Continuation of lysimeter operations and consumptive use quantification in high-altitude, irrigated meadows in the Yampa /White Basin

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Background: This report details efforts conducted by the Colorado Climate Center (CCC) and Colorado Division of Water Resources (DWR) to derive crop coefficients for grass hay in the Yampa River Valley. Back in 2010 the CCC and Colorado DWR began a collaboration with the support of the Yampa River Basin Round Table to 1. Improve historical lysimeter operations in the Yampa River Basin with a more representative site and better lysimeter equipment, and 2. Calculate new crop coefficients for grass using the new lysimeter plot, corroborating data from a Colorado Agricultural Meteorological (CoAgMET) Network weather station, and more sophisticated techniques for estimating reference evapotranspiration (ET_r).

Collection of data was extended in 2015 as drought conditions early in the project delayed the buildup of sufficient vegetation at Carpenter Ranch for the new site to be considered a representative location. The new statement of work was comprised of three major tasks detailed below:

Task 1 – Continue Data Collection from Lysimeters and CoAgMET Weather Station

Task 2 – Development of Crop Coefficients

Task 3 – Calculate Crop ET_r

Results of these efforts have the potential to improve on previous methods of historical consumptive use computations in the Yampa River Basin.

Executive Summary: The CCC and DWR have completed a crop coefficient derivation study for grass in the Yampa River Basin. This was made possible via funding from the Yampa Roundtable. Crop coefficients derived here offer a few key advantages over the crop coefficients used in previous historic consumptive use analyses. These are as follows:

1. Lysimeter Management: Lysimeters in this study were monitored weekly by the DWR. The measurement site was directly next to an irrigated grass field using two types of grass representative of local conditions, making the data more practically usable for computing crop coefficients. Previous consumptive use studies (e.g. Alvarado and Wilson 2009) have made use of high altitude crop coefficients derived in other parts of the state. Previous lysimeter operations in the Yampa River Basin were not well-suited for crop coefficient derivation as the former site was not representative of irrigated field conditions, and was only monitored once/month.
2. Data Collection: The lysimeter plots used were collocated with a Colorado Agricultural Meteorological (CoAgMET) Network station. This station was monitored and maintained by CCC staff. These stations monitor temperature, wind speed, solar intensity, and surface humidity, so any temperature-based estimates of PET can be checked against American Society of Civil Engineers (ASCE) Standard computations of PET using the Penman-Monteith Method.
3. PET Computation Methods: The temperature-based PET formula used in this study was the Hargreaves method. Previous consumptive use models have used the Blaney-Criddle method.

The Hargreaves method is an improvement as it uses both high and low daily temperature data. The Blaney-Criddle method uses average temperatures only to compute PET, but the difference between high and low daily temperatures is a proxy for how dry the air is. Dry vs moist air is one of the controls on PET.

Results from this study indicate that crop coefficients are fairly steady throughout the season for some native grasses (~0.75 using the Hargreaves method). Orchard grasses, on the other hand, see crop coefficients vary considerably as a function of season 0.9-0.95 early in the season, and 0.65-0.7 late in the season. Full crop coefficient tables as a function of season have been provided (tables 2 and 3). In addition, both a seasonal solar intensity adjustment (table 1), and an elevation-driven crop coefficient adjustment (table 4) have been provided. These are necessary for ensuring grass reference ET (ET_r) can be computed in the basin anywhere temperature is monitored.

The crop coefficients computed did vary considerably from week-to-week (+/- 0.15). While more precision would be desirable, these results are not unusual for this kind of study. Similar uncertainties were reported in Alvarado and Wilson 2009. Potential sources of uncertainty include, but are not limited to, direct surface evaporation/infiltration after a precipitation event, slightly inconsistent lysimeter measurement intervals, and differences in management of the adjacent hay field from year-to-year.

The results captured here can be used to improve on historical consumptive use analyses. These analyses can be used to A: estimate the amount of water needed to be applied to a field, or B: determine the worth of a water right given a more accurate measure of how much water is needed in the basin to sustain grass hay.

The remainder of this report restates each of the three agreed upon tasks, and details the work completed:

Task 1 – Continue Data Collection from Lysimeters and CoAgMET Weather Station:

Lysimeter Operations: Lysimeter operations in the Yampa River Basin were moved to Carpenter Ranch near Hayden, CO, which was determined to be a more representative location for capturing basin-scale conditions. Carpenter Ranch is an irrigated hay field whereas the previous site was non-irrigated. The old lysimeters were replaced with newer, more accurate weighing lysimeters. Lysimeters were weighed and watered roughly once/week. While the actual interval varied from 4-12 days during the growing season, this was a large improvement in operations over the previously used once/month interval.

Site Vegetation: There were four weighing lysimeters installed at Carpenter Ranch. The lysimeters 1-4 were named after the DWR staff who oversaw their maintenance: 1. Brian, 2. Erin, 3. Dana, and 4. Lynne. Sites 1 and 3 were filled with native grass. Sites 2 and 4 were filled with orchard grass. The soils in the lysimeter cores were constructed soil profiles consisting of local topsoil, over a base layer mixture of sand, peat moss, and gravel.

Lysimeter dimensions: 1.5 ft18-inch diameter by 1.6 feet depth. The soil in the lysimeter cylinder was estimated to have a height of 1.5 feet.

Lysimeter soil volume, V (ft3) = π D2/4 * H = 2.65

Lysimeter surface area, A (ft2) = π D2/4 = 1.77

Weekly Management: Typical weekly operations were as follows:

1. weight lysimeter upon arrival
2. add measured amount of irrigation water (if needed)
3. take photos
4. return later in day to re-weigh the lysimeter

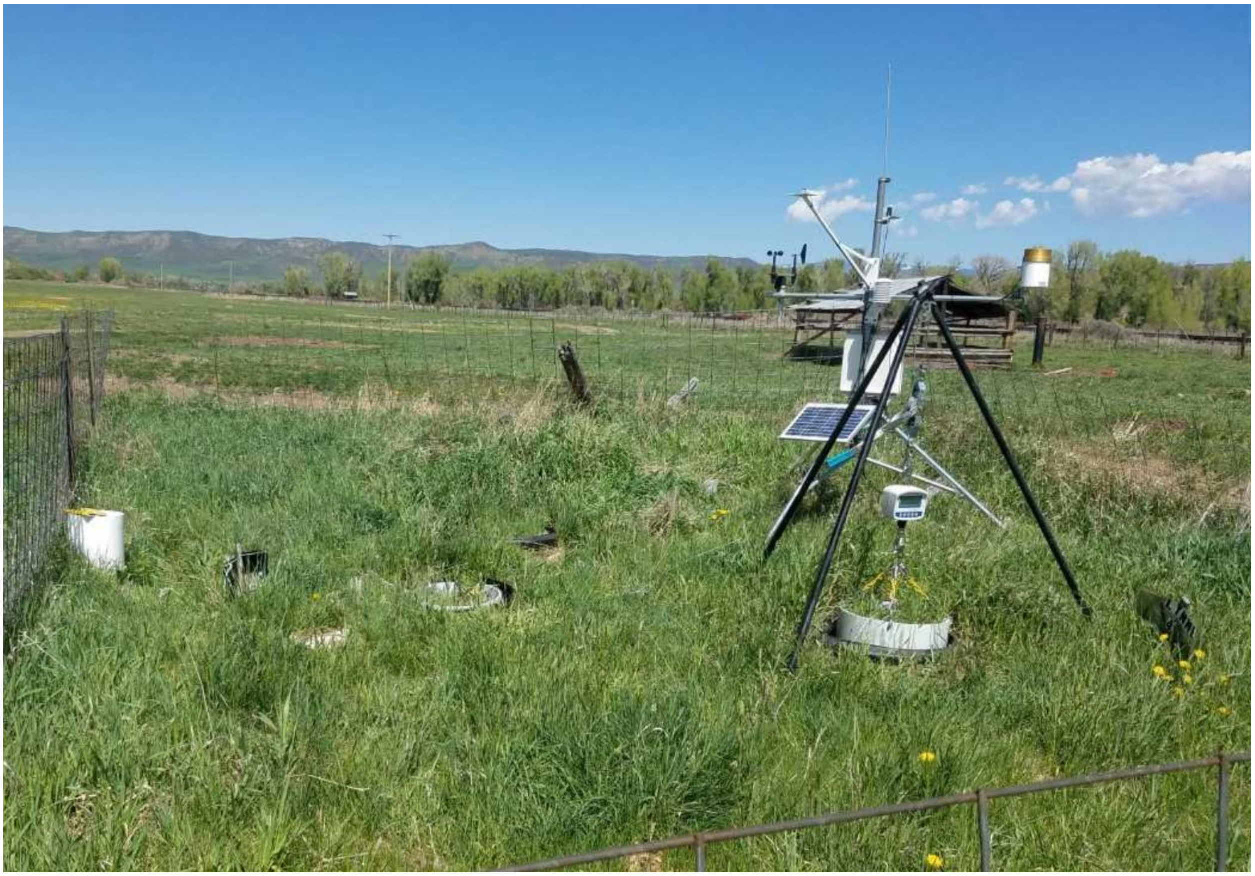

Photo 1: Experiment plot in Hayden, CO. (Credit: Brian Romig DWR)

CoAgMET Weather Station Maintenance: As a part of the original 2010 grant, a CoAgMET weather station was installed at Carpenter Ranch next to the new lysimeters. These weather stations are instrumented to measure temperature, solar radiation, wind speed, and surface humidity, allowing for fully-physical computations of American Society of Civil Engineers (ASCE) Potential Evapotranspiration (PET).

Between 2016 and 2020, annual visits were made to the CoAgMET weather station for preventative maintenance. Each year a check of all instruments was performed to ensure proper function and accurate data collection. With each annual visit, anemometer bearings were replaced to keep the sensor spinning with as little friction as possible. Every other year, the temperature and relative humidity sensor was replaced with a factory calibrated sensor. The bearings for the wind vane were also replaced every other year for accurate wind direction measurement. If during an annual visit a sensor was not recording data properly, it would be replaced regardless of where it was in the maintenance schedule.

In the even a sensor failed, or the station failed to report, a special visit was made to address the issue. In 2017 a nearby lightning strike damaged the solar radiation sensor and one of the soil temperature sensors. A special visit was made a couple of weeks after the sensors failed to replace these. The station also had some brief downtimes in the winter due to a drained battery. Snow was deep enough to cover the solar panel and causing the battery to be completely drained and lose power. Once the snow melted enough, the station came back online. During the site visit, the battery was checked and replaced and the solar panel was raised up and re-angled to avoid the snow.

The station also had some intermittent communication failures that were quickly fixed by a manual reset of the modem. In early 2017 the datalogger program was updated to power cycle the modem daily. This program update also added 5-minute data collection to allow for real-time tracking of weather.

In 2020 the modem was replaced to avoid communication losses when Verizon upgraded their cell network.

Task 2 – Development of Crop Coefficients: Evapotranspiration was measured over two grass types using four lysimeters. Using these measurements, and temperature data from the Hayden CoAgMET station, crop coefficient estimates were developed for two types of grass: the locally-occurring vegetation, which was determined to be brome and timothy grass, and orchard grass. Orchard grass was chosen as a representative species for grass hay product in the basin.

Lysimeter ET Calculation: To determine weekly transpiration (inches), the weekly weight loss was converted to a volume loss, and then divided by the surface area of the lysimeter plot exposed to the sky (equation 1).

$$Water\ Lost\ (inches) = \frac{[FC\ Mass\ (previous) - Dry\ Mass\ (current)]}{[density\ of\ water] * [lysimter\ surface\ area]} + Precipitation\ (inches)$$

Equation 1: Procedure for calculating water loss to transpiration from lysimeter plots. FC = "field capacity."

It was assumed that all weight lost was water weight lost through the top of the plot via transpiration. Any precipitation measured by the CoAgMET weather station was added to the mass loss measurement. Here's a simple example to explain why: if a mass loss equivalent to one inch of water is measured, but an inch of water was gained through precipitation, then the true loss was two inches. All precipitation is assumed to infiltrate the soil surface without evaporating directly, and not to infiltrate beyond the lysimeter. This is a source of uncertainty. It is likely some precipitation in larger storms infiltrated through holes in the bottom of the lysimeters and some precipitation was lost directly to evaporation before ever penetrating the soil surface. Water losses to transpiration can be overestimated by lysimeters using this set of assumptions, but not underestimated, which, if anything, would lead to a high bias in crop coefficients computed below.

Weather Station ET_r Calculation: Transpiration measured from each lysimeter was compared to PET from the Hayden CoAgMET station, which was computed using the Hargreaves method. Hargreaves PET was computed using equation 2 (From Hargreaves et al. 1985). Each lysimeter measurement from 2016-2019 could then be used to estimate crop coefficients for grass hay using equation 3. Note in equation 2 that Q_{day} is effectively a sunlight intensity adjustment, and is a function of day of the year. These adjustments are included in table 1.

$$PET_{Hargreaves} = 0.0022 * Q_{day} * (T_{max} + 17.8) * \sqrt{(T_{max} - T_{min})}$$

Equation 2: Computation of Hargreaves Potential Evapotranspiration. T_{max} is the day's high temperature (Celsius), T_{min} is the day's low temperature (Celsius), Q_{day} is a sunlight intensity adjustment based on the day of the year (Table 1), and 0.0022 is a derived constant used to convert units (Hargreaves 1985).

In figure 1 we plotted the computed seasonal ET from the weather station (solid lines) and the lysimeter plots (dotted lines) for years 2016-2019. One can see from this figure that transpiration computed from the lysimeter and PET from the weather station generally track with one another. Water use rates go up during the peak of each growing season, and are lower during the shoulder seasons. Furthermore, the lysimeter and weather station data show similar interannual variability. 2016 and 2018 were warmer years with more transpiration/PET, and 2017/2019 were lower water loss years by comparison. While the length of the season monitored is not the same for each year, this is an important finding as it shows the lysimeter measurements and weather station measurements agree on which years were high and low.

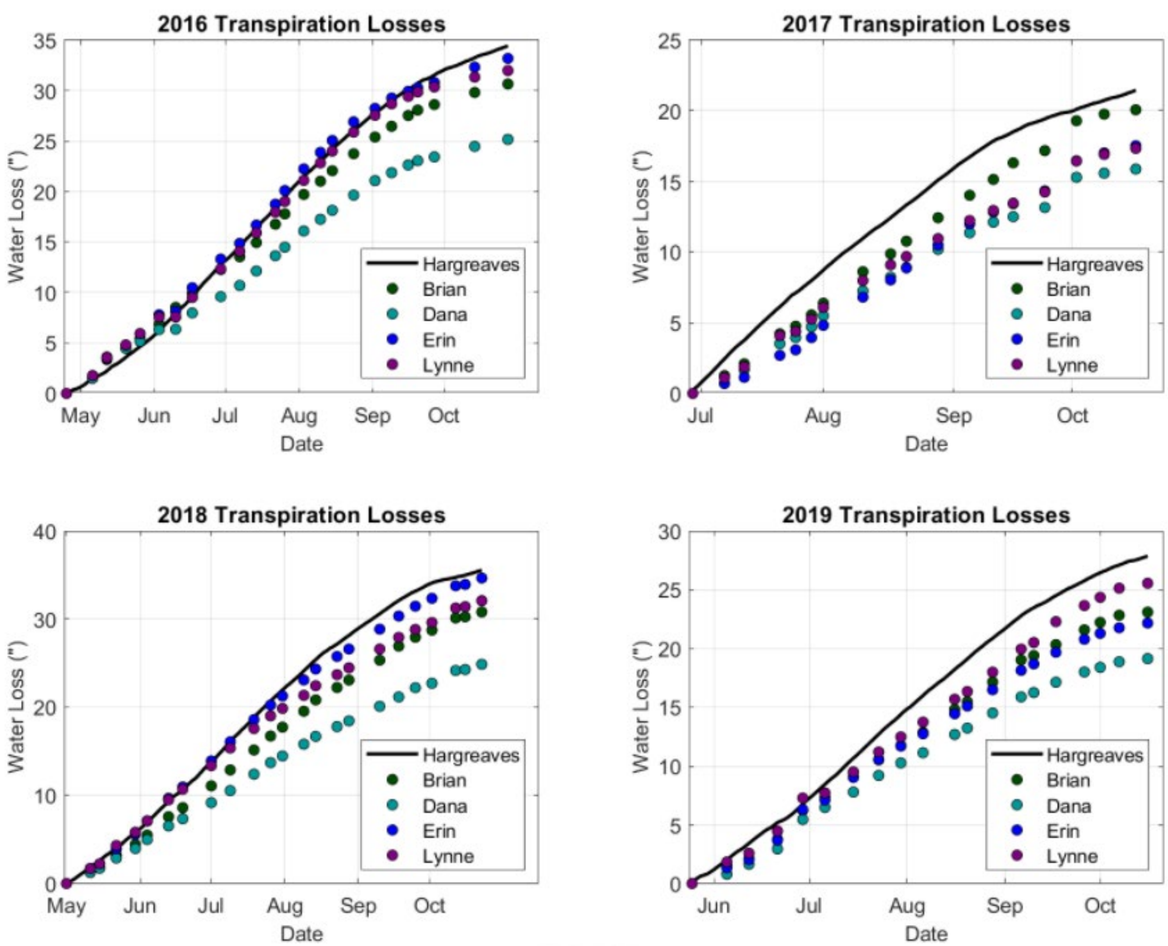

Figure 1: Weather station seasonal PET accumulation using Hargreaves method (solid black line) and water loss measured by lysimeters (dotted lines).

Crop Coefficient Calculation: The lysimeters represent two different grass types: orchard grass and the local vegetation at Carpenter Ranch. Crop coefficients for these two grass types were compared to weather station Hargreaves ET estimates as a function of season (figure 2). Equation 3 explains how to calculate a crop coefficient given the PET.

$$K_c = \frac{Water\ Lost}{PET_{Hargreaves}}$$

Equation 3: Crop coefficient estimate. Water Lost is computed as in equation 1. $PET_{Hargreaves}$ is computed as in equation 2.

A first and second-order polynomial fit was applied to the data for each grass type. These lines of best fit relate lysimeter measurements to weather station PET measurements as a function of season to determine a reasonable average crop coefficient curve. Several obvious outliers in the data (e.g. the 2017 lightning strike) were removed. For the orchard grass, a second-order (curved) polynomial fit explained the variance between lysimeter and weather station readings better than a first-order fit. Crop coefficients are 0.9-0.95 in the early and mid-season, but are lower later in the growing season (~0.;7). A first-order fit was selected for the local vegetation as there was relatively little seasonality the crop coefficients computed. The polynomial fits give us our final crop coefficient recommendations (Tables 2,3).

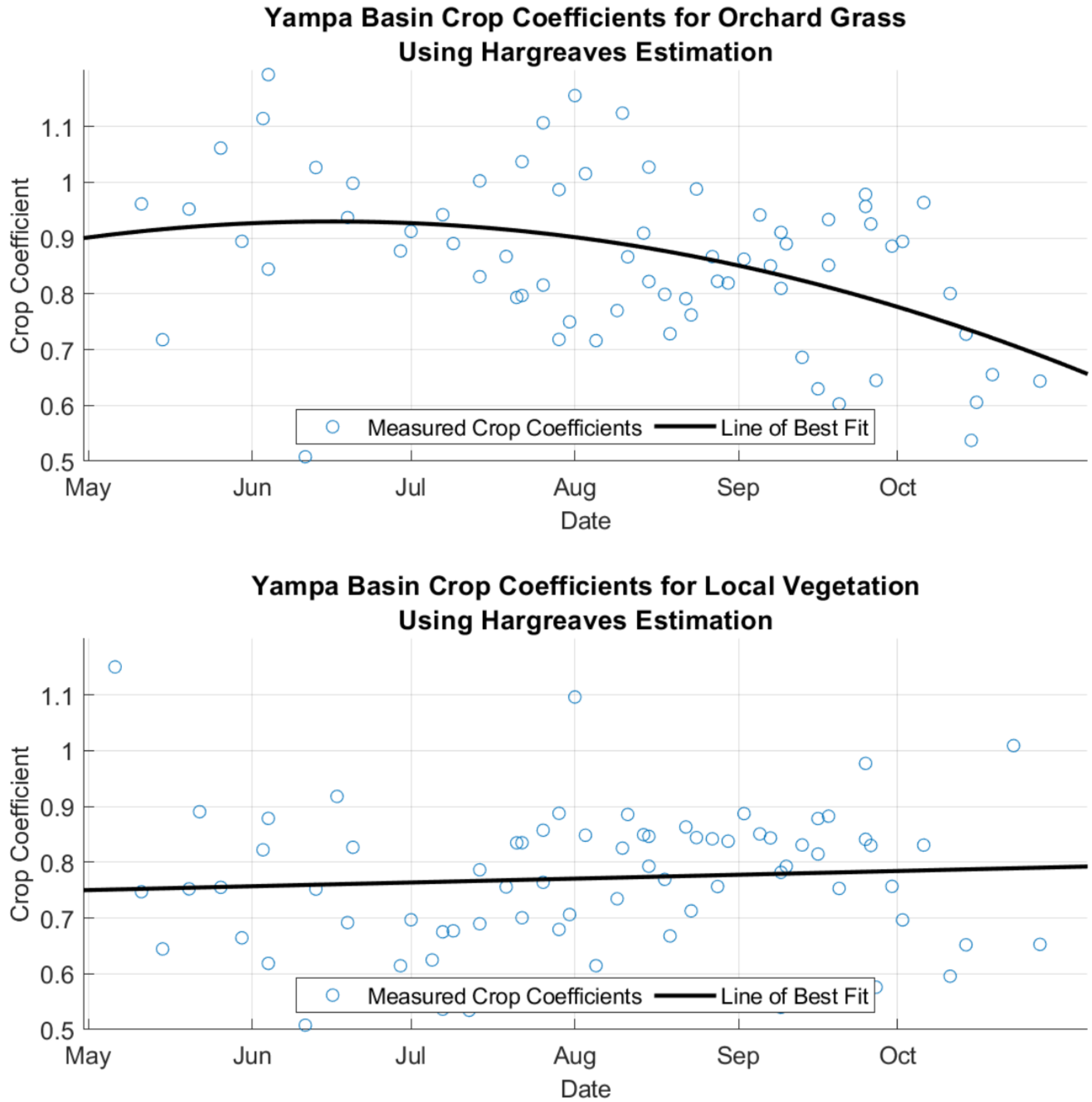

Figure 2: Crop coefficients computed as defined in equation 3 as a function of season. Blue dots represent individual measurements. Black lines represent lines of best fit.

Task 3 – Calculate Crop ET: The CoAgMET weather station was used to calculate Hargreaves PET. The lysimeter data was used to compute crop coefficients. By combining these resources, and applying an elevation adjustment, tables have been derived for computing grass ET_r anywhere in the basin. This can be done for either grass type. Figure 3 serves as an example of annual ET_r computation for both orchard grass and local vegetation.

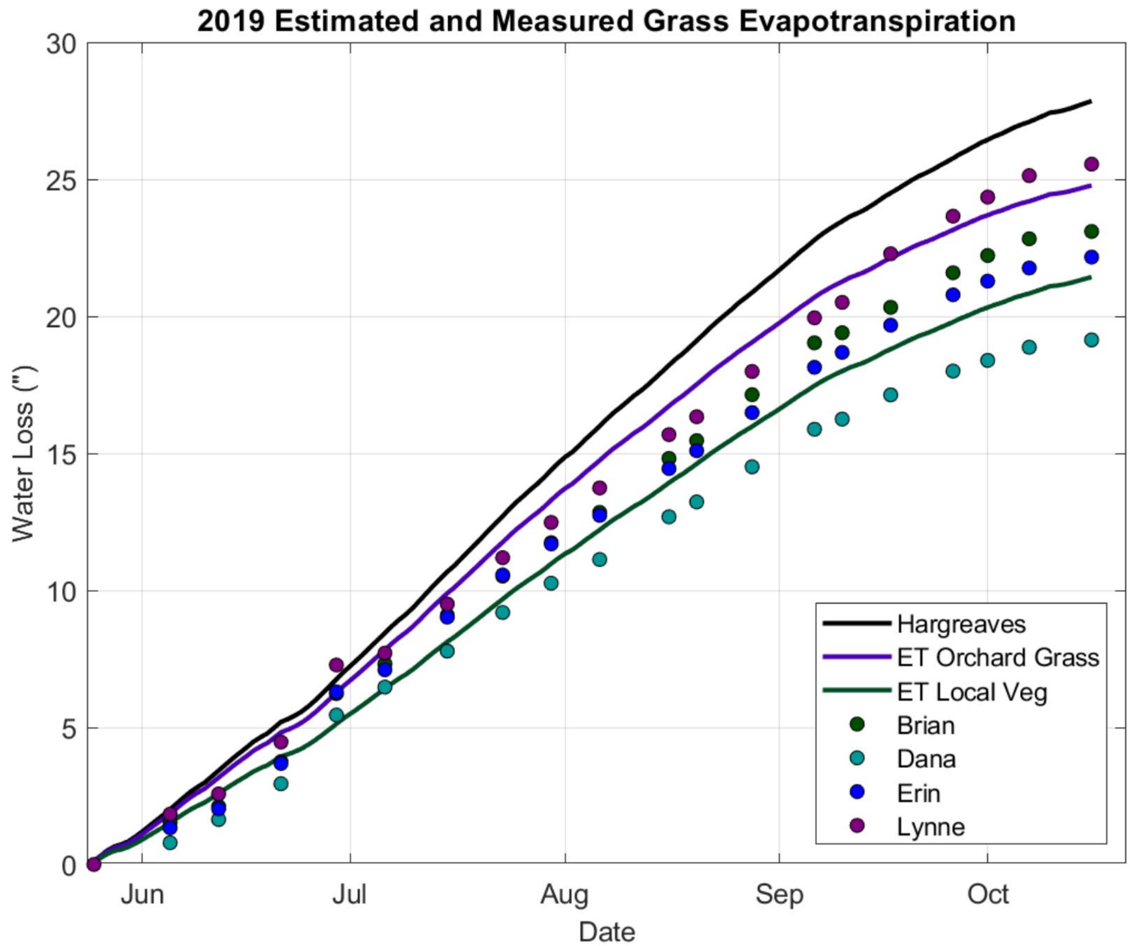

Figure 3: Comparison between lysimeter transpiration, and Hargreaves ET estimate with crop coefficients applied for both orchard grass and local vegetation.

Elevation Adjustment**:** The crop coefficients developed in this study were developed at a base elevation of 6200 ft. The recommended adjustment to these crop coefficients is 10%/3300 ft. For example, grass produced at an elevation of 7800 ft would average ~5% higher than at 6200 ft. Most of the grass in the Yampa River Basin is between 6000 and 7500 ft in elevation. An elevation adjustment table has been included (table 4). This elevation adjustment is statistically-derived, and not without uncertainty. However, the uncertainty produced by changes in elevation throughout the basin is small.

The CoAgMET weather station is also instrumented to measure surface humidity, wind speed, and solar intensity. These are the necessary components for computing the American Society for Civil Engineers (ASCE) Standard Penman-Monteith PET. We call this measurement of PET "fully-physical" because it includes all the necessary measured components of ET to be applied universally. We also computed ASCE crop coefficients for grass hay in the Yampa River Basin. These crop coefficients were then compared to those derived using the Hargreaves method. One can use the Hargreaves crop coefficients (tables 1-3), and the provided elevation adjustment (table 4) to compute PET in the basin anywhere temperature is monitored. The ASCE crop coefficients can be used without an elevation adjustment anywhere in the basin temperature is monitored.

The process for creating figures 4 and 5 mirror the work done for Hargreaves crop coefficients in figures 1 and 2.

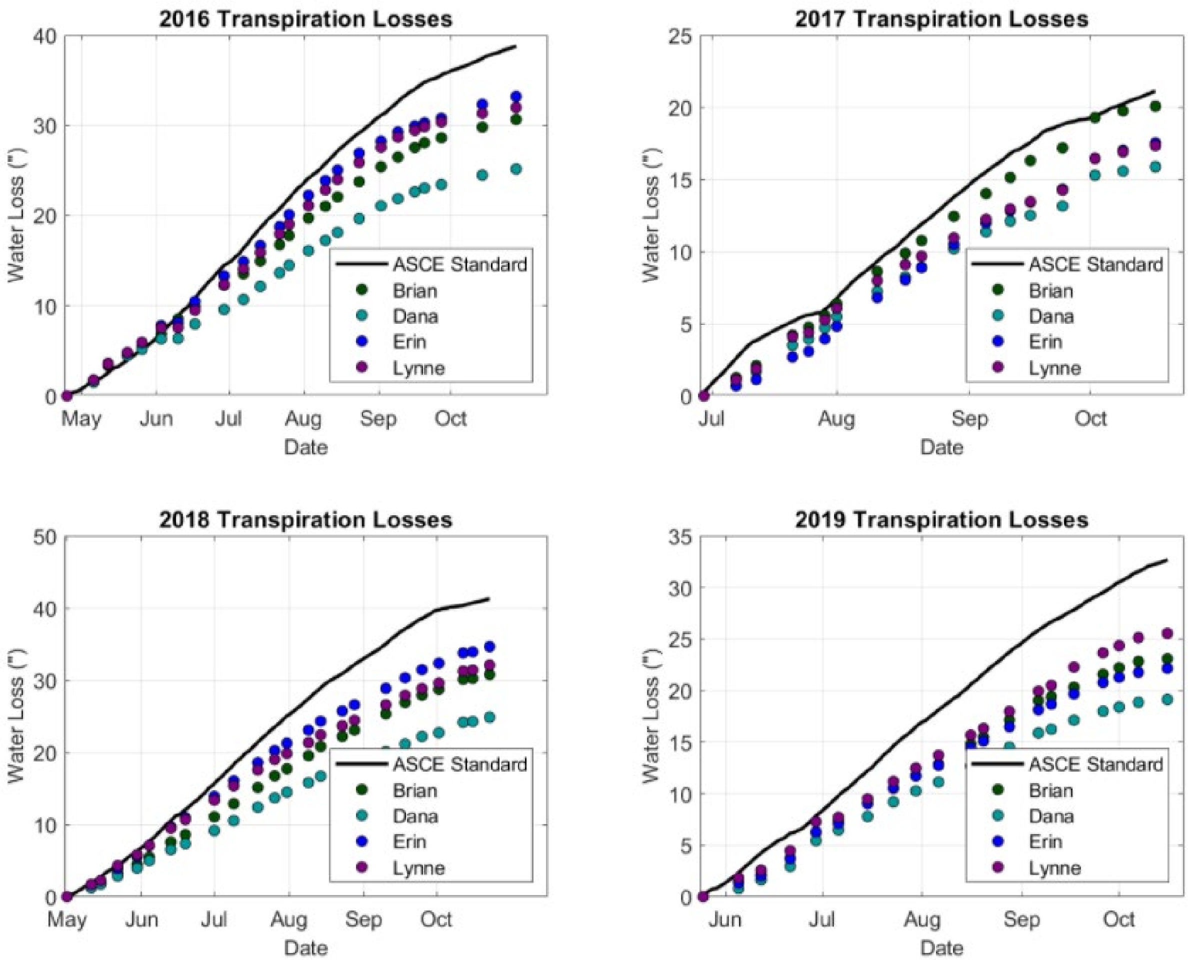

Figure 4: Weather station seasonal PET accumulation using ASCE-standard method (solid black line) and water loss measured by lysimeters (dotted lines).

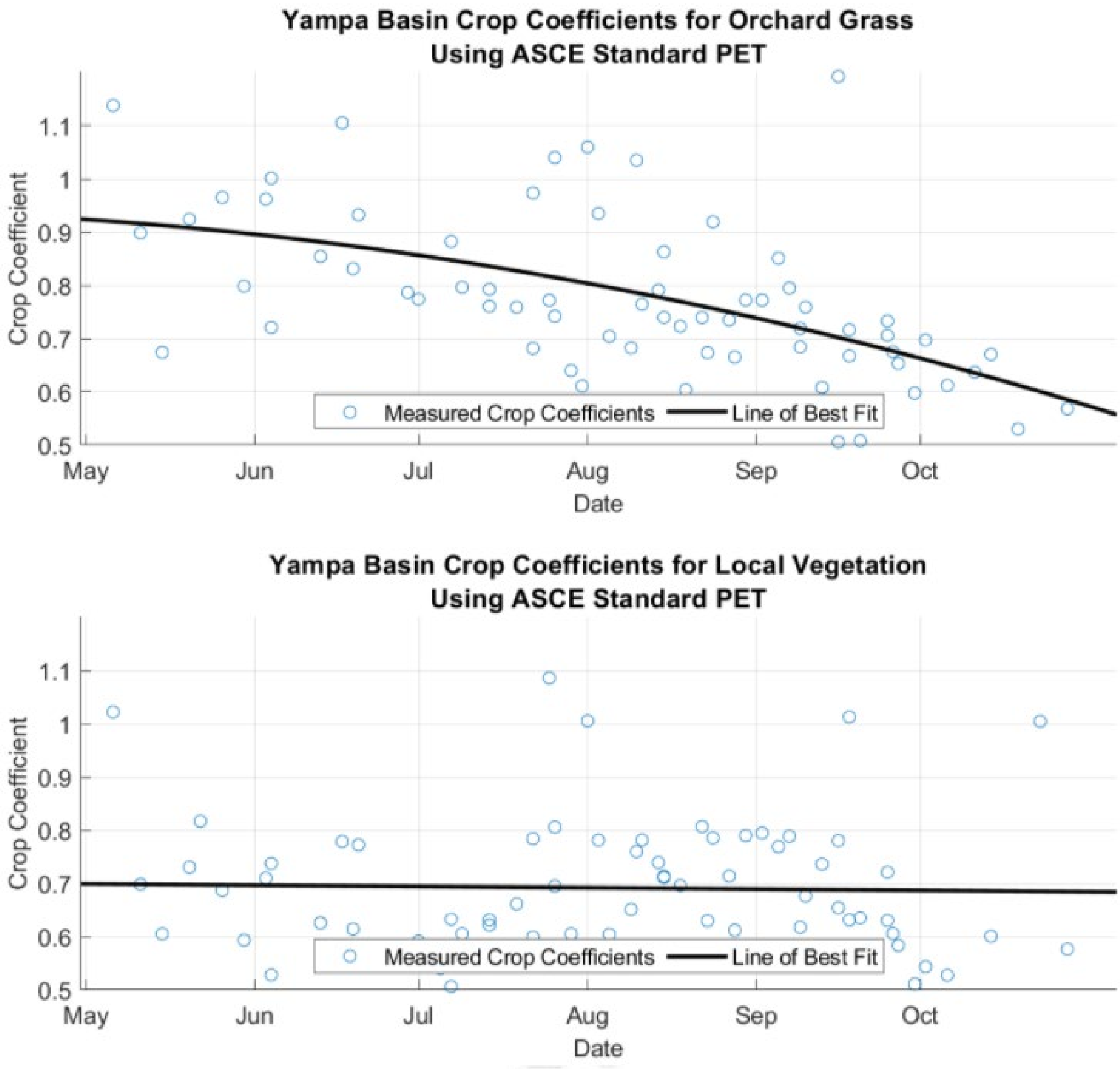

Figure 5: Crop Coefficients for orchard grass (top), and local vegetation (bottom) using ASCE standard computation of PET as a function of season.

Since both ASCE and Hargreaves-based crop coefficients were computed off of the same lysimeter data, it is not particularly important which method shows higher PET. Once fit to the same lysimeter data, the end result will be roughly the same ET_r. What is important is if there are predictable seasonal variations between ASCE and Hargreaves PET.

There were some minor seasonal differences between Hargreaves and ASCE-derived PET as a function of season, particularly for orchard grass. Early in the growing season the two measures were quite similar, but later in the season ASCE PET was higher than Hargreaves PET. Thus, the reverse was true for the crop coefficients. This is likely because daytime surface humidity is quite low in the Yampa River Basin in late summer. Those monitoring ET_r for grass with Hargreaves PET derived in this study may have better results lowering crop coefficients slightly for May and June, but raising crop coefficients slightly from mid-July onward.

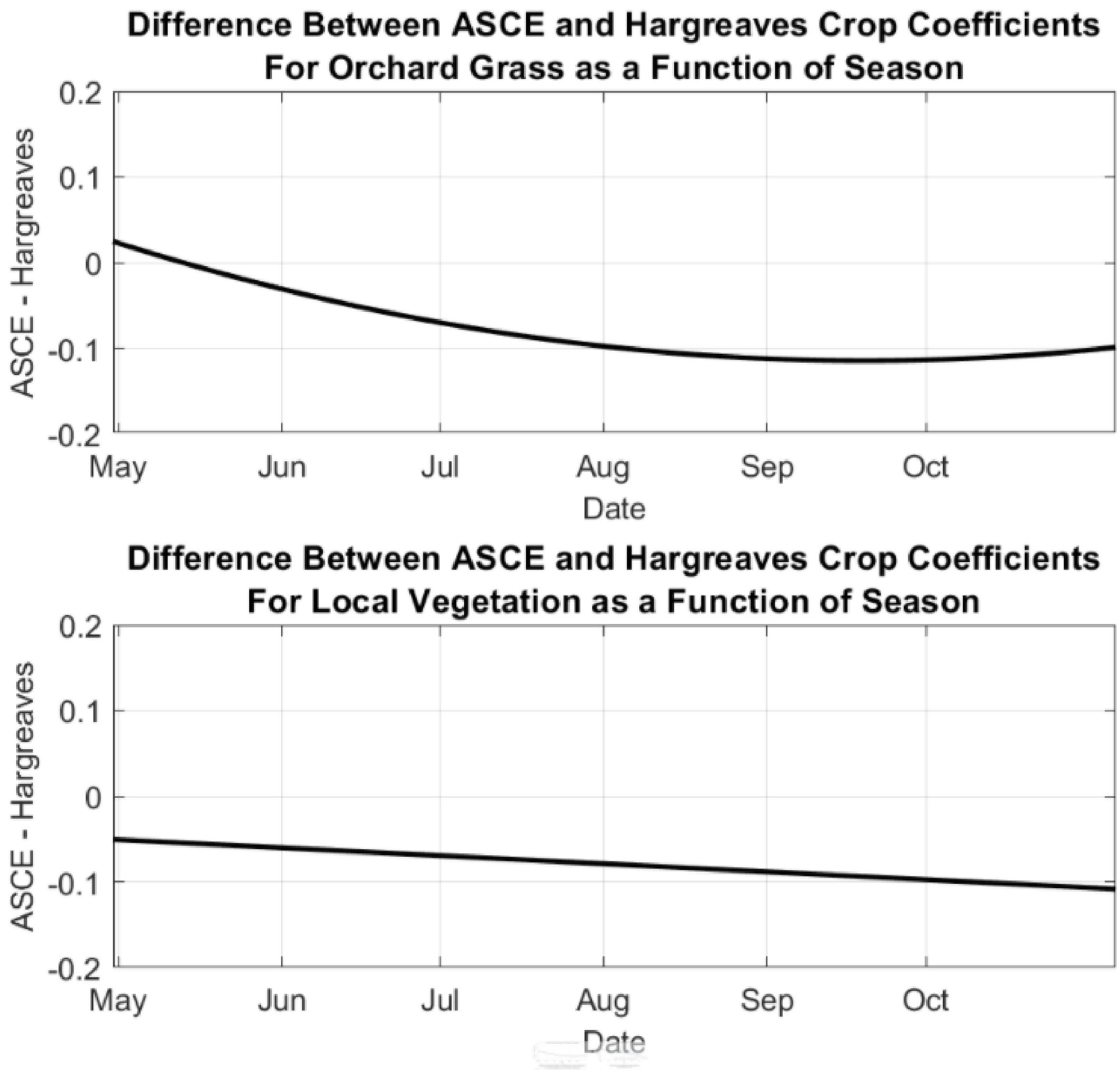

Figure 6: Seasonal comparison between ASCE-standard and Hargreaves crop coefficients for orchard grass (top) and local vegetation (bottom).

Documentation:

Alvarado, R., Wilson, E.M. 2009. “Historical Crop Consumptive Use Analysis Colorado River Basin.” Leonard Rice Engineers Inc.

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Jensen, M. E., Burman, R. D., and Allen, R. G., eds. (1990). “Evapotranspiration and irrigation water requirements.” ASCE Manuals and Reports on Engineering Practice No. 70, ASCE, Reston, Va.

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Evapotranspiration Code – https://coagmet.colostate.edu/projects/coagmet/browser/trunk/src/ETR.pm.

Crop Coefficient Code - https://coagmet.colostate.edu/projects/coagmet/browser/trunk/info/info.et

Glossary:

Consumptive Use – Water loss due to plant growth and evaporation.

Crop Coefficient – A derived multiplier that relates PET to a specified vegetated surface.

Lysimeter – A weighing device used to measure water loss from vegetation via transpiration.

Potential Evapotranspiration (PET) – The amount of water lost to evaporation and transpiration from a vegetated surface, assuming enough moisture is available for transpiration to occur. Since vegetation transpiration rates are variable, PET is typically computed for a well-watered, mature alfalfa landscape, but can be adjusted to fit other crops using a crop coefficient.

Reference Evapotranspiration (ET_r) – The amount of water lost to evaporation and transpiration from a specified a specifically calibrated vegetated surface assuming, enough moisture is available for transpiration to occur.

Tables:

Table 1: Hargreaves Solar Adjustment by Calendar Day (larger version attached via spreadsheet)

1-Jan	0.21387	1-Feb	0.270653	1-Mar	0.369634	1-Apr	0.501128	1-May	0.61185	1-Jun	0.680628
2-Jan	0.214664	2-Feb	0.273522	2-Mar	0.373723	2-Apr	0.505282	2-May	0.614892	2-Jun	0.681909
3-Jan	0.215531	3-Feb	0.276449	3-Mar	0.377838	3-Apr	0.509416	3-May	0.617884	3-Jun	0.683129
4-Jan	0.216468	4-Feb	0.279434	4-Mar	0.381976	4-Apr	0.513528	4-May	0.620825	4-Jun	0.684286
5-Jan	0.217477	5-Feb	0.282475	5-Mar	0.386136	5-Apr	0.517615	5-May	0.623714	5-Jun	0.685383
6-Jan	0.218558	6-Feb	0.285571	6-Mar	0.390316	6-Apr	0.521677	6-May	0.626552	6-Jun	0.686417
7-Jan	0.219709	7-Feb	0.288722	7-Mar	0.394515	7-Apr	0.525713	7-May	0.629337	7-Jun	0.687389
8-Jan	0.220931	8-Feb	0.291926	8-Mar	0.398731	8-Apr	0.529722	8-May	0.632069	8-Jun	0.688299
9-Jan	0.222224	9-Feb	0.295183	9-Mar	0.402963	9-Apr	0.533701	9-May	0.634747	9-Jun	0.689147
10-Jan	0.223587	10-Feb	0.298492	10-Mar	0.407209	10-Apr	0.537651	10-May	0.637371	10-Jun	0.689932
11-Jan	0.22502	11-Feb	0.301852	11-Mar	0.411468	11-Apr	0.541569	11-May	0.639941	11-Jun	0.690655
12-Jan	0.226524	12-Feb	0.305261	12-Mar	0.415738	12-Apr	0.545456	12-May	0.642455	12-Jun	0.691316
13-Jan	0.228096	13-Feb	0.308718	13-Mar	0.420017	13-Apr	0.549309	13-May	0.644914	13-Jun	0.691913
14-Jan	0.229738	14-Feb	0.312223	14-Mar	0.424305	14-Apr	0.553127	14-May	0.647317	14-Jun	0.692448
15-Jan	0.231449	15-Feb	0.315773	15-Mar	0.428599	15-Apr	0.55691	15-May	0.649664	15-Jun	0.692921
16-Jan	0.233229	16-Feb	0.319369	16-Mar	0.432898	16-Apr	0.560657	16-May	0.651954	16-Jun	0.69333
17-Jan	0.235077	17-Feb	0.323009	17-Mar	0.437201	17-Apr	0.564366	17-May	0.654187	17-Jun	0.693677
18-Jan	0.236992	18-Feb	0.326691	18-Mar	0.441505	18-Apr	0.568037	18-May	0.656363	18-Jun	0.69396
19-Jan	0.238975	19-Feb	0.330415	19-Mar	0.44581	19-Apr	0.571668	19-May	0.658481	19-Jun	0.694181
20-Jan	0.241025	20-Feb	0.334178	20-Mar	0.450114	20-Apr	0.575259	20-May	0.660541	20-Jun	0.694338
21-Jan	0.243141	21-Feb	0.337981	21-Mar	0.454415	21-Apr	0.578808	21-May	0.662542	21-Jun	0.694433
22-Jan	0.245324	22-Feb	0.34182	22-Mar	0.458712	22-Apr	0.582315	22-May	0.664485	22-Jun	0.694465
23-Jan	0.247572	23-Feb	0.345696	23-Mar	0.463003	23-Apr	0.58578	23-May	0.666369	23-Jun	0.694433
24-Jan	0.249885	24-Feb	0.349607	24-Mar	0.467287	24-Apr	0.5892	24-May	0.668194	24-Jun	0.694338
25-Jan	0.252262	25-Feb	0.353551	25-Mar	0.471562	25-Apr	0.592576	25-May	0.669959	25-Jun	0.694181
26-Jan	0.254703	26-Feb	0.357527	26-Mar	0.475828	26-Apr	0.595906	26-May	0.671664	26-Jun	0.69396
27-Jan	0.257207	27-Feb	0.361534	27-Mar	0.480082	27-Apr	0.59919	27-May	0.67331	27-Jun	0.693677
28-Jan	0.259774	28-Feb	0.36557	28-Mar	0.484322	28-Apr	0.602427	28-May	0.674895	28-Jun	0.69333
29-Jan	0.262403			29-Mar	0.488549	29-Apr	0.605616	29-May	0.676419	29-Jun	0.692921
30-Jan	0.265093			30-Mar	0.492759	30-Apr	0.608758	30-May	0.677883	30-Jun	0.692448
31-Jan	0.267843			31-Mar	0.496953			31-May	0.679286		
1-Jul	0.691913	1-Aug	0.644914	1-Sep	0.545456	1-Oct	0.420017	1-Nov	0.298492	1-Dec	0.22502
2-Jul	0.691316	2-Aug	0.642455	2-Sep	0.541569	2-Oct	0.415738	2-Nov	0.295183	2-Dec	0.223587
3-Jul	0.690655	3-Aug	0.639941	3-Sep	0.537651	3-Oct	0.411468	3-Nov	0.291926	3-Dec	0.222224
4-Jul	0.689932	4-Aug	0.637371	4-Sep	0.533701	4-Oct	0.407209	4-Nov	0.288722	4-Dec	0.220931
5-Jul	0.689147	5-Aug	0.634747	5-Sep	0.529722	5-Oct	0.402963	5-Nov	0.285571	5-Dec	0.219709
6-Jul	0.688299	6-Aug	0.632069	6-Sep	0.525713	6-Oct	0.398731	6-Nov	0.282475	6-Dec	0.218558
7-Jul	0.687389	7-Aug	0.629337	7-Sep	0.521677	7-Oct	0.394515	7-Nov	0.279434	7-Dec	0.217477
8-Jul	0.686417	8-Aug	0.626552	8-Sep	0.517615	8-Oct	0.390316	8-Nov	0.276449	8-Dec	0.216468
9-Jul	0.685383	9-Aug	0.623714	9-Sep	0.513528	9-Oct	0.386136	9-Nov	0.273522	9-Dec	0.215531
10-Jul	0.684286	10-Aug	0.620825	10-Sep	0.509416	10-Oct	0.381976	10-Nov	0.270653	10-Dec	0.214664
11-Jul	0.683129	11-Aug	0.617884	11-Sep	0.505282	11-Oct	0.377838	11-Nov	0.267843	11-Dec	0.21387
12-Jul	0.681909	12-Aug	0.614892	12-Sep	0.501128	12-Oct	0.373723	12-Nov	0.265093	12-Dec	0.213147
13-Jul	0.680628	13-Aug	0.61185	13-Sep	0.496953	13-Oct	0.369634	13-Nov	0.262403	13-Dec	0.212497
14-Jul	0.679286	14-Aug	0.608758	14-Sep	0.492759	14-Oct	0.36557	14-Nov	0.259774	14-Dec	0.211918
15-Jul	0.677883	15-Aug	0.605616	15-Sep	0.488549	15-Oct	0.361534	15-Nov	0.257207	15-Dec	0.211412
16-Jul	0.676419	16-Aug	0.602427	16-Sep	0.484322	16-Oct	0.357527	16-Nov	0.254703	16-Dec	0.210978
17-Jul	0.674895	17-Aug	0.59919	17-Sep	0.480082	17-Oct	0.353551	17-Nov	0.252262	17-Dec	0.210616
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19-Jul	0.671664	19-Aug	0.592576	19-Sep	0.471562	19-Oct	0.345696	19-Nov	0.247572	19-Dec	0.210109
20-Jul	0.669959	20-Aug	0.5892	20-Sep	0.467287	20-Oct	0.34182	20-Nov	0.245324	20-Dec	0.209964
21-Jul	0.668194	21-Aug	0.58578	21-Sep	0.463003	21-Oct	0.337981	21-Nov	0.243141	21-Dec	0.209891
22-Jul	0.666369	22-Aug	0.582315	22-Sep	0.458712	22-Oct	0.334178	22-Nov	0.241025	22-Dec	0.209891
23-Jul	0.664485	23-Aug	0.578808	23-Sep	0.454415	23-Oct	0.330415	23-Nov	0.238975	23-Dec	0.209964
24-Jul	0.662542	24-Aug	0.575259	24-Sep	0.450114	24-Oct	0.326691	24-Nov	0.236992	24-Dec	0.210109
25-Jul	0.660541	25-Aug	0.571668	25-Sep	0.44581	25-Oct	0.323009	25-Nov	0.235077	25-Dec	0.210326
26-Jul	0.658481	26-Aug	0.568037	26-Sep	0.441505	26-Oct	0.319369	26-Nov	0.233229	26-Dec	0.210616
27-Jul	0.656363	27-Aug	0.564366	27-Sep	0.437201	27-Oct	0.315773	27-Nov	0.231449	27-Dec	0.210978
28-Jul	0.654187	28-Aug	0.560657	28-Sep	0.432898	28-Oct	0.312223	28-Nov	0.229738	28-Dec	0.211412
29-Jul	0.651954	29-Aug	0.55691	29-Sep	0.428599	29-Oct	0.308718	29-Nov	0.228096	29-Dec	0.211918
30-Jul	0.649664	30-Aug	0.553127	30-Sep	0.424305	30-Oct	0.305261	30-Nov	0.226524	30-Dec	0.212497
31-Jul	0.647317	31-Aug	0.549309			31-Oct	0.301852			31-Dec	0.213147

Table 2: Mean Estimate of Hargreaves Crop Coefficients for Orchard Grass by Calendar Day (larger version attached via spreadsheet)

1-May	0.899916	1-Jun	0.926246	1-Jul	0.927194	1-Aug	0.902824	1-Sep	0.852688	1-Oct	0.779637
2-May	0.901168	2-Jun	0.926666	2-Jul	0.92681	2-Aug	0.901608	2-Sep	0.850641	2-Oct	0.776786
3-May	0.902392	3-Jun	0.92706	3-Jul	0.926399	3-Aug	0.900366	3-Sep	0.848568	3-Oct	0.773909
4-May	0.90359	4-Jun	0.927427	4-Jul	0.925962	4-Aug	0.899098	4-Sep	0.846468	4-Oct	0.771005
5-May	0.904761	5-Jun	0.927766	5-Jul	0.925497	5-Aug	0.897802	5-Sep	0.844342	5-Oct	0.768073
6-May	0.905906	6-Jun	0.92808	6-Jul	0.925006	6-Aug	0.89648	6-Sep	0.842188	6-Oct	0.765116
7-May	0.907023	7-Jun	0.928366	7-Jul	0.924488	7-Aug	0.895131	7-Sep	0.840008	7-Oct	0.762131
8-May	0.908114	8-Jun	0.928625	8-Jul	0.923943	8-Aug	0.893755	8-Sep	0.837801	8-Oct	0.75912
9-May	0.909178	9-Jun	0.928858	9-Jul	0.923371	9-Aug	0.892352	9-Sep	0.835567	9-Oct	0.756081
10-May	0.910215	10-Jun	0.929064	10-Jul	0.922773	10-Aug	0.890922	10-Sep	0.833306	10-Oct	0.753016
11-May	0.911225	11-Jun	0.929243	11-Jul	0.922148	11-Aug	0.889466	11-Sep	0.831018	11-Oct	0.749924
12-May	0.912208	12-Jun	0.929395	12-Jul	0.921496	12-Aug	0.887983	12-Sep	0.828704	12-Oct	0.746806
13-May	0.913165	13-Jun	0.929521	13-Jul	0.920817	13-Aug	0.886473	13-Sep	0.826363	13-Oct	0.74366
14-May	0.914095	14-Jun	0.929619	14-Jul	0.920111	14-Aug	0.884936	14-Sep	0.823995	14-Oct	0.740488
15-May	0.914998	15-Jun	0.929691	15-Jul	0.919378	15-Aug	0.883372	15-Sep	0.8216	15-Oct	0.737289
16-May	0.915874	16-Jun	0.929736	16-Jul	0.918619	16-Aug	0.881782	16-Sep	0.819178	16-Oct	0.734063
17-May	0.916723	17-Jun	0.929754	17-Jul	0.917833	17-Aug	0.880164	17-Sep	0.81673	17-Oct	0.73081
18-May	0.917546	18-Jun	0.929746	18-Jul	0.91702	18-Aug	0.87852	18-Sep	0.814255	18-Oct	0.72753
19-May	0.918341	19-Jun	0.92971	19-Jul	0.91618	19-Aug	0.876849	19-Sep	0.811753	19-Oct	0.724224
20-May	0.91911	20-Jun	0.929648	20-Jul	0.915314	20-Aug	0.875152	20-Sep	0.809224	20-Oct	0.720891
21-May	0.919852	21-Jun	0.929559	21-Jul	0.91442	21-Aug	0.873427	21-Sep	0.806668	21-Oct	0.717531
22-May	0.920568	22-Jun	0.929443	22-Jul	0.9135	22-Aug	0.871676	22-Sep	0.804086	22-Oct	0.714144
23-May	0.921256	23-Jun	0.9293	23-Jul	0.912553	23-Aug	0.869898	23-Sep	0.801476	23-Oct	0.71073
24-May	0.921918	24-Jun	0.929131	24-Jul	0.911579	24-Aug	0.868093	24-Sep	0.79884	24-Oct	0.70729
25-May	0.922553	25-Jun	0.928935	25-Jul	0.910579	25-Aug	0.866261	25-Sep	0.796177	25-Oct	0.703822
26-May	0.923161	26-Jun	0.928712	26-Jul	0.909551	26-Aug	0.864402	26-Sep	0.793488	26-Oct	0.700328
27-May	0.923742	27-Jun	0.928462	27-Jul	0.908497	27-Aug	0.862517	27-Sep	0.790771	27-Oct	0.696807
28-May	0.924296	28-Jun	0.928185	28-Jul	0.907416	28-Aug	0.860605	28-Sep	0.788028	28-Oct	0.69326
29-May	0.924824	29-Jun	0.927881	29-Jul	0.906308	29-Aug	0.858666	29-Sep	0.785258	29-Oct	0.689685
30-May	0.925325	30-Jun	0.927551	30-Jul	0.905173	30-Aug	0.8567	30-Sep	0.782461	30-Oct	0.686084
31-May	0.925799			31-Jul	0.904012	31-Aug	0.854707			31-Oct	0.682456

Table 3: High Estimate of Hargreaves Crop Coefficient for Local Vegetation by Calendar Day (larger version attached via spreadsheet)

1-May	0.749847	1-Jun	0.756778	1-Jul	0.763486	1-Aug	0.770417	1-Sep	0.777349	1-Oct	0.784057
2-May	0.750071	2-Jun	0.757002	2-Jul	0.76371	2-Aug	0.770641	2-Sep	0.777572	2-Oct	0.78428
3-May	0.750294	3-Jun	0.757226	3-Jul	0.763933	3-Aug	0.770865	3-Sep	0.777796	3-Oct	0.784504
4-May	0.750518	4-Jun	0.757449	4-Jul	0.764157	4-Aug	0.771088	4-Sep	0.77802	4-Oct	0.784727
5-May	0.750741	5-Jun	0.757673	5-Jul	0.76438	5-Aug	0.771312	5-Sep	0.778243	5-Oct	0.784951
6-May	0.750965	6-Jun	0.757896	6-Jul	0.764604	6-Aug	0.771535	6-Sep	0.778467	6-Oct	0.785174
7-May	0.751189	7-Jun	0.75812	7-Jul	0.764828	7-Aug	0.771759	7-Sep	0.77869	7-Oct	0.785398
8-May	0.751412	8-Jun	0.758343	8-Jul	0.765051	8-Aug	0.771983	8-Sep	0.778914	8-Oct	0.785622
9-May	0.751636	9-Jun	0.758567	9-Jul	0.765275	9-Aug	0.772206	9-Sep	0.779138	9-Oct	0.785845
10-May	0.751859	10-Jun	0.758791	10-Jul	0.765498	10-Aug	0.77243	10-Sep	0.779361	10-Oct	0.786069
11-May	0.752083	11-Jun	0.759014	11-Jul	0.765722	11-Aug	0.772653	11-Sep	0.779585	11-Oct	0.786292
12-May	0.752306	12-Jun	0.759238	12-Jul	0.765946	12-Aug	0.772877	12-Sep	0.779808	12-Oct	0.786516
13-May	0.75253	13-Jun	0.759461	13-Jul	0.766169	13-Aug	0.773101	13-Sep	0.780032	13-Oct	0.78674
14-May	0.752754	14-Jun	0.759685	14-Jul	0.766393	14-Aug	0.773324	14-Sep	0.780255	14-Oct	0.786963
15-May	0.752977	15-Jun	0.759909	15-Jul	0.766616	15-Aug	0.773548	15-Sep	0.780479	15-Oct	0.787187
16-May	0.753201	16-Jun	0.760132	16-Jul	0.76684	16-Aug	0.773771	16-Sep	0.780703	16-Oct	0.78741
17-May	0.753424	17-Jun	0.760356	17-Jul	0.767064	17-Aug	0.773995	17-Sep	0.780926	17-Oct	0.787634
18-May	0.753648	18-Jun	0.760579	18-Jul	0.767287	18-Aug	0.774218	18-Sep	0.78115	18-Oct	0.787858
19-May	0.753872	19-Jun	0.760803	19-Jul	0.767511	19-Aug	0.774442	19-Sep	0.781373	19-Oct	0.788081
20-May	0.754095	20-Jun	0.761027	20-Jul	0.767734	20-Aug	0.774666	20-Sep	0.781597	20-Oct	0.788305
21-May	0.754319	21-Jun	0.76125	21-Jul	0.767958	21-Aug	0.774889	21-Sep	0.781821	21-Oct	0.788528
22-May	0.754542	22-Jun	0.761474	22-Jul	0.768182	22-Aug	0.775113	22-Sep	0.782044	22-Oct	0.788752
23-May	0.754766	23-Jun	0.761697	23-Jul	0.768405	23-Aug	0.775336	23-Sep	0.782268	23-Oct	0.788976
24-May	0.75499	24-Jun	0.761921	24-Jul	0.768629	24-Aug	0.77556	24-Sep	0.782491	24-Oct	0.789199
25-May	0.755213	25-Jun	0.762145	25-Jul	0.768852	25-Aug	0.775784	25-Sep	0.782715	25-Oct	0.789423
26-May	0.755437	26-Jun	0.762368	26-Jul	0.769076	26-Aug	0.776007	26-Sep	0.782939	26-Oct	0.789646
27-May	0.75566	27-Jun	0.762592	27-Jul	0.769299	27-Aug	0.776231	27-Sep	0.783162	27-Oct	0.78987
28-May	0.755884	28-Jun	0.762815	28-Jul	0.769523	28-Aug	0.776454	28-Sep	0.783386	28-Oct	0.790094
29-May	0.756108	29-Jun	0.763039	29-Jul	0.769747	29-Aug	0.776678	29-Sep	0.783609	29-Oct	0.790317
30-May	0.756331	30-Jun	0.763262	30-Jul	0.76997	30-Aug	0.776902	30-Sep	0.783833	30-Oct	0.790541
31-May	0.756555			31-Jul	0.770194	31-Aug	0.777125			31-Oct	0.790764

Table 4: Adjustment to Crop Coefficient by Elevation

Elevation (ft)	ET_r Adjustment (%)
5000	-3.636363636
5100	-3.333333333
5200	-3.03030303
5300	-2.727272727
5400	-2.424242424
5500	-2.121212121
5600	-1.818181818
5700	-1.515151515
5800	-1.212121212
5900	-0.909090909
6000	-0.606060606
6100	-0.303030303
6200	0
6300	0.303030303
6400	0.606060606
6500	0.909090909
6600	1.212121212
6700	1.515151515
6800	1.818181818
6900	2.121212121
7000	2.424242424
7100	2.727272727
7200	3.03030303
7300	3.333333333
7400	3.636363636
7500	3.939393939
7600	4.242424242
7700	4.545454545
7800	4.848484848
7900	5.151515152
8000	5.454545455
8100	5.757575758
8200	6.060606061
8300	6.363636364
8400	6.666666667
8500	6.96969697
8600	7.272727273

8700	7.575757576
8800	7.878787879
8900	8.181818182
9000	8.484848485