	13.9	0.02	0.23
180	14.83	1.71	2.01	11.11	0.18	1.39	10.08	0.23	223.2	390.3	241.0	590.4	22.45	0.27	20.1	14.6	0.13	0.19
181	14.16	0.91	4.49	8.76	0.51	1.17	9.42	0.23	231.9	404.5	250.4	612.8	22.42	0.27	14.2	15.1	0.16	0.21
182	2.10	-0.78	1.23	1.65	0.75	1.12	1.85	0.30	233.6	406.6	252.2	616.1	3.28	0.20	6.4	10.4	0.03	0.03
183	3.88	0.31	1.10	2.47	0.44	1.31	2.38	0.38	236.1	410.4	254.6	622.5	6.45	0.22	7.9	9.0	0.04	0.06
184	15.21	1.66	4.61	8.94	0.52	1.18	9.54	0.46	245.0	425.6	264.1	647.0	24.48	0.26	13.3	11.7	0.16	0.19
185	13.56	1.95	2.63	8.98	0.29	1.30	8.67	0.48	254.0	439.2	272.8	667.4	20.37	0.25	16.8	12.0	0.11	0.22
186	15.82	2.13	2.39	11.29	0.21	1.28	11.10	0.47	265.3	455.0	283.9	689.7	22.35	0.25	19.7	14.1	0.11	0.21
187	16.36	1.76	2.08	12.49	0.17	1.37	11.45	0.46	277.8	471.4	295.4	714.3	24.59	0.26	20.2	15.0	0.08	0.20
188	5.72	0.72	0.36	4.63	0.08	1.56	3.75	0.46	282.4	477.1	299.1	724.6	10.30	0.25	15.4	13.2	0.04	0.06
189	13.07	1.20	2.50	9.37	0.27	1.32	8.97	0.45	291.8	490.2	308.1	744.8	20.19	0.27	17.3	14.1	0.08	0.18
190	16.44	2.01	2.81	11.59	0.24	1.32	11.07	0.44	303.4	506.6	319.2	768.6	23.83	0.25	16.3	14.3	0.11	0.22
191	5.48	0.71	0.47	4.30	0.11	1.46	3.71	0.46	307.7	512.1	322.9	777.1	8.47	0.25	16.4	13.9	0.02	0.09
192	2.45	0.19	0.57	1.69	0.34	1.23	1.73	0.47	309.4	514.5	324.6	780.9	3.76	0.24	15.2	14.0	0.07	0.10
193	7.93	0.24	1.83	5.86	0.31	1.27	5.82	0.48	315.2	522.5	330.4	792.1	11.28	0.24	14.7	14.8	0.10	0.10
194	2.61	0.02	0.39	2.19	0.18	1.53	1.81	0.49	317.4	525.1	332.2	796.4	4.25	0.23	10.8	12.7	0.04	0.03
195	1.93	0.45	0.19	1.28	0.15	1.26	1.28	0.51	318.7	527.0	333.5	800.0	3.60	0.25	19.1	13.4	0.0	0.0
196	13.94	1.84	0.63	11.47	0.06	1.34	10.81	0.49	330.2	540.9	344.3	820.8	20.82	0.24	21.7	14.3	0.08	0.16
197	15.58	2.01	1.51	12.06	0.12	1.26	12.06	0.48	342.2	556.5	356.4	843.9	23.13	0.24	21.3	15.1	0.0	0.0
198	13.42	2.30	1.99	9.13	0.22	1.22	9.45	0.47	351.4	570.0	365.8	864.7	20.82	0.24	23.8	16.1	0.08	0.17
199	14.85	2.06	1.25	11.54	0.11	1.35	10.74	0.46	362.9	584.8	376.6	888.2	23.41	0.24	25.0	16.9	0.05	0.18
201	15.23	1.79	4.31	9.14	0.47	1.05	10.97	0.43	372.0	600.0	387.6	910.7	22.57	0.24	21.0	17.7	0.15	0.16
202	14.16	0.93	4.07	9.16	0.44	1.15	10.08	0.42	381.2	614.2	397.6	933.2	22.43	0.25	17.8	17.5	0.09	0.08
203	10.24	0.55	3.19	6.51	0.49	1.18	6.92	0.43	387.7	624.4	404.6	949.3	16.12	0.26	14.5	14.8	0.10	0.12
204	11.98	1.05	2.66	8.27	0.32	1.31	7.94	0.43	396.0	636.4	412.5	966.3	16.99	0.24	13.7	14.9	0.07	0.13
205	10.31	1.18	3.22	5.91	0.54	1.08	6.87	0.43	401.9	646.7	419.4	984.1	17.84	0.24	15.0	15.1	0.11	0.12
206	15.02	1.69	4.17	9.16	0.46	1.12	10.26	0.43	411.0	661.7	429.6	1007.3	23.18	0.25	16.9	14.9	0.16	0.21
207	14.04	1.72	3.06	9.24	0.33	1.19	9.74	0.43	420.3	675.8	439.4	1028.5	21.18	0.24	19.2	15.1	0.14	0.23

DAY	QSTAR	GZERO	QHEAT	QEVAP	BOWEN	ALPHA	P & T	WATER	SUMQE	SUMQ*	SUMPT	SUMKD	KDOWN	ABDO	TDBAR	TSBAR	DLTD	DLTW
208	13.05	1.74	2.22	9.09	0.24	1.26	9.12	0.43	429.4	688.8	448.5	1048.0	19.58	0.24	20.9	15.7	0.08	0.22
209	6.00	0.74	1.39	3.87	0.36	1.18	4.15	0.43	433.2	694.8	452.6	1057.5	9.43	0.23	17.2	15.7	0.06	0.09
210	11.24	1.21	2.74	7.29	0.38	1.15	8.01	0.41	440.5	706.1	460.7	1073.8	16.38	0.23	18.4	15.6	0.12	0.13
211	13.20	1.32	2.10	9.78	0.21	1.29	9.56	0.40	450.3	719.3	470.2	1094.2	20.34	0.25	20.4	15.6	0.11	0.14
212	12.33	0.87	2.97	8.49	0.35	1.20	8.92	0.38	458.8	731.6	479.1	1113.1	18.95	0.24	18.9	16.2	0.07	0.09
213	10.97	0.75	2.20	8.03	0.27	1.31	7.73	0.37	466.8	742.6	486.9	1131.0	17.90	0.26	16.9	14.9	0.04	0.09
214	9.00	0.88	2.52	5.59	0.45	1.19	5.91	0.36	472.4	751.6	492.8	1144.6	13.56	0.24	14.5	14.5	0.11	0.15
215	5.67	0.27	2.28	3.12	0.73	1.08	3.64	0.35	475.5	757.2	496.4	1152.9	8.30	0.22	9.6	14.0	0.09	0.11
216	7.74	0.70	2.55	4.50	0.57	1.16	4.90	0.35	480.0	765.0	501.3	1164.2	11.37	0.22	11.6	13.6	0.11	0.14
217	6.32	0.51	1.55	4.26	0.36	1.26	4.25	0.36	484.3	771.3	505.6	1174.3	10.05	0.24	12.1	12.9	0.07	0.10
218	5.50	0.65	1.08	3.79	0.28	1.23	3.87	0.37	488.1	776.8	509.4	1182.2	7.91	0.23	12.1	13.1	0.06	0.06
219	8.01	1.03	1.75	5.23	0.33	1.23	5.34	0.38	493.3	784.8	514.8	1193.1	10.87	0.22	15.3	14.2	0.09	0.13
220	13.21	1.36	3.86	7.99	0.48	1.11	9.07	0.38	501.3	798.0	523.9	1212.4	19.34	0.24	16.1	14.9	0.13	0.15
221	13.77	1.52	3.36	8.89	0.38	1.17	9.55	0.40	510.2	811.8	533.4	1232.6	20.19	0.24	18.2	14.1	0.14	0.20
222	10.93	1.24	1.05	8.63	0.12	1.44	7.55	0.41	518.8	822.7	540.9	1249.0	16.44	1.29	19.8	14.8	0.08	0.11
223	13.10	1.16	2.52	9.42	0.27	1.27	9.36	0.42	528.3	835.8	550.3	1268.6	19.55	0.24	18.8	15.2	0.11	0.12
224	12.41	1.26	2.89	8.26	0.35	1.19	8.77	0.41	536.5	848.2	559.1	1287.0	18.40	0.24	18.7	14.5	0.12	0.18
225	12.97	0.96	3.89	8.12	0.48	1.10	9.33	0.40	544.6	861.2	568.4	1306.4	19.44	0.25	17.1	14.6	0.13	0.16
226	12.16	1.36	3.77	7.04	0.54	1.02	8.73	0.39	551.7	873.4	577.1	1325.7	19.26	0.20	17.7	14.1	0.14	0.15
227	11.79	1.48	2.53	7.78	0.33	1.17	8.38	0.38	559.5	885.2	585.5	1344.1	18.43	0.23	20.9	14.3	0.12	0.15
228	11.70	1.26	1.86	8.59	0.22	1.27	8.54	0.37	568.0	896.9	594.1	1362.0	17.86	0.23	21.1	15.7	0.11	0.13
229	12.08	1.08	2.06	8.94	0.23	1.25	8.99	0.35	577.0	908.9	603.1	1380.1	18.17	0.25	21.7	15.4	0.09	0.10
230	1.74	0.13	0.47	1.13	0.41	1.17	1.22	0.34	578.1	910.7	604.3	1383.3	3.13	0.18	13.0	13.4	0.04	0.05
231	10.50	1.07	2.41	7.02	0.34	1.19	7.40	0.33	585.1	921.2	611.7	1399.2	15.98	0.23	15.8	13.4	0.11	0.10
232	10.09	1.08	2.13	6.88	0.31	1.21	7.15	0.33	592.0	931.3	618.8	1414.0	14.81	0.22	18.3	13.9	0.12	0.11
233	12.00	1.24	2.39	8.36	0.29	1.22	8.65	0.32	600.4	943.3	627.5	1432.9	18.87	0.23	20.1	14.1	0.11	0.19
234	11.50	1.23	2.65	7.61	0.35	1.16	8.30	0.31	608.0	954.8	635.8	1450.5	17.61	0.23	19.1	14.1	0.11	0.13
235	2.75	0.02	1.86	0.87	2.14	0.55	1.98	0.30	608.9	957.5	637.7	1454.5	3.93	0.19	10.9	13.9	0.05	0.04
236	0.18	-0.03	0.12	0.09	1.33	0.79	0.14	0.33	608.9	957.7	637.9	1454.8	0.39	0.24	9.0	12.1	0.06	0.05
SUM	*****	*****	*****	*****	0.39	1.20	*****	0.33	608.9	957.7	637.9	1454.8	*****	0.27	15.4	12.9	0.10	0.14

APPENDIX 2.

Listing of Growth-Water Balance Program.

P R O G R A M   L I S T I N G   FOR G R O W T H   AND   W A T E R   B A L A N C E

```
      INTEGER ICUT(5)
      REAL FC/215./,WP/0.15/,PEMAX/27./,ALPHA/1.26/,TOT(5)/4*0.,0.01/,
     $GSLOPE/0.026/,INTRCP/0./,INFILT/4./,CUTGRO/0.01/
C READ IN THE STARTING DATE, STORAGE(WATER), AND CUTTING DATES(ICUT(I))
      READ (5,501) IDAY,WATER,(ICUT(I),I=1,5)
      I=1
C READ IN THE TEMPERATURE, RAINFALL, AND MODELLED NET RADIATION FOR THE DAY
CHECK TO SEE THAT THE DAY IS LATER THAN THE SPECIFIED STARTING DATE AND
C THAT THE SEASON IS NOT OVER (DAY=999).  CHECK TO SEE IF CUTTING IS TODAY.
   10 READ(5,500) NDAY,TBAR,PREC,QSTAR
      IF(NDAY.LT.IDAY) GO TO 10
      IF(NDAY.EQ.999) STOP
      IF(NDAY.NE.ICUT(I)) GO TO 20
      CUTGRO=0.01
      I=I+1
   20 QG=0.1*QSTAR
COMPUTE PRIESTLEY AND TAYLOR EVAPOTRANSPIRATION, AND ASSUME THE SOIL HEAT
C FLUX IS 10% OF THE NET RADIATION FLUX.
      SSG=0.432+0.0124*TBAR
      EVAP=0.4065*ALPHA*SSG*(QSTAR-QG)
      ETSOIL=EVAP-INTRCP
      IF(ETSOIL.LT.0)ETSOIL=0
      SMAV=(WATER-WP*FC)/(FC*(1-WP))
COMPUTE SOIL LIMITED TRANSPIRATION AND CHECK TO SEE IF EMAX EXCEEDS THIS.
      PELIM=PEMAX*SMAV
      IF(PELIM.LT.ETSOIL)ETSOIL=PELIM
COMPUTE TRANSPIRATION BY THE TANNER AND JURY METHOD.
      FRAC=EXP(-3.*CUTGRO)
      ALFAS=ALPHA-((ALPHA-1.)*(1.-FRAC)/(1.-0.35))
      TRANS=(1.-FRAC*ALFAS/ALPHA)*ETSOIL
COMPUTE GROWTH FROM TRANSPIRATION, AND COMPUTE DRAINAGE AND INTERCEPTION
      GROWTH=TRANS*GSLOPE
      DRAIN=0.
      PREC=1.1*PREC
      INTRCP=0.55*PREC**(0.53-0.0085*(PREC-5.))
      PRECEF=PREC-INTRCP
COMPUTE HORTON RUNOFF
      RUNOFF=0.
      DT=2
      IF(PRECEF.GT.10)DT=12.
      IF(PRECEF/DT.LT.INFILT) GO TO 30
      RUNOFF=PRECEF-INFILT*DT
      PRECEF=PRECEF-RUNOFF
   30 CONTINUE
COMPUTE THE WATER BALANCE
      WATER=WATER+PRECEF-ETSOIL-DRAIN
      IF(WATER.LT.FC) GO TO 50
```

```
COMPUTE DUNNE RUNOFF AND ADD TO HORTON RUNOFF FOR DAY.
      RUNOFF=WATER-FC+RUNOFF
      WATER=FC
   50 CONTINUE
COMPUTE THE DAILY TOTALS, WRITE A LINE, AND GO TO THE NEXT DAY.
      TOT(1)=TOT(1)+ETSOIL
      TOT(2)=TOT(2)+PRECEF
      TOT(3)=TOT(3)+INTRCP
      TOT(4)=TOT(4)+RUNOFF
      TOT(5)=TOT(5)+GROWTH
      CUTGRO=CUTGRO+GROWTH
      WRITE(6,600) NDAY,WATER,PRECEF,INTRCP,TRANS,EVAP,(TOT(I),I=1,5),GROWTH
      GO TO 10
  500 FORMAT(I3,2X,2(F4.1,1X),F5.2)
  501 FORMAT(I3,2X,F3.0,5(I3,2X))
  600 FORMAT(I3,2X,9(F6.1,1X),2X,2(F5.2,1X))
      END
```

APPENDIX 3.

Output of Growth-Water Balance Program.

W A T E R   B A L A N C E   A N D   G R O W T H   F O R   1 9 7 8

ALL VALUES ARE IN MILLIMETRES, EXCEPT FOR THE GROWTH, WHICH IS IN TONNES/HA.

THE COLUMN HEADINGS ARE DEFINED AS FOLLOWS:

DAY: THE JULIAN CALENDAR DAY NUMBER
WATER: THE WATER STORAGE IN THE ROOT ZONE
PRECEF:THE EFFECTIVE PRECIPITATION (PRECIP MINUS INTERCEPTION AND RUNOFF)
INTRCP:THE AMOUNT OF PRECIPITATION INTERCEPTED BY THE FOLIAGE
TRANSP:TRANSPIRATION CALCULATED BY TANNER AND JURY METHOD
EVAPOT:EVAPOTRANSPIRATION(ETSOIL PLUS INTRCP FROM PREVIOUS DAY)
TOTET: CUMULATIVE EVAP FOR THE SEASON
TOTPCF:CUMULATIVE PRECEF FOR THE SEASON
TOTINT:CUMULATIVE INTRCP FOR THE SEASON
TOTRNF:CUMULATIVE RUNOFF FOR THE SEASON
TOTGRO:CUMULATIVE GROWTH FOR THE SEASON
GROWTH:PREDICTED FORAGE GROWTH FOR THE DAY

DAY	WATER	PRECEF	INTRCP	TRANSP	EVAPOT	TOTET	TOTPCF	TOTINT	TOTRNF	TOTGRO	GROWTH
145	202.9	0.0	0.0	0.1	2.1	2.1	0.0	0.0	0.0	0.01	0.00
146	199.6	0.0	0.0	0.2	3.3	5.4	0.0	0.0	0.0	0.02	0.00
147	197.0	0.0	0.3	0.2	2.7	8.0	0.0	0.3	0.0	0.02	0.00
148	194.2	0.0	0.0	0.2	3.1	10.8	0.0	0.3	0.0	0.03	0.01
149	192.6	0.0	0.0	0.2	1.6	12.4	0.0	0.3	0.0	0.03	0.00
150	189.3	0.0	0.0	0.4	3.3	15.7	0.0	0.3	0.0	0.04	0.01
151	185.6	0.0	0.0	0.5	3.7	19.4	0.0	0.3	0.0	0.05	0.01
152	181.5	0.0	0.0	0.8	4.1	23.5	0.0	0.3	0.0	0.07	0.02
153	177.2	0.0	0.0	1.1	4.4	27.9	0.0	0.3	0.0	0.10	0.03
154	172.9	0.0	0.0	1.4	4.3	32.2	0.0	0.3	0.0	0.14	0.04
155	168.5	0.0	0.0	1.8	4.3	36.5	0.0	0.3	0.0	0.18	0.05
156	166.9	0.0	0.0	0.8	1.6	38.1	0.0	0.3	0.0	0.20	0.02
157	163.4	0.0	0.0	1.9	3.6	41.7	0.0	0.3	0.0	0.25	0.05
158	159.1	0.0	0.0	2.6	4.2	45.9	0.0	0.3	0.0	0.32	0.07
159	155.8	0.0	0.0	2.3	3.4	49.3	0.0	0.3	0.0	0.38	0.06
160	153.5	0.8	0.7	2.3	3.1	52.3	0.9	1.0	0.0	0.44	0.06
161	152.6	0.0	0.3	0.8	1.7	53.3	0.9	1.3	0.0	0.46	0.02
162	150.4	0.0	0.0	1.7	2.4	55.5	0.9	1.3	0.0	0.51	0.04
163	149.1	2.2	1.0	2.9	3.5	59.0	3.1	2.3	0.0	0.58	0.08
164	147.9	0.4	0.5	1.4	2.6	60.6	3.4	2.8	0.0	0.62	0.04
165	145.9	0.5	0.6	2.2	3.0	63.0	4.0	3.4	0.0	0.68	0.06
166	142.6	0.0	0.0	3.1	4.0	66.4	4.0	3.4	0.0	0.76	0.08
167	138.9	0.0	0.0	3.3	3.6	70.0	4.0	3.4	0.0	0.84	0.09
168	141.8	5.5	1.5	2.6	2.7	72.7	9.5	4.9	0.0	0.91	0.07
169	140.6	0.0	0.0	1.1	2.7	73.9	9.5	4.9	0.0	0.94	0.03
170	137.1	0.0	0.0	3.4	3.5	77.4	9.5	4.9	0.0	1.03	0.09
171	133.5	0.2	0.4	3.7	3.8	81.2	9.7	5.3	0.0	1.12	0.10

DAY	WATER	PRECEF	INTRCP	TRANSP	EVAPOT	TOTET	TOTPCF	TOTINT	TOTRNF	TOTGRO	GROWTH
172	136.5	3.9	1.3	0.8	1.2	82.0	13.5	6.6	0.0	1.14	0.02
173	135.1	0.0	0.0	1.4	2.7	83.4	13.5	6.6	0.0	1.18	0.04
174	131.6	0.0	0.0	3.4	3.5	86.9	13.5	6.6	0.0	1.27	0.09
175	127.4	0.0	0.0	4.1	4.2	91.2	13.5	6.6	0.0	1.37	0.11
176	123.2	0.0	0.0	4.1	4.1	95.3	13.5	6.6	0.0	1.48	0.11
177	118.9	0.0	0.0	4.3	4.3	99.6	13.5	6.6	0.0	1.59	0.11
178	114.6	0.0	0.0	4.3	4.3	103.9	13.5	6.6	0.0	1.70	0.11
179	110.1	0.0	0.0	4.4	4.4	108.4	13.5	6.6	0.0	1.82	0.12
180	105.9	0.0	0.0	4.2	4.2	112.6	13.5	6.6	0.0	1.93	0.11
181	103.5	0.0	0.0	2.4	2.5	115.1	13.5	6.6	0.0	1.99	0.06
182	99.4	0.0	0.0	4.0	4.0	119.1	13.5	6.6	0.0	2.10	0.10
183	95.0	0.0	0.0	4.4	4.4	123.5	13.5	6.6	0.0	2.21	0.11
184	90.7	0.0	0.0	4.3	4.4	127.9	13.5	6.6	0.0	2.32	0.11
185	86.8	0.0	0.0	3.8	3.9	131.7	13.5	6.6	0.0	2.42	0.10
186	89.8	5.7	1.5	2.8	2.8	134.5	19.3	8.1	0.0	2.50	0.07
187	90.3	0.5	0.6	-0.0	1.4	134.5	19.8	8.7	0.0	2.50	0.0
188	88.8	0.0	0.0	1.5	2.1	136.0	19.8	8.7	0.0	2.54	0.04
189	85.4	0.0	0.0	3.4	3.4	139.3	19.8	8.7	0.0	2.62	0.09
190	83.7	0.1	0.3	1.8	1.8	141.2	19.9	9.0	0.0	2.67	0.05
191	87.9	4.9	1.4	0.8	1.1	141.9	24.8	10.5	0.0	2.69	0.02
192	85.0	0.0	0.0	2.9	4.3	144.8	24.8	10.5	0.0	2.77	0.08
193	82.3	0.0	0.0	2.7	2.7	147.5	24.8	10.5	0.0	2.84	0.07
194	78.9	0.0	0.0	3.4	3.4	150.9	24.8	10.5	0.0	2.92	0.09
195	74.4	0.0	0.0	4.5	4.5	155.4	24.8	10.5	0.0	3.04	0.12
196	70.5	0.0	0.0	3.9	3.9	159.3	24.8	10.5	0.0	3.14	0.10
197	67.4	-0.0	0.2	3.1	3.1	162.5	24.8	10.7	0.0	3.22	0.08
198	64.6	0.0	0.0	2.7	2.9	165.2	24.8	10.7	0.0	3.29	0.07
199	62.3	0.0	0.0	2.3	2.3	167.5	24.8	10.7	0.0	3.36	0.06
200	60.0	1.3	0.9	3.7	3.7	171.2	26.2	11.6	0.0	3.45	0.10
201	57.4	0.0	0.0	2.6	3.4	173.8	26.2	11.6	0.0	3.52	0.07
202	53.7	0.0	0.0	3.7	4.4	177.5	26.2	11.6	0.0	3.62	0.10
203	50.5	0.0	0.0	3.2	4.3	180.7	26.2	11.6	0.0	3.70	0.08
204	47.8	0.0	0.0	2.7	3.3	183.4	26.2	11.6	0.0	3.77	0.07
205	45.5	0.0	0.0	2.3	3.1	185.7	26.2	11.6	0.0	3.83	0.06
206	43.5	0.0	0.0	2.0	4.3	187.6	26.2	11.6	0.0	3.88	0.05
207	59.2	17.3	1.8	1.7	4.0	189.3	43.5	13.4	0.0	3.92	0.04
208	60.4	1.3	0.8	-0.0	1.6	189.3	44.7	14.2	0.0	3.92	0.0
209	58.1	0.0	0.0	2.3	3.2	191.6	44.7	14.2	0.0	3.98	0.06
210	56.7	1.5	0.9	2.9	2.9	194.5	46.2	15.1	0.0	4.06	0.07
211	53.9	-0.0	0.2	2.8	3.7	197.3	46.2	15.4	0.0	4.13	0.07
212	52.2	1.4	0.9	3.2	3.6	200.5	47.7	16.2	0.0	4.21	0.08
213	49.8	-0.0	0.2	2.4	3.2	202.9	47.7	16.5	0.0	4.27	0.06
214	47.2	0.0	0.0	2.6	3.7	205.4	47.7	16.5	0.0	4.34	0.07
215	45.0	0.0	0.0	2.2	4.0	207.7	47.7	16.5	0.0	4.40	0.06
216	50.9	7.8	1.7	1.9	3.6	209.5	55.5	18.1	0.0	4.45	0.05
217	49.0	0.0	0.0	1.9	3.6	211.5	55.5	18.1	0.0	4.50	0.05
218	47.1	0.0	0.0	1.9	1.9	213.3	55.5	18.1	0.0	4.55	0.05

DAY	WATER	PRECEF	INTRCP	TRANSP	EVAPOT	TOTET	TOTPCF	TOTINT	TOTRNF	TOTGRO	GROWTH
219	44.9	0.0	0.0	2.2	3.2	215.5	55.5	18.1	0.0	4.60	0.06
220	43.0	0.0	0.0	1.9	4.0	217.4	55.5	18.1	0.0	4.65	0.05
221	41.5	0.0	0.0	1.6	3.7	219.0	55.5	18.1	0.0	4.69	0.04
222	40.1	0.0	0.0	1.4	2.3	220.4	55.5	18.1	0.0	4.73	0.04
223	39.7	0.8	0.7	1.2	1.4	221.5	56.2	18.8	0.0	4.76	0.03
224	41.6	2.1	1.0	0.1	0.8	221.6	58.3	19.8	0.0	4.76	0.00
225	40.3	0.0	0.0	1.4	2.8	223.0	58.3	19.8	0.0	4.80	0.04
226	39.1	0.0	0.0	1.2	3.2	224.2	58.3	19.8	0.0	4.83	0.03
227	60.6	22.5	1.8	1.0	1.7	225.2	80.8	21.6	0.0	4.86	0.03
228	63.4	2.8	1.2	-0.0	1.0	225.2	83.6	22.7	0.0	4.86	0.0
229	63.2	0.9	0.7	1.1	2.2	226.3	84.5	23.5	0.0	4.88	0.03
230	65.6	2.9	1.2	0.5	1.3	226.8	87.4	24.6	0.0	4.90	0.01
231	65.6	-0.0	0.2	-0.0	0.9	226.8	87.4	24.9	0.0	4.90	0.0
232	63.3	0.0	0.0	2.3	2.6	229.2	87.4	24.9	0.0	4.96	0.06
233	61.1	0.0	0.0	2.1	2.1	231.3	87.4	24.9	0.0	5.01	0.06
234	59.5	1.3	0.8	2.9	2.9	234.2	88.7	25.7	0.0	5.09	0.07
235	69.8	10.6	1.8	0.4	1.2	234.6	99.3	27.5	0.0	5.10	0.01
236	70.4	0.7	0.6	-0.0	1.7	234.6	100.0	28.1	0.0	5.10	0.0
237	69.9	0.2	0.4	0.7	1.4	235.3	100.2	28.5	0.0	5.12	0.02
238	69.7	1.6	0.9	1.8	2.2	237.1	101.8	29.4	0.0	5.17	0.05
239	67.7	0.0	0.0	2.0	2.9	239.1	101.8	29.4	0.0	5.22	0.05
240	64.7	0.0	0.0	3.0	3.0	242.1	101.8	29.4	0.0	5.29	0.08
241	61.8	0.0	0.0	2.9	2.9	245.0	101.8	29.4	0.0	5.37	0.08
242	58.9	0.0	0.0	2.8	2.8	247.8	101.8	29.4	0.0	5.44	0.07
243	58.5	1.3	0.9	1.8	1.8	249.6	103.1	30.3	0.0	5.49	0.05

APPENDIX 4.

Measured and Modelled Net
Radiation Data for 1978 and 1979.

1978 NET RADIATION ESTIMATES

THE COLUMN HEADINGS BELOW ARE DEFINED AS FOLLOWS:

- DAY: THE JULIAN CALENDAR DAY NUMBER
- QSTAR: THE MEASURED VALUE OF NET RADIATION FLUX DENSITY
- EST1: THE ESTIMATE OF QSTAR AS EXPLAINED BELOW
- ERR1: QSTAR-EST1
- ERSUM: THE CUMULATIVE SUM OF ERR1 OVER ALL DAYS

ESTIMATES ARE:
1. IDSO-JACKSON USING 24HR MEAN TEMP
2. IDSO-JACKSON USING DAYTIME MEAN (FROM EB OR 3TMAX+TMIN/4)
3. REGRESSION FROM KDOWN(SP) CALCULATED FROM KDOWN(FSJ)
4. REGRESSION DIRECTLY FROM KDOWN(FSJ)

DAY	QSTAR	EST1	ERR1	ERSUM	EST2	ERR2	ERSUM	EST3	ERR3	ERSUM	EST4	ERR4	ERSUM
121	MISSED	9.94			9.87			11.22			10.40		
122	MISSED	12.21			11.97			13.53			12.34		
123	MISSED	12.91			12.47			14.05			12.78		
124	MISSED	13.14			12.54			14.09			12.82		
125	MISSED	13.05			12.59			14.13			12.85		
126	MISSED	10.17			9.93			11.16			10.35		
127	MISSED	13.18			13.04			14.56			13.21		
128	MISSED	11.28			11.32			12.63			11.59		
129	MISSED	8.84			8.59			9.62			9.05		
130	MISSED	6.97			6.47			7.29			7.09		
131	MISSED	10.20			9.93			11.05			10.25		
132	MISSED	13.44			13.33			14.73			13.35		
133	MISSED	9.05			8.83			9.81			9.21		
134	MISSED	6.99			6.93			7.74			7.46		
135	MISSED	1.64			1.47			1.83			2.48		
136	MISSED	12.85			12.77			14.01			12.75		
137	MISSED	9.54			9.53			10.50			9.79		
138	MISSED	13.19			13.13			14.36			13.04		
139	MISSED	10.57			10.64			11.65			10.76		
140	MISSED	5.16			5.18			5.79			5.82		
141	MISSED	4.00			3.94			4.45			4.69		
142	MISSED	4.19			3.87			4.37			4.63		
143	MISSED	8.39			7.98			8.74			8.31		
144	MISSED	12.54			12.26			13.29			12.14		
145	MISSED	8.29			8.27			9.03			8.55		
146	MISSED	12.93			13.00			14.03			12.77		
147	MISSED	10.56			10.58			11.45			10.59		
148	MISSED	13.22			13.13			14.13			12.85		
149	MISSED	6.96			6.79			7.42			7.19		
150	MISSED	13.82			13.77			14.76			13.38		

DAY	QSTAR	EST1	ERR1	ERSUM	EST2	ERR2	ERSUM	EST3	ERR3	ERSUM	EST4	ERR4	ERSUM
151	MISSED	14.88			14.96			15.99			14.42		
152	MISSED	15.36			15.49			16.53			14.87		
153	MISSED	15.64			15.75			16.78			15.08		
154	MISSED	15.01			15.09			16.06			14.47		
155	MISSED	15.21			15.30			16.26			14.64		
156	MISSED	5.84			5.87			6.38			6.32		
157	MISSED	14.53			14.56			15.44			13.95		
158	13.07	16.00	-2.93	-2.93	16.13	-3.06	-3.06	17.06	-3.99	-3.99	15.32	-2.25	-2.25
159	13.43	12.77	0.66	-2.28	12.91	0.52	-2.55	13.65	-0.22	-4.21	12.45	0.98	-1.27
160	10.20	12.75	-2.55	-4.82	12.80	-2.60	-5.15	13.47	-3.27	-7.48	12.29	-2.09	-3.36
161	MISSED	7.06			6.93			7.49			7.25		
162	MISSED	10.02			9.92			10.59			9.87		
163	MISSED	14.42			14.36			15.19			13.74		
164	MISSED	10.32			10.29			10.95			10.17		
165	MISSED	11.34			11.35			12.03			11.08		
166	MISSED	15.06			15.10			15.90			14.34		
167	MISSED	13.89			13.92			14.66			13.30		
168	MISSED	10.34			10.35			10.96			10.17		
169	MISSED	11.31			11.16			11.77			10.86		
170	MISSED	13.95			13.94			14.62			13.26		
171	MISSED	14.59			14.61			15.30			13.84		
172	MISSED	4.60			4.56			4.94			5.11		
173	MISSED	10.77			10.74			11.28			10.45		
174	11.30	14.03	-2.73	-7.55	14.01	-2.71	-7.86	14.62	-3.32	-10.81	13.26	-1.96	-5.32
175	MISSED	15.47			15.47			16.15			14.55		
176	14.70	15.44	-0.74	-8.29	15.45	-0.75	-8.60	16.10	-1.40	-12.21	14.51	0.19	-5.13
177	15.98	16.14	-0.16	-8.45	16.14	-0.16	-8.76	16.79	-0.81	-13.02	15.09	0.89	-4.25
178	15.42	16.35	-0.93	-9.38	16.34	-0.92	-9.68	16.98	-1.56	-14.59	15.25	0.17	-4.08
179	16.17	16.40	-0.23	-9.61	16.41	-0.24	-9.92	17.02	-0.85	-15.44	15.29	0.88	-3.20
180	13.60	15.14	-1.54	-11.15	15.13	-1.53	-11.45	15.70	-2.10	-17.54	14.17	-0.57	-3.76
181	10.15	8.62	1.53	-9.62	8.62	1.53	-9.92	9.04	1.11	-16.43	8.56	1.59	-2.18
182	15.25	16.12	-0.87	-10.48	16.05	-0.80	-10.72	16.61	-1.36	-17.78	14.93	0.32	-1.86
183	16.16	16.19	-0.03	-10.51	16.19	-0.03	-10.75	16.72	-0.56	-18.35	15.03	1.13	-0.74
184	15.83	15.58	0.25	-10.26	15.58	0.25	-10.49	16.07	-0.24	-18.58	14.48	1.35	0.61
185	16.03	13.81	2.22	-8.04	13.82	2.21	-8.29	14.26	1.77	-16.81	12.95	3.08	3.69
186	MISSED	9.65			9.65			10.02			9.39		
187	MISSED	5.30			5.24			5.55			5.62		
188	MISSED	7.97			7.92			8.25			7.90		
189	MISSED	13.69			13.61			13.99			12.73		
190	MISSED	6.78			6.77			7.07			6.90		
191	MISSED	3.78			3.77			4.04			4.35		
192	MISSED	15.53			15.53			15.88			14.32		
193	MISSED	9.29			9.29			9.58			9.01		
194	MISSED	11.95			11.95			12.24			11.26		
195	MISSED	16.47			16.48			16.78			15.08		
196	MISSED	13.76			13.76			14.03			12.76		
197	MISSED	11.44			11.45			11.70			10.80		

DAY	QSTAR	EST1	ERR1	ERSUM	EST2	ERR2	ERSUM	EST3	ERR3	ERSUM	EST4	ERR4	ERSUM
198	MISSED	11.25			11.24			11.48			10.62		
199	MISSED	8.93			8.90			9.13			8.63		
200	13.50	14.18	-0.68	-8.72	14.18	-0.68	-8.97	14.40	-0.90	-17.71	13.07	0.43	4.11
201	10.08	12.29	-2.21	-10.93	12.28	-2.20	-11.17	12.49	-2.41	-20.12	11.47	-1.39	2.72
202	13.86	15.25	-1.39	-12.32	15.23	-1.37	-12.54	15.39	-1.53	-21.65	13.91	-0.05	2.67
203	12.07	14.81	-2.74	-15.06	14.76	-2.69	-15.23	14.92	-2.85	-24.50	13.51	-1.44	1.23
204	10.05	11.37	-1.32	-16.37	11.35	-1.30	-16.53	11.51	-1.46	-25.96	10.65	-0.60	0.64
205	9.74	10.67	-0.93	-17.30	10.64	-0.90	-17.43	10.80	-1.06	-27.02	10.05	-0.31	0.33
206	13.51	15.04	-1.53	-18.83	15.02	-1.51	-18.94	15.14	-1.63	-28.66	13.70	-0.19	0.14
207	12.16	13.80	-1.64	-20.47	13.77	-1.61	-20.55	13.88	-1.72	-30.38	12.64	-0.48	-0.34
208	5.75	5.22	0.53	-19.94	5.22	0.53	-20.02	5.39	0.36	-30.02	5.49	0.26	-0.08
209	11.68	11.74	-0.06	-19.99	11.74	-0.06	-20.07	11.86	-0.18	-30.20	10.94	0.74	0.66
210	13.04	10.37	2.67	-17.32	10.38	2.66	-17.42	10.50	2.54	-27.66	9.79	3.25	3.92
211	12.85	13.89	-1.04	-18.36	13.89	-1.04	-18.46	13.97	-1.12	-28.78	12.72	0.13	4.05
212	11.55	13.47	-1.92	-20.29	13.48	-1.93	-20.39	13.55	-2.00	-30.78	12.36	-0.81	3.23
213	12.05	13.32	-1.27	-21.56	13.21	-1.16	-21.55	13.28	-1.23	-32.02	12.14	-0.09	3.15
214	MISSED	15.39			15.27			15.32			13.85		
215	MISSED	14.72			14.73			14.77			13.39		
216	MISSED	12.39			12.33			12.39			11.38		
217	MISSED	13.80			13.78			13.82			12.59		
218	MISSED	6.81			6.80			6.90			6.76		
219	MISSED	11.90			11.90			11.94			11.00		
220	MISSED	13.95			13.92			13.93			12.68		
221	MISSED	12.85			12.81			12.83			11.76		
222	6.15	8.04	-1.89	-23.46	8.05	-1.90	-23.45	8.12	-1.97	-33.99	7.79	-1.64	1.51
223	5.56	5.21	0.35	-23.10	5.13	0.43	-23.02	5.24	0.32	-33.66	5.36	0.20	1.72
224	1.87	2.79	-0.92	-24.02	2.71	-0.84	-23.86	2.83	-0.96	-34.63	3.33	-1.46	0.26
225	11.41	11.51	-0.10	-24.13	11.42	-0.01	-23.86	11.43	-0.02	-34.65	10.57	0.84	1.09
226	8.30	12.02	-3.72	-27.85	12.01	-3.71	-27.57	12.03	-3.73	-38.37	11.08	-2.78	-1.69
227	5.13	6.75	-1.62	-29.47	6.68	-1.55	-29.12	6.75	-1.62	-39.99	6.63	-1.50	-3.19
228	MISSED	4.06			4.35			4.04			4.35		
229	MISSED	8.55			9.27			8.57			8.17		
230	MISSED	4.95			5.31			4.92			5.09		
231	MISSED	3.79			3.96			3.67			4.04		
232	MISSED	11.32			11.97			11.06			10.26		
233	MISSED	8.50			9.16			8.47			8.08		
234	MISSED	11.96			12.81			11.84			10.92		
235	MISSED	4.40			4.81			4.45			4.70		
236	MISSED	6.40			6.98			6.45			6.38		
237	MISSED	4.92			5.39			4.98			5.14		
238	MISSED	8.72			9.42			8.70			8.28		
239	MISSED	11.16			12.12			11.20			10.38		
240	MISSED	11.53			12.49			11.55			10.67		
241	MISSED	11.48			12.45			11.51			10.64		
242	MISSED	10.58			11.51			10.65			9.92		
243	MISSED	6.67			7.27			6.73			6.61		

VARIANCE OF ESTIMATE1=2.710
VARIANCE OF ESTIMATE2=2.690
VARIANCE OF ESTIMATE3=3.392
VARIANCE OF ESTIMATE4=1.873

1 9 7 9 N E T R A D I A T I O N E S T I M A T E S

THE COLUMN HEADINGS BELOW ARE DEFINED AS FOLLOWS:

DAY: THE JULIAN CALENDAR DAY NUMBER
QSTAR: THE MEASURED VALUE OF NET RADIATION FLUX DENSITY
EST1: THE ESTIMATE OF QSTAR AS EXPLAINED BELOW
ERR1: QSTAR-EST1
ERSUM: THE CUMULATIVE SUM OF ERR1 OVER ALL DAYS

ESTIMATES ARE:
1.IDSO-JACKSON USING 24HR MEAN TEMP
2.IDSO-JACKSON USING DAYTIME MEAN (FROM EB OR 3TMAX+TMIN/4)
3.REGRESSION FROM KDOWN(SP) CALCULATED FROM KDOWN(FSJ)
4.REGRESSION DIRECTLY FROM KDOWN(FSJ)

DAY	QSTAR	EST1	ERR1	ERSUM	EST2	ERR2	ERSUM	EST3	ERR3	ERSUM	EST4	ERR4	ERSUM
139	6.84	8.30	-1.46	-1.46	8.29	-1.45	-1.45	9.05	-2.21	-2.21	9.09	-2.25	-2.25
140	3.13	6.88	-3.75	-5.21	6.84	-3.71	-5.16	7.48	-4.35	-6.57	7.60	-4.47	-6.72
141	6.17	10.53	-4.36	-9.58	10.53	-4.36	-9.52	11.41	-5.24	-11.80	11.32	-5.15	-11.87
142	11.88	13.06	-1.18	-10.76	13.05	-1.17	-10.70	13.81	-1.93	-13.73	13.60	-1.72	-13.59
143	7.62	7.28	0.34	-10.41	7.31	0.31	-10.38	7.92	-0.30	-14.03	8.02	-0.40	-13.98
144	11.45	11.15	0.30	-10.12	11.14	0.31	-10.07	11.98	-0.53	-14.56	11.86	-0.41	-14.39
145	11.89	10.94	0.95	-9.17	10.97	0.92	-9.15	11.76	0.13	-14.43	11.65	0.24	-14.15
146	6.61	5.35	1.26	-7.91	5.36	1.25	-7.89	5.90	0.71	-13.72	6.10	0.51	-13.65
147	2.71	2.63	0.08	-7.83	2.61	0.10	-7.79	2.93	-0.22	-13.94	3.29	-0.58	-14.23
148	10.81	MISSING SOLAR FSJ.											
149	6.34	8.71	-2.37	-10.19	8.73	-2.39	-10.18	9.32	-2.98	-16.92	9.34	-3.00	-17.23
150	12.97	13.97	-1.00	-11.20	14.00	-1.03	-11.21	14.85	-1.88	-18.80	14.58	-1.61	-18.84
151	12.70	13.80	-1.10	-12.30	13.76	-1.06	-12.27	14.59	-1.89	-20.69	14.33	-1.63	-20.47
152	10.17	10.90	-0.73	-13.03	10.93	-0.76	-13.03	11.60	-1.43	-22.12	11.50	-1.33	-21.81
153	10.06	12.57	-2.51	-15.54	12.62	-2.56	-15.60	13.34	-3.28	-25.39	13.15	-3.09	-24.90
154	13.68	13.34	0.34	-15.20	13.39	0.29	-15.30	14.11	-0.43	-25.82	13.88	-0.20	-25.10
155	10.09	9.26	0.83	-14.36	9.27	0.82	-14.48	9.87	0.22	-25.61	9.87	0.22	-24.87
156	6.81	6.67	0.14	-14.22	6.66	0.15	-14.33	7.17	-0.36	-25.97	7.31	-0.50	-25.37
157	10.25	9.51	0.74	-13.48	9.50	0.75	-13.58	10.09	0.16	-25.81	10.07	0.18	-25.20
158	9.83	11.00	-1.17	-14.65	11.00	-1.17	-14.75	11.64	-1.81	-27.62	11.54	-1.71	-26.91
159	14.77	14.53	0.24	-14.41	14.51	0.26	-14.49	15.23	-0.46	-28.09	14.94	-0.17	-27.08
160	7.73	7.34	0.39	-14.02	7.33	0.40	-14.10	7.83	-0.10	-28.19	7.93	-0.20	-27.28
161	9.90	8.52	1.38	-12.64	8.50	1.40	-12.69	9.01	0.89	-27.30	9.05	0.85	-26.43
162	14.35	MISSING SOLAR FSJ.											
163	14.70	MISSING SOLAR FSJ.											
164	5.82	MISSING SOLAR FSJ.											
165	6.00	MISSING SOLAR FSJ.											
166	10.92	MISSING SOLAR FSJ.											
167	7.34	MISSING SOLAR FSJ.											
168	13.04	MISSING SOLAR FSJ.											

DAY	QSTAR	EST1	ERR1	ERSUM	EST2	ERR2	ERSUM	EST3	ERR3	ERSUM	EST4	ERR4	ERSUM
169	10.00	MISSING SOLAR FSJ.											
170	11.18	MISSING SOLAR FSJ.											
171	9.46	MISSING SOLAR FSJ.											
172	14.08	MISSING SOLAR FSJ.											
173	14.36	MISSING SOLAR FSJ.											
174	16.16	MISSING SOLAR FSJ.											
175	9.41	MISSING SOLAR FSJ.											
176	13.21	MISSING SOLAR FSJ.											
177	16.32	MISSING SOLAR FSJ.											
178	12.94	MISSING SOLAR FSJ.											
179	14.34	MISSING SOLAR FSJ.											
180	14.83	MISSING SOLAR FSJ.											
181	14.77	MISSING SOLAR FSJ.											
182	2.10	MISSING SOLAR FSJ.											
183	3.88	MISSING SOLAR FSJ.											
184	15.21	MISSING SOLAR FSJ.											
185	13.56	MISSING SOLAR FSJ.											
186	15.82	MISSING SOLAR FSJ.											
187	16.47	15.46	1.01	-11.63	15.62	0.85	-11.84	15.54	0.93	-26.37	15.23	1.24	-25.20
188	5.72	9.61	-3.89	-15.51	9.63	-3.91	-15.75	9.82	-4.10	-30.47	9.82	-4.10	-29.29
189	15.07	12.27	2.80	-12.71	12.33	2.74	-13.01	12.41	2.66	-27.81	12.27	2.80	-26.49
190	16.44	15.30	1.14	-11.57	15.37	1.07	-11.94	15.43	1.01	-26.80	15.13	1.31	-25.19
191	5.51	MISSING SOLAR FSJ.											
192	6.16	MISSING SOLAR FSJ.											
193	8.36	9.35	-0.99	-12.56	9.37	-1.01	-12.94	9.51	-1.15	-27.95	9.52	-1.16	-26.35
194	2.58	2.69	-0.11	-12.68	2.70	-0.12	-13.06	2.93	-0.35	-28.30	3.29	-0.71	-27.05
195	7.44	8.07	-0.63	-13.31	8.17	-0.73	-13.78	8.20	-0.76	-29.06	8.28	-0.84	-27.89
196	14.10	14.21	-0.11	-13.43	14.41	-0.31	-14.09	14.10	0.00	-29.06	13.87	0.23	-27.66
197	15.58	11.94	3.64	-9.79	12.08	3.50	-10.59	11.87	3.71	-25.34	11.76	3.82	-23.84
198	13.42	13.01	0.41	-9.37	13.21	0.21	-10.38	12.78	0.64	-24.70	12.62	0.80	-23.04
199	14.85	14.83	0.02	-9.35	14.97	-0.12	-10.50	14.33	0.52	-24.18	14.09	0.76	-22.27
200	13.95	14.87	-0.92	-10.27	15.05	-1.10	-11.60	14.56	-0.61	-24.79	14.31	-0.36	-22.63
201	15.23	14.15	1.08	-9.19	14.24	0.99	-10.61	13.91	1.32	-23.47	13.69	1.54	-21.09
202	15.51	13.11	2.40	-6.78	13.22	2.29	-8.32	13.08	2.43	-21.03	12.90	2.61	-18.48
203	10.80	11.57	-0.77	-7.55	11.58	-0.78	-9.10	11.56	-0.76	-21.79	11.46	-0.66	-19.14
204	11.98	7.32	4.66	-2.89	7.33	4.65	-4.45	7.41	4.57	-17.22	7.53	4.45	-14.70
205	10.31	12.81	-2.50	-5.39	12.81	-2.50	-6.95	12.73	-2.42	-19.64	12.57	-2.26	-16.96
206	15.02	14.54	0.48	-4.91	14.42	0.60	-6.35	14.22	0.80	-18.84	13.99	1.03	-15.92
207	14.04	13.72	0.32	-4.59	13.86	0.18	-6.17	13.56	0.48	-18.36	13.36	0.68	-15.24
208	13.05	13.36	-0.31	-4.90	13.49	-0.44	-6.61	13.10	-0.05	-18.41	12.92	0.13	-15.12
209	6.00	MISSING SOLAR FSJ.											
210	11.24	MISSING SOLAR FSJ.											
211	13.20	MISSING SOLAR FSJ.											
212	12.83	13.01	-0.18	-5.07	13.07	-0.24	-6.85	12.75	0.08	-18.33	12.59	0.24	-14.88
213	10.97	9.75	1.22	-3.85	9.79	1.18	-5.67	9.66	1.31	-17.03	9.67	1.30	-13.58
214	9.00	9.47	-0.47	-4.32	9.49	-0.49	-6.16	9.41	-0.41	-17.44	9.42	-0.42	-14.00
215	5.67	6.08	-0.41	-4.73	6.08	-0.41	-6.57	6.10	-0.43	-17.87	6.29	-0.62	-14.63

DAY	QSTAR	EST1	ERR1	ERSUM	EST2	ERR2	ERSUM	EST3	ERR3	ERSUM	EST4	ERR4	ERSUM
216	7.74	7.16	0.58	-4.15	7.16	0.58	-5.98	7.15	0.59	-17.27	7.29	0.45	-14.17
217	6.32	5.70	0.62	-3.53	5.70	0.62	-5.37	5.74	0.58	-16.69	5.95	0.37	-13.80
218	5.50	5.27	0.23	-3.31	5.27	0.23	-5.14	5.31	0.19	-16.51	5.55	-0.05	-13.85
219	8.01	10.58	-2.57	-5.88	10.60	-2.59	-7.73	10.43	-2.42	-18.92	10.39	-2.38	-16.23
220	13.21	MISSING SOLAR FSJ.											
221	13.77	MISSING SOLAR FSJ.											
222	11.80	10.62	1.18	-4.70	10.75	1.05	-6.68	10.41	1.39	-17.53	10.37	1.43	-14.80
223	13.10	11.77	1.33	-3.37	11.85	1.25	-5.43	11.49	1.61	-15.92	11.40	1.70	-13.10
224	12.41	11.97	0.44	-2.94	12.10	0.31	-5.12	11.72	0.69	-15.23	11.61	0.80	-12.30
225	12.97	11.93	1.04	-1.89	12.00	0.97	-4.14	11.68	1.29	-13.93	11.58	1.39	-10.91
226	12.16	11.93	0.23	-1.66	11.97	0.19	-3.96	11.63	0.53	-13.40	11.53	0.63	-10.28
227	11.79	11.25	0.54	-1.12	11.38	0.41	-3.55	10.92	0.87	-12.53	10.86	0.93	-9.34
228	11.70	11.25	0.45	-0.67	11.35	0.35	-3.21	10.87	0.83	-11.70	10.81	0.89	-8.46
229	12.08	10.97	1.11	0.44	11.13	0.95	-2.25	10.62	1.46	-10.24	10.57	1.51	-6.95
230	1.74	1.85	-0.11	0.33	1.85	-0.11	-2.36	1.96	-0.22	-10.47	2.37	-0.63	-7.59
231	10.50	9.63	0.87	1.20	9.66	0.84	-1.53	9.45	1.05	-9.41	9.46	1.04	-6.55
232	10.09	10.73	-0.64	0.56	10.78	-0.69	-2.22	10.44	-0.35	-9.76	10.40	-0.31	-6.86
233	12.00	11.28	0.72	1.28	11.41	0.59	-1.63	10.96	1.04	-8.72	10.89	1.11	-5.76
234	11.50	9.83	1.67	2.95	9.90	1.60	-0.04	9.57	1.93	-6.79	9.58	1.92	-3.83
235	2.75	2.17	0.58	3.53	2.17	0.58	0.54	2.26	0.49	-6.30	2.66	0.09	-3.74

VARIANCE OF ESTIMATE1=2.438
VARIANCE OF ESTIMATE2=2.387
VARIANCE OF ESTIMATE3=3.021
VARIANCE OF ESTIMATE4=3.036

APPENDIX 5.

Forage Production at Sunset Prairie
in 1977, 1978 and 1979.

Forage production at Sunset Prairie in 1977, 1978 and 1979.

A. Accumulated Hay Growth at Site 1 (tonnes/hectare)

1977		1978		1979	
Date	Growth	Date	Growth	Date	Growth
		May 31	1.32		
June 7	2.74	June 7	1.79		
14	3.24			June 18	0.74
21	5.26	23	3.43		
28	5.29				
July 5	----	July 4	4.18	July 5	1.99
12	5.82				
19	7.62	20	4.69	16	3.03
26	----				
Aug. 2	7.52	Aug. 1	5.59	30	4.07
8	8.10	11	4.82	Aug. 13	5.20
		16	4.96		

B. Cut Growth at Sites 1 to 7 in 1979. (tonnes/hectare)

Site	1 Fert.	2	3	4	4 Fert.	5	6	6 Fert.	7
June 18	0.74	0.27	0.41	0.84	1.42	0.58	0.40	1.02	1.17
July 16	0.84	0.47	0.50	0.49	1.37	0.71	0.87	1.63	1.31
Total:	1.58	0.74	0.91	1.33	2.79	1.29	1.27	2.65	2.48
Aug. 13	1.11	0.68	0.68	0.47	0.82	0.75	----	----	1.69
Total:	2.69	1.42	1.59	1.80	3.61	2.04	----	----	3.17
Aug. 24	0.65	0.45	0.28	0.40	0.84	0.81	----	----	----
Total:	3.34	1.87	1.87	2.20	4.45	2.85	----	----	----