Determination of Seasonal Crop Coefficients for the Cal Poly Campus Vineyard Using the "Paso Panel"

A Senior Project

Presented to
The Faculty of the Wine and Viticulture
Department at California Polytechnic State University, San Luis Obispo
in Partial Fulfillment,
of the Requirements, for the Degree:
Bachelor of Science, Wine and Viticulture

by
Daniel L. Vyenielo
December 12, 2014

Vineyard water use (ETc) is characterized by age, seasonal development, canopy size, row spacing, final use, and evaporative demand (Allen et al. 1998). Furthermore, vine water use is dependent on the physical availability of water within the soil profile from precipitation or supplemental irrigation, among other hydrologic factors (Williams L.E., 2014). In the often arid drought conditions of California, agricultural ecosystems have historically relied on the supply and management of irrigation water for production. Thus, water availability for crop production is variable by location and specific management conditions (primarily trellis type and irrigation scheduling) (Williams and Matthews, 1990).

ETc is calculated as the product of reference evapotranspiration (ETo) and the crop coefficient (Kc).

Eq. 1

$$ETc$$

For agricultural applications, reference evapotranspiration is commonly calculated through the use of hydrometeorological equations such as the Penman-Monteith equation, used by the California Irrigation Management Information System (CIMIS). ETo measurements have been standardized to reflect the depth of water leaving the earth’s surface as the sum of evaporation and transpiration. Additional methods, such as the catchment water balance equation, exist for calculating this value, or for the regression modeling of Kc values, but are typically reserved for more in-depth analysis and research based applications. Nevertheless, the goal of both methods is to quantify the loss of water from the field standardized against a reference crop.

Theoretically, crop coefficient values are for non-stressed crops cultivated under excellent agronomic and water management conditions and achieving maximum crop yield; considered to be standard conditions for commercial agriculture (Allen et al. 1998). Therefore, the adaptation of Kc values has been the result of continued experimentation and research as methods have produced variable results. Methods to determine Kc have historically included measures of Leaf Area (LA) (Williams et al., 2003b), Leaf Area Index (LAI) (de Medeiros et al., 2001), canopy cover (de Medeiros et al., 2001), and the fraction of light intercepting the canopy (Ayars et al., 2003). These studies have shown a high degree of correlation between leaves, light and water use from a catchment balance standpoint through the use of lysimeters and soil probes in the calculation of ETc. The correlation of these factors is expected from a physiological standpoint, given the necessity of water and light for photosynthesis (Williams, 2000). Therefore, if the need for water is biologically linked, Kc values are highly correlated with biological time and could be modeled as such to offset the differences of seasonal development (Wright 1985). However, practical location specific and useful measurable parameters from empirical research have only recently been developed.

Grape vine water use has been shown to be a linear function of vine shaded area measured beneath the canopy (Williams and Ayars, 2005). Following these findings, the development of localized crop coefficients no longer requires the use of expensive machinery, equipment, or laborious methods. For example, “A digital camera (and the appropriate software to digitize the amount of shade) would be the only hardware required to follow the seasonal development of the grapevine canopy under most circumstances.” (Williams and Ayars, 2005). Vineyard managers now have the tools necessary to document and calculate seasonal site specific crop coefficients to refine their management practices.

Additional tools for measuring shaded area have been developed; one example is the Paso Panel. Developed by Mark Battany, a UC Cooperative Extension Viticulture Farm Advisor, Paso Panel units are homemade devices typically built by the end user, fashioned from an aluminum frame with a solar panel, voltage meter, and switch attached. The device works through the direct relationship between light and amperage. Any object placed between the sun and solar panel will result in a direct reduction in amperage (Battany, M.). Differential reductions in amperage will then be produced depending on the size of the vine canopy and resulting shaded area. Measurements are calibrated against a full sun reading and the difference calculated to measure a percent shaded area of the panel and vine (Battany, M). Solar panel measurements are easily effected by atmospheric conditions such as cloud cover, and the sun's position. Therefore, to minimize variation in measurements, atmospheric conditions must be clear and measurements conducted at solar noon. The effects of the latter on measurements are dependent on the row orientation of the vineyard. East-West oriented rows will experience less of an error due to the changing position of the sun.

Utilizing this fairly new biological and technological knowledge it was the primary goal of this project to model the seasonal change of crop coefficients indirectly measured as shaded area with the Paso Panel in accordance with vine biological time as a measure of degree days from bud break till leaf fall. Shaded area measurements were collected monthly during the 2014 season from June until October. Measurements were plotted and supporting models were adapted for each of the two varieties and upper and lower blocks. In total, four different blocks were analyzed and equations adapted to modeling the Kc value in accordance with the historical date of bud break and leaf fall. Degree Days were determined and modeled from the UC-IPM website with the degree day calculator using the double sine method, an intermediate cutoff, a base temperature of 50 degrees Fahrenheit, and an upper threshold of 95 degrees Fahrenheit.

It was the secondary objective of this study to adapt a historical model of ETo from the CIMIS Station (#52), San Luis Obispo, using annual mean daily historical ETo values. The conjunctive use of both models could be used to calculate ETc in an average year using the standard ETc Formula (Eq. 1) for a vertically shoot positioned (VSP) vineyard with similar shaded areas, phenology, and seasonal development located near CIMIS Station (#52) in San Luis Obispo, Ca.

Materials and Methods

Location and Cultivar information. The project was conducted at the Trestle Vineyard (lat: 35.316382, long: -120.683846) from June until October during the 2014 growing season. The Trestle

Vineyard is owned by the California State University System, operate by the Wine and Viticulture Department of California Polytechnic State University, and (during the duration of this project) managed by Pacific Vineyard Management. The vineyard is located on a 14 acre parcel planted on a predominantly south facing slope (<10%). Three Blocks are divided with rows oriented north-south (parallel to slope). Two blocks were used in this study. The first, was trained to a unilateral cordon, and planted with spacing of 8ft x 5ft (row x vine) for a density of 1,089 vines per acre in 2003. The second, was trained to a unilateral cordon, planted with two spacing configurations: 8ft x 5ft in the lower section, and 8ft x 4ft in the upper section, and densities of 1,089 and 1,361 vines per acre, respectively. Vines in block 2 were planted in 2007. Both blocks were planted with grafted rootstock and scion *Vitis .spp* combinations and trained to a Vertical Shoot Positioned (VSP) trellis. Block 1, SYU and SYL, consisted of variable *Vitis spp.* rootstocks and *Vitis viniferea* L. cv. Syrah scion of variable clones. Block 2, PNU and PNL, was planted to a *V. berlanderi x V. riparia* (SO4) cross rootstock with grafted *V. viniferea* L. cv. Pinot Noir scion of various clones. Both blocks received similar canopy and water management during the course of this study, with all blocks receiving a single mechanical leafing pass, in the fruit zone, prior to beginning measurements in June. A single hedging pass conducted between the June and July measurement occurred in the Syrah block as shoots were beginning to overtop the highest trellis wire. No clusters were removed during the course of this study.

Grapevine phenology. Vine phenology was monitored during the course of this study. Specific stages were noted using the modified E-L system (B.G. Coombe, 1995). Phenology data was available for previous growing seasons, but phonological dates were often spotty and many holes were present in the data. Nevertheless, all available data was used in the determination of the average bud break and leaf fall dates for model computations. Modified E-L stages were determined using visual best educated guesses of appearance assuming 50% of the vineyard was at the given stage.

Experimental design and methods. Two blocks each with two sub-blocks, separated by an irrigation break near the midpoint of the block, were studied in this project. In each of the 4 blocks, forty sample vines were selected at random accounting for a 10 vine buffer and 3 row buffer from the edge of rows and blocks. Selected vines were tagged, and locations noted in accordance with a grid pattern. Grid origins were determined by on site row markings. In blocks 1, the eastern most rows were row 1 increasing toward the west. In block 2, the westernmost rows were considered to be row 1, increasing toward the east. In both blocks, vines were numbered in row increasing up slope, toward the north. Measurements of shaded areas values were repeated, approximately, monthly. Measurements were conducted on June 17, July 18, August 15, September 29, and October 27 during the 2014 season. On each measurement date, shaded area measurements were conducted around solar noon, typically beginning measurements 1 hour before and ending 1 hour after. Weather conditions were optimal on all sampling dates with no obstructing cloud layers.

Shaded area measurements were conducted at each vine on each date in accord with the following protocol: (1) prior to entering the vine row a full sun reading was observed, values recorded and the time noted, (2) in row, sample vines were approached and solar panel held directly below the canopy at the trunk of the vine as close to the canopy as possible, (3) the panel was leveled in accordance with a bubble level (on paso panel), (4) the switch was engaged, (4) the resulting amperage was recorded. This protocol was repeated for each row and sample vine. (Battany, M)

Time values were recorded with each row full sun reading in order to model the probably full sun reading at the time of vine sample readings. Interpolated values were then used in the calculation of the amperage reduction caused by the vine’s shaded area.

Kc calculation from shaded area. Crop coefficient values were calculated using an equation determined by L.E. Williams and J.E. Ayars (2005) relating shaded area and vine Kc as a linear function of water use (Eq. 2)

Eq. 2

$$y$$

Therefore, using the Paso Panel, determining shaded area, x, from the amperage measurements, for each block (5.75 = length of solar panel, 8 is the distance between rows, constant between blocks), is:

Eq. 3

$$x = \left[\left(1-\left(\frac{Vine\ Amps}{Full\ Sun\ Amps}\right)\right)*100\right]$$

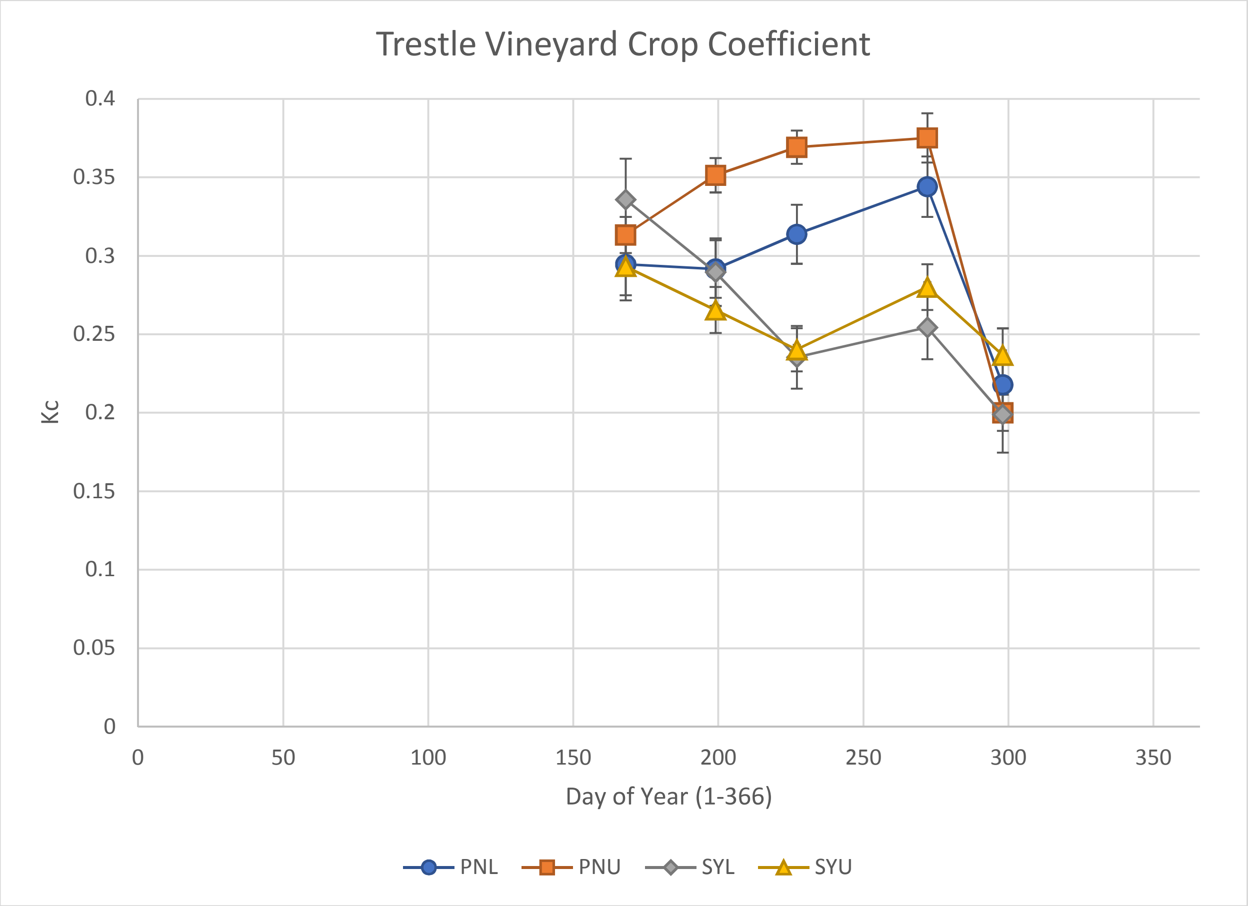
Seasonal Kc interpolation. Post calculation of Kc values with equations 2 and 3, mean Kc values were computed for each block on all dates. Mean values were represented with standard error and the relative changed in mean Kc values reflected a change in average shaded area for each of the study blocks. With known Kc values for each of the blocks from June until October of 2014, and known average phenological data, seasonal Kc values were interpolated using an Excel Add-in called XonGrid (XonGrid). Bud break and leaf fall were assumed to have a Kc value of 0.

Degree Day, and ETo Model data and design. All weather data was sourced from the CIMIS weather station #52 located in San Luis Obispo, Ca and maintained by the Bio Resource and Agriculture Engineering (BRAE) department on the California Poly Technic State University Campus. The CIMIS #52 weather station (lat: 35.305462, long: -120.661807) is located approximately 1.5 miles from the trestle vineyard. All data values were downloaded from 1986-2014 using the UC-IPM weather models and data portal website. All necessary data was used to adapt averages for each day of the year. Averages for

Degree Days and ETo, were then calculated over the 28 year period for each day per year. Standard Error was calculated for each average day and included in the models. A polynomial line of best fit was then computed with excel for each of the graphs and the resulting equations were considered to be an accurate model of average ETo and Degree day values annually (R-squared > .95).

Results

Grapevine Kc values depicted relatively differing development paths throughout the season between varieties and irrigation blocks (fig 1.)



In block 1, Syrah, crop coefficients reached a peak during the June measurement. Between June and July measurements, a hedging pass was completed expectedly reducing the Kc value. However, this downward trend continued from July until August. An upward trend was produced from august till

September. Without, examining soil moisture and the irrigation, little more than speculative conclusions can be drawn as to the causes and reasoning behind the trend witnessed in this data.

Day of Year	PNL Kc	PNL_SE	PNU Kc	PNU_SE	SYL Kc	SYL_SE	SYU Kc	SYU_SE
168	0.294638	0.019637	0.313327	0.011565	0.335928	0.026077	0.29328	0.02161
199	0.291639	0.01834	0.351381	0.010905	0.289639	0.021518	0.265543	0.014646
227	0.313802	0.018778	0.369247	0.010576	0.235398	0.019913	0.240227	0.013737
272	0.344125	0.019284	0.375229	0.015717	0.254444	0.020206	0.280124	0.014608
298	0.217899	0.014618	0.200034	0.011586	0.198846	0.024146	0.236694	0.017126

Table 1. Measured Kc values for individual blocks by day of the year during the 2014 season. Standard error was calculated through the division of standard deviation by the square root of the sample number.

The SYL block displayed a large degree of variation across all measurement dates, especially in the lower block. Variation is common place in agriculture, however a larger number of blank vines existed in the lower block. Having been selected by chance and all vines having an equal opportunity , the variation amongst these large sample sizes with fairly consistent errors, indicates that the largest amount of variability is in the lower block of the Syrah. With an examination of table 2, it is obvious that standard error values are greatest for the SYL block.

Between the SYL and SYU blocks, both experienced a general downward trend until the August measurement. Prior to August, the SYL block maintained a greater KC value. Post August, an inversion of this trend occurred, and the SYU block had a greater shaded area. I am not sure what caused this.

In block 2, the PN, crop coefficients seemed to follow a more normalized curve, especially in the PNU block. In the PNU block an upward trending Kc value was tracked throughout all measurements until October; after harvest had occurred and subsequent leaf fall begun. The same positive trend is visible in the PNL block, but here too a greater degree of variation between measurements; again mainly due to the non-uniform conditions of the field with contributing error from blank values.

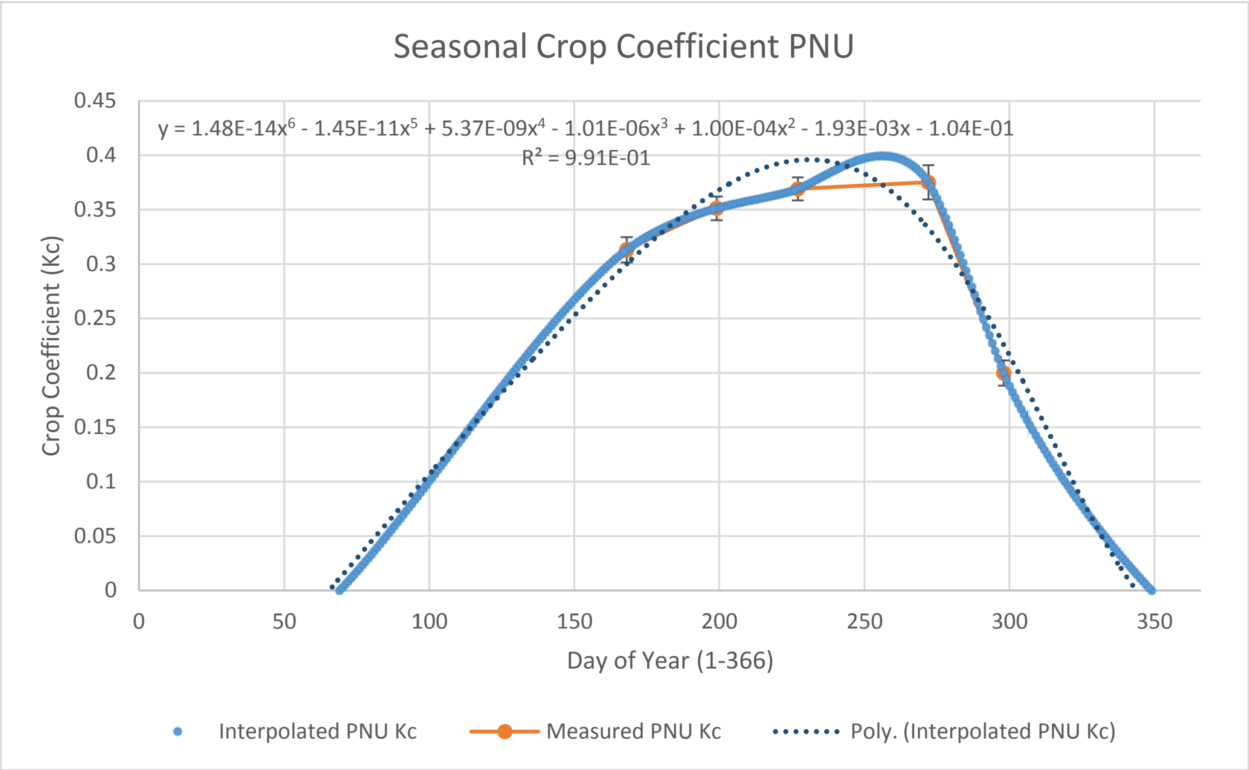
A comparison between the two varieties yields an obvious difference in the shaded area and relative water requirements for each variety. Under the current agronomic conditions, the approximate water use of the Syrah variety is below that of the Pinot based on shaded area. However, these measurements do not take into account the physical availability of water in the root zone. A further expansion of these data sets could be make use of the soil moisture monitors in the vineyard to draw a more accurate conclusion.

Mean Day of Year For E/L Stage					
PNL	**PNU**	**SYL**	**SYU**	**E/L #**	**Description**
69	69	78.5	79	4	Green tip; first leaf tissue visible
140	140	157	157	23	17-20 leaves separated; 50% caps off (=full bloom)
205	205	237	237	35	Veraison: berries begin to color and enlarge
257.5	257.5	298	298	38	Berries harvest-ripe
349	349	354	354	47	End of leaf fall

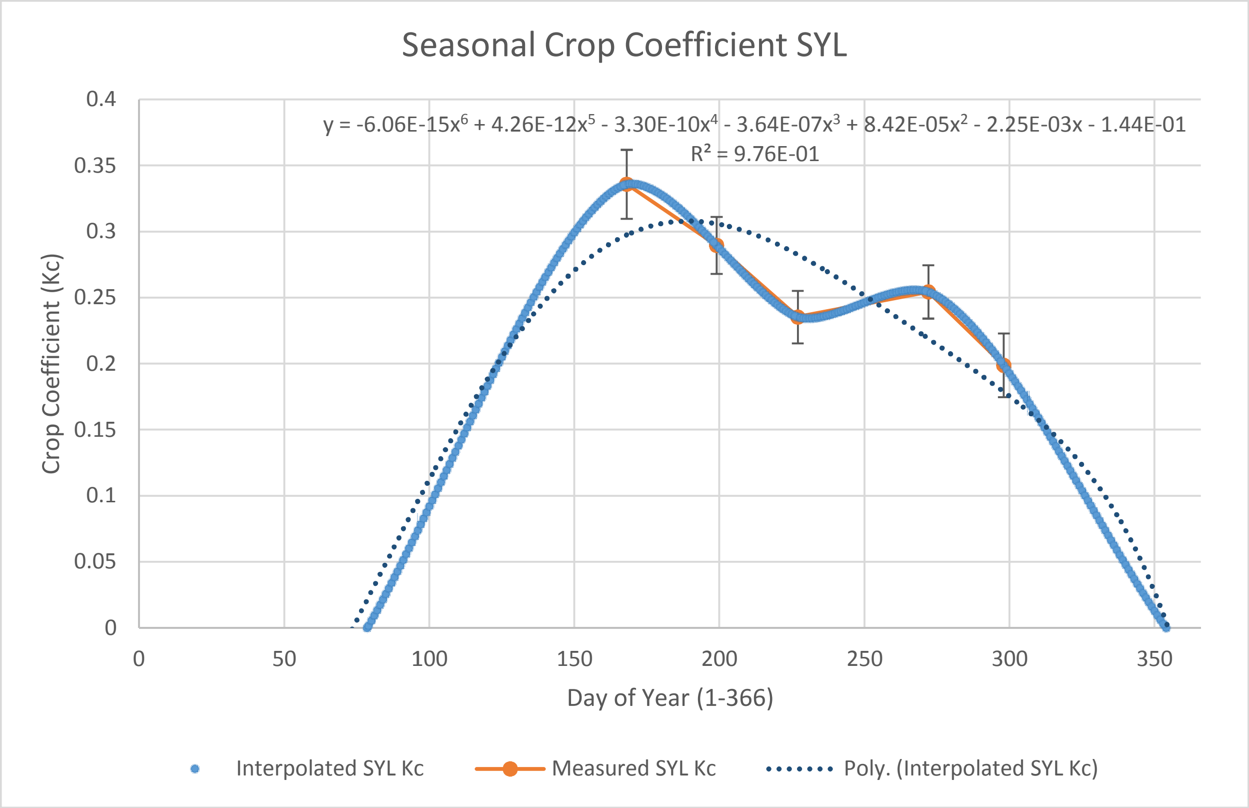
Table 2 Mean day of year occurrences of modified E/L # Stages. Phenology data was sparse, but averages reflect the relative averages of data from the 2012-2014 seasons. No leaf fall data was available, so a best guess approximation was assumed.

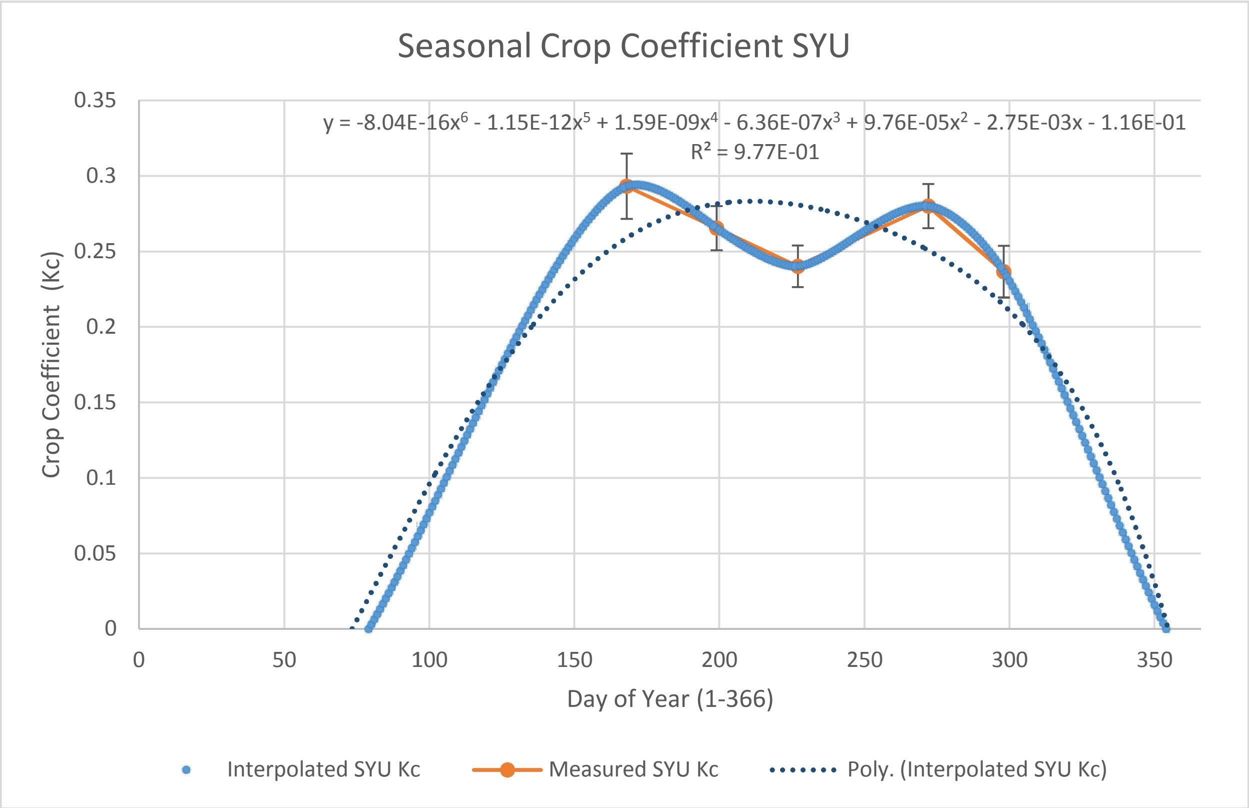
Further expanding these ideas, data points were interpolated based on historical averages and available phenological dates for the Trestle Vineyard (table 2).

The following are individual block graphs representing the relative formulas adapted for each block for



determining the Kc value from the day of the year as the x variable. Bud break and leaf fall dates were assumed to have a Kc value equal to 0.

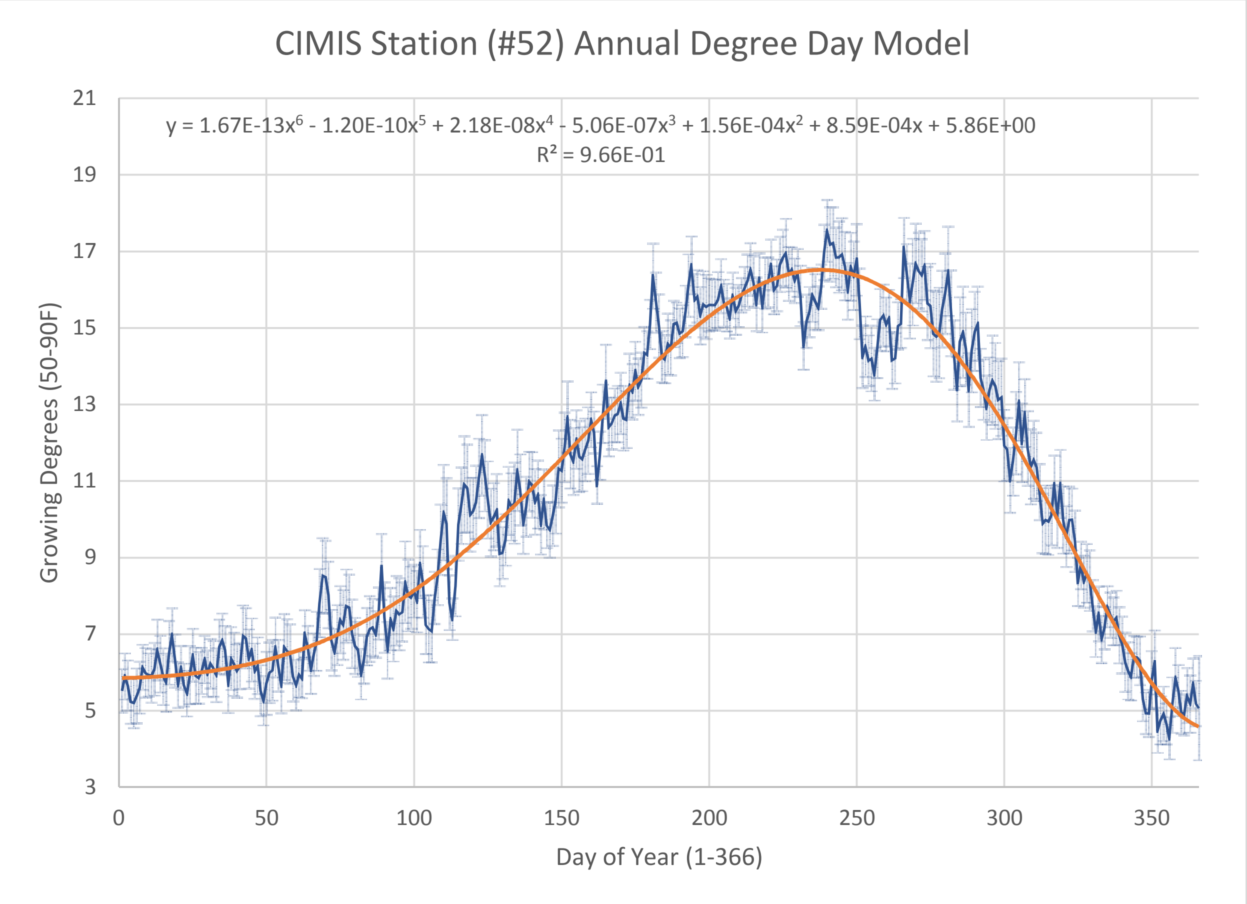




Degree Day Model. Conjunctively, a degree day model was generated to adapt the established crop coefficients by day of year to a more biologically synced timeframe. The use of degree days was first used in the grape industry to establish the differences in growing regions developed by A. J. Winkler and Maynard Amerine, for the University of California Davis, in the 1944 (Winkler et. Al, 1944).

A total of 28 years, from 1986 till 2014, with 96% of the data present for download was used to adapt the average growing degree days earned per day for the 28 year time period. To calculate daily degree days, the UC-IPM website was used.

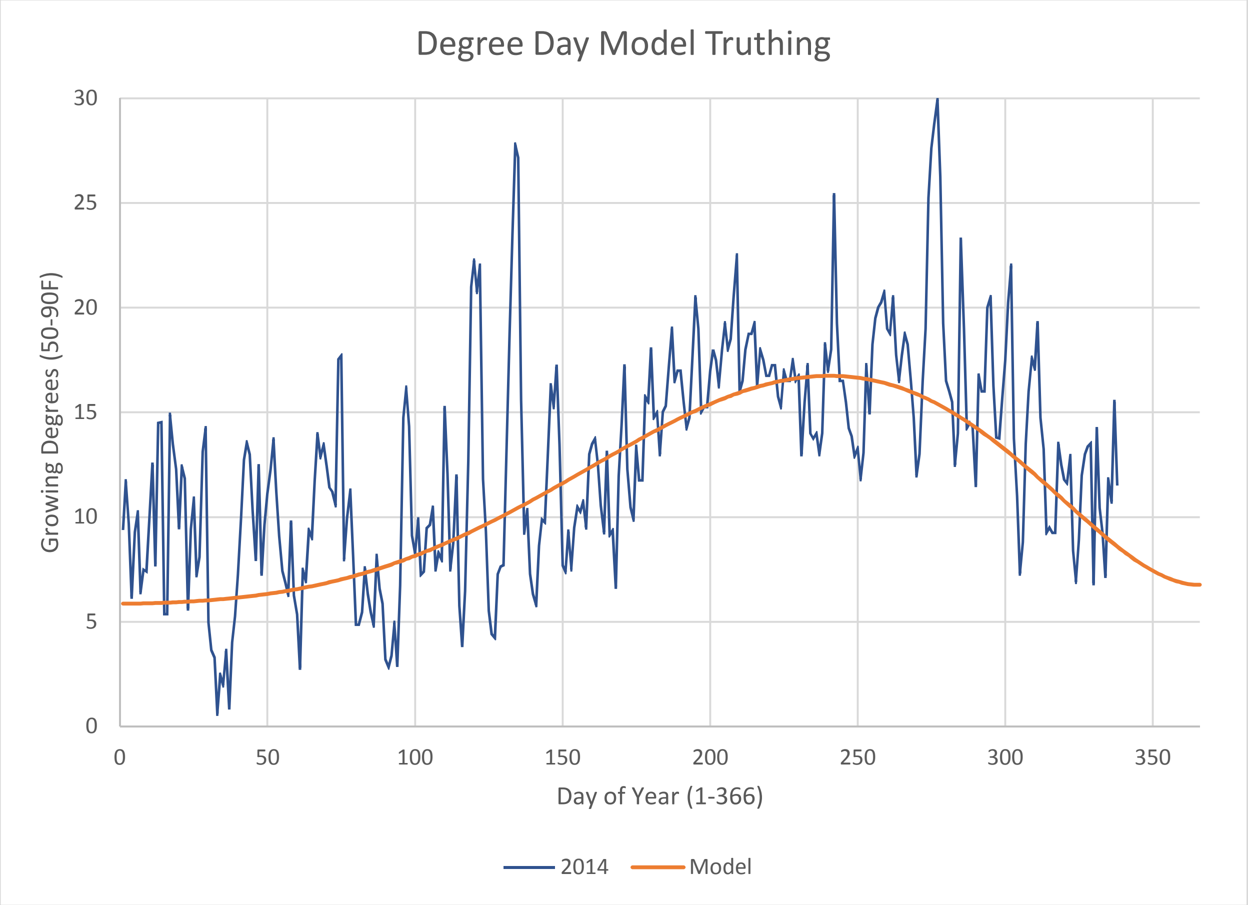
The generated model is below:



As is to be expected, all dates had a wide standard error when averaged from a 28 year sample size. Unfortunately, data was not available for a longer time period. The resulting equation, generated in excel, is useful as a representation of degree days earned for the Trestle Vineyard, and can be used to model a typical year.

To calculate cumulative degree days, a few options existed. First, I could have found the integral of the equation, which is possible, but degree days are typically counted as the summation between days over a time interval. Therefore, finding the integral of the equation, while possibly a more accurate measure of the true area under the curve, would introduce error for practical application. Therefore, the calculation of cumulative degree days was computed as the summation for each day to replicate real world conditions of degree day calculation.

An analysis of the model's accuracy was conducted in comparison of the 2014 growing season. I termed this "model truthing" and a comparison of the 2014 season and above model are visible in the graph below.



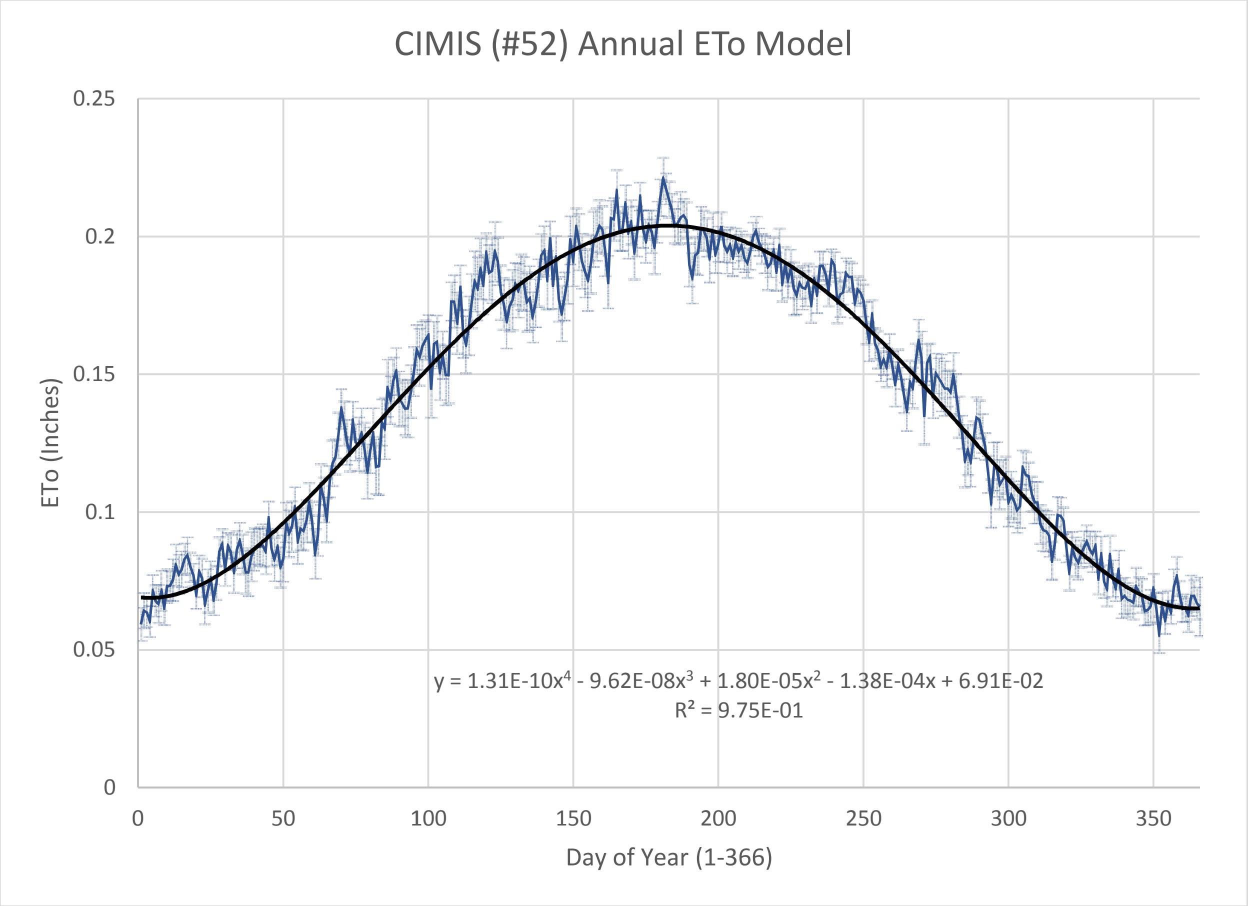
Degree Day Comparison	
2014 DD	**Model**
3731	3405
% Error	9.6%

Table 3. Degree day comparison between the 2014 season and the generated degree day model.

As you can see, the graph was generated prior to the end of the 2014, and a data gap is present. Nevertheless, between bud break and December 4, 2014 a total of 3731 Degree Days accumulated. Using a lower limit of 50 degrees and upper of 90 degrees Farhenheit, calculated with a double sine method and intermediate limit, the model proved to be quite accurate. During the same time period, 3405 degree days accumulated in the model. Results are presented in table 3.

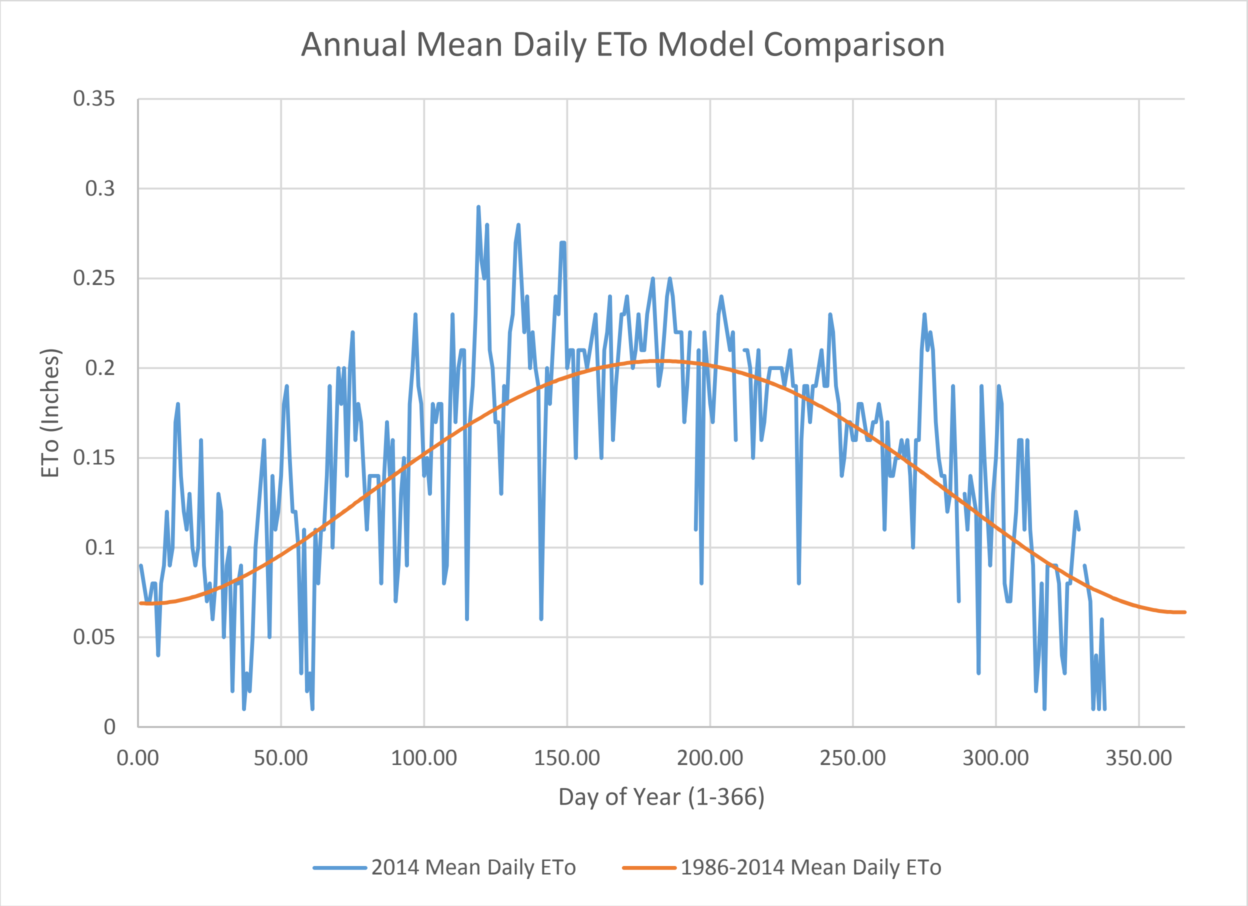
A truthing comparison of the model during the 2014 season shows the accuracy of the model over a longer time interval. In the short term, degree days can be more variable. For example, Bud Break occurrs on the 69th day of the year on average in the Pinot Noir block. The following week, posted degree days far above what the model projected. This trend continued until about the 81st day of the year when degree days were below the projected amounts. Therefore, the model is excellent at predicting a long term trend, but specific growth rates will be variable season to season due to the variance of weather in the short term.

ETo Model. A model was generated using the same procedures as for the degree day model, but with ETo values instead. Data was gathered from the CIMIS station and date points represent the average of daily ETo over a 28 year period. The model is presented below.

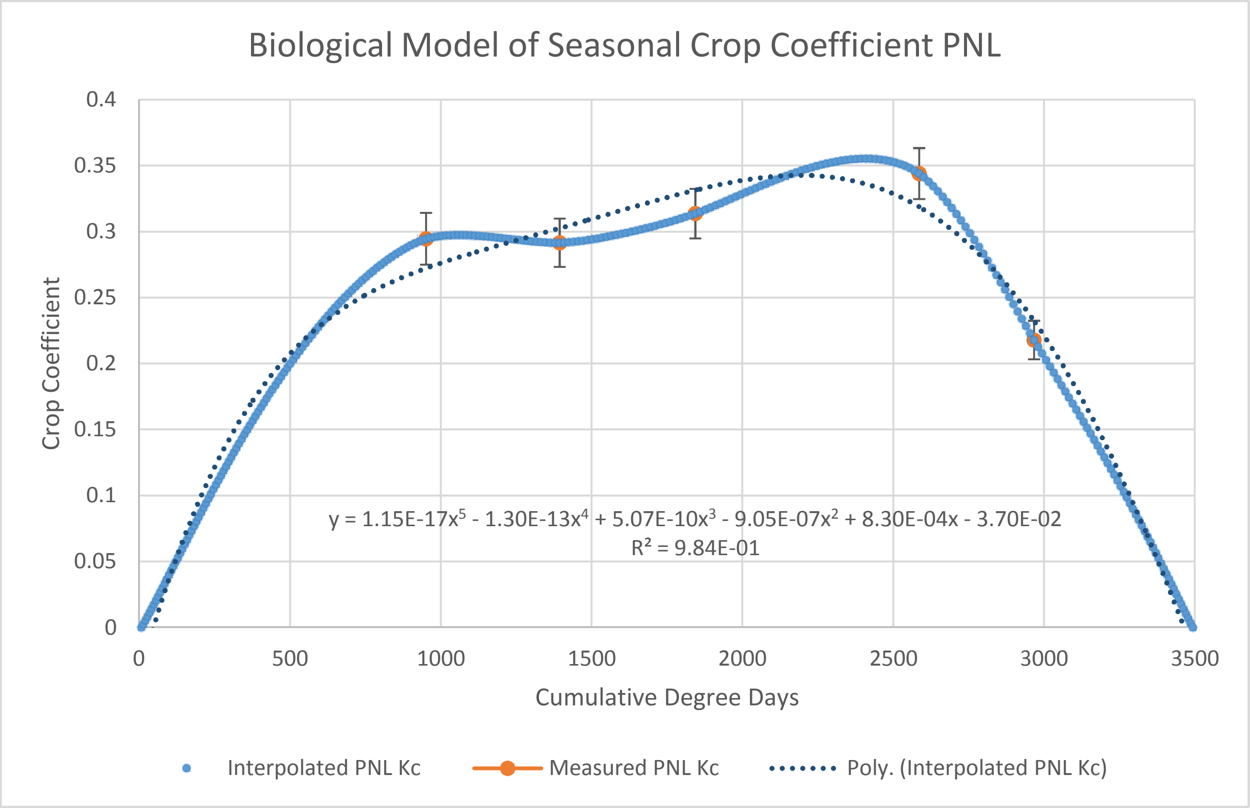


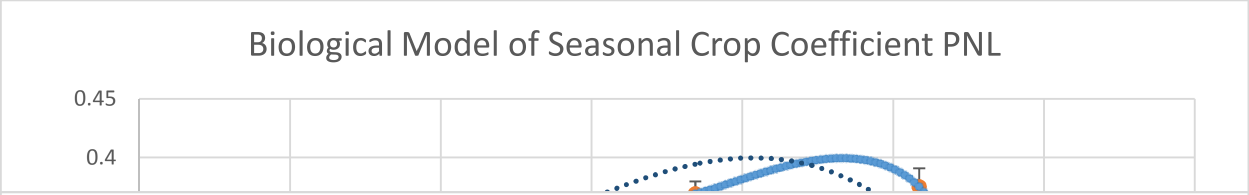
As with the Degree Day model, ETo values were historically quite variable, but a normal curve was generated. From the above graph, the peak of ETo values occurs from late May until August, with a slight tailing off of the graph in the fall months. The polynomial equation represents a high degree of correlation with the long term mean annual ETo graph.

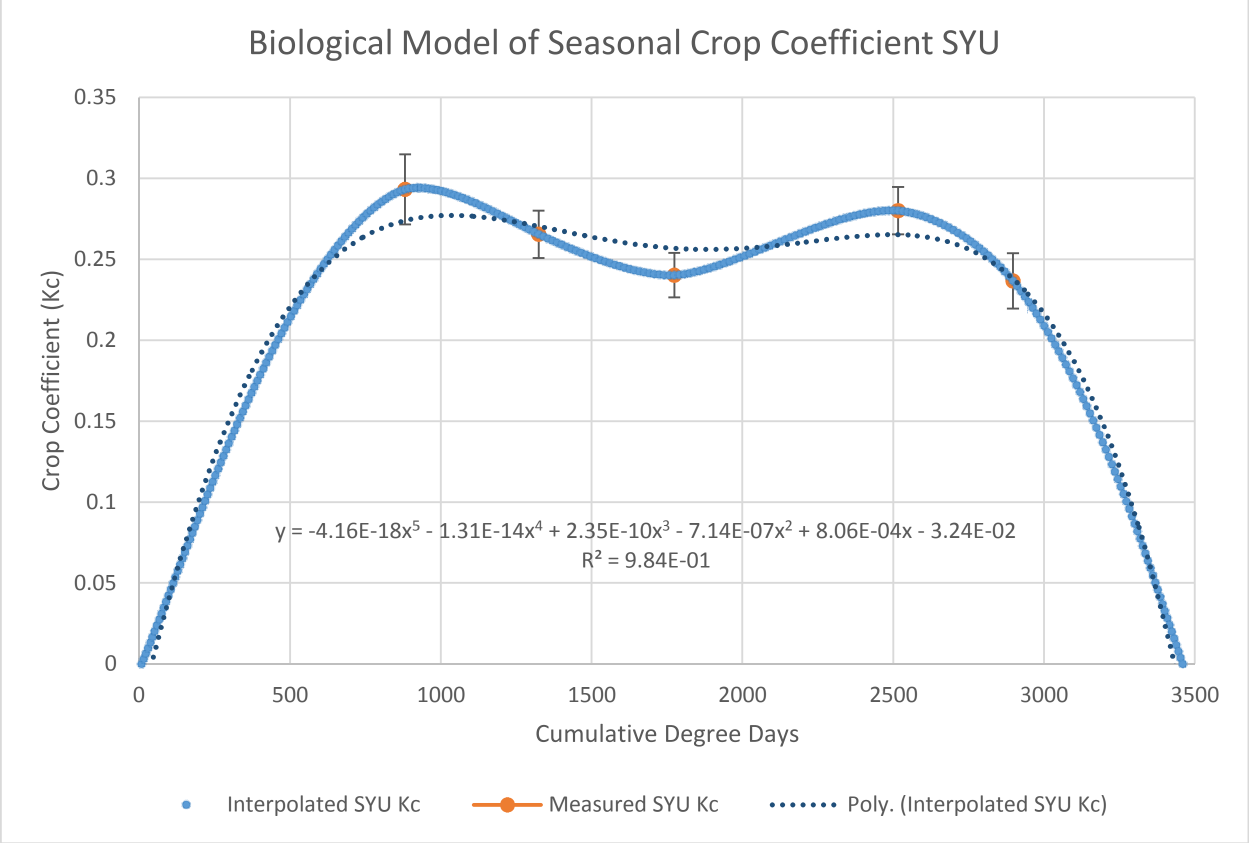
Model analysis was conducted with the 2014 season. As in the degree day model, the ETo model produced results below what was recorded during the 2014 season. A comparison is presented below.

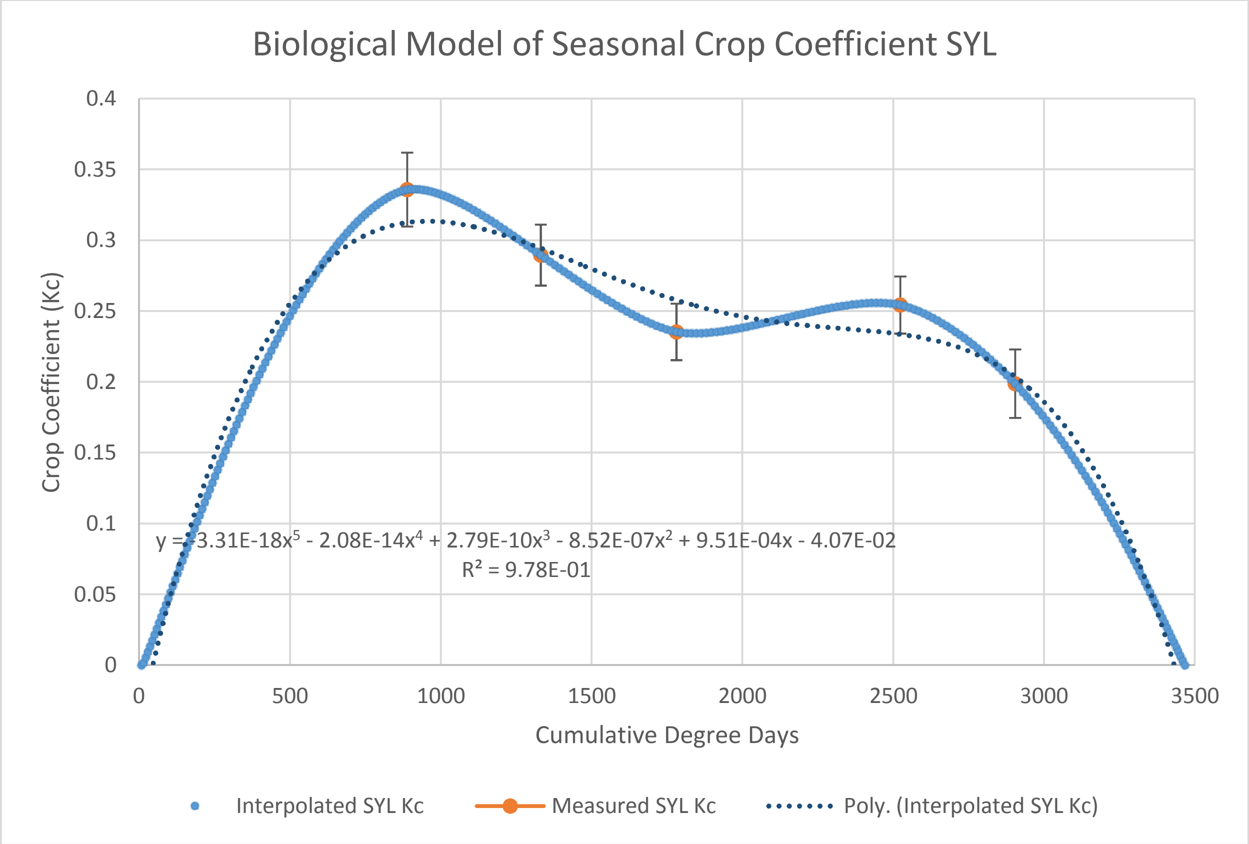


Adaptation of the crop coefficient as a function of degree days. Using the Degree day model adapted from CIMIS station 52 data, historical phenology dates were averaged and the crop coefficient plotted as a function of the cumulative growing degree day model. Phenology data was averaged and presented in table 2, above. Below, the models for each of the blocks are presented.




Biological Model of Seasonal Crop Coefficient PNL
0.45
0.4


Biological Model of Seasonal Crop Coefficient SYU
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Crop Coefficient (Kc)
y = -4.16E-18x⁵ - 1.31E-14x⁴ + 2.35E-10x³ - 7.14E-07x² + 8.06E-04x - 3.24E-02
R² = 9.84E-01
0
500
1000
1500
2000
2500
3000
3500
Cumulative Degree Days
Interpolated SYU Kc
Measured SYU Kc
Poly. (Interpolated SYU Kc)


Biological Model of Seasonal Crop Coefficient SYL
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Crop Coefficient (Kc)
y = -3.31E-18x⁵ - 2.08E-14x⁴ + 2.79E-10x³ - 8.52E-07x² + 9.51E-04x - 4.07E-02
R² = 9.78E-01
0
500
1000
1500
2000
2500
3000
3500
Cumulative Degree Days
Interpolated SYL Kc
Measured SYL Kc
Poly. (Interpolated SYL Kc)

Discussion

Shaded area measurements conducted during this experiment produced variable results depending on the block and variety. The results, shown above, demonstrate a trend far from the normal curves expected for the development of a vine canopy, particularly in the Syrah block. Emphasizing the non-ideal conditions, the models produced here were affected by the site conditions and more years of data would be necessary to generate a more normalized curve. Nevertheless, the curves generated here for the Syrah depict the necessary amounts of water for the given area measured and determined independently of the next measurement. Therefore, site conditions and the management decisions between measurements continually effected the growth and development of the vine canopy, contributing to the deformed shape of the graph. The development of these curves proves seasonal development has an effect on the amount of water used by a grape vine. (Williams, 2014)

Likewise, for similar trellis types but different variety combinations, water use can be drastically different. A comparison of the Syrah and Pinot shows that while the Syrah continued to lose shaded area, the Pinot continued the expected trend of a saturated curve. In hindsight, the deviation of the Syrah from the normalized curve while the Pinot block managed to maintain a normalized curve under the same management suggests the need for differing management tactics tailored to the needs of a specific variety (Williams, 2014).

Additionally, per vine spacing was altered between the Pinot upper and lower block. The differing needs of the upper block compared to the lower block, show an increased shaded area for closer planted vines. However, row spacing, not vine spacing, has been shown to affect vine water use (Allen et al 1998). Moreover, the reduction in element area per vine, (in the lower 40sqft/vine, upper 32sqft/vine) suggests a larger percent wetted area by the emitters relative to element size in the upper block. Terry Prichard, recommends near 40-60% of the soil volume be wetted with irrigation (Prichard, T.) On the surface, emitters point drop water into a vine element, once in a soil the movement of water is then governed by gravity and soil physics. Nevertheless, if an emitter point dropped water into the soil and that point produced a radius of 2ft the area covered by that emitter would equal approximately 12.57sqft, as a percent of the soil area in the upper PN block, a wetted area of approximately 12.57/32 = .39. In the lower block, vine spacing is greater while emitter wetted area is kept constant, but element area increased 12.57/40 = .31. Therefore, poor vineyard design, and lack of percent wetted area maybe contributing to a lack of available water for plant roots within the vine element of the lower block. Wetted area is of a large concern with table and raisin grape growers in the central valley and has been shown as a possible contributing factor, potentially indirect, as having an effect on the canopy shaded area and resulting Kc value. (Burt et al. 2007) However, the need to cross reference this data with soil moisture analysis, and supplemental irrigation amounts is necessary before more than speculation can be drawn from the results.

The Kc models developed from the data collected during this project represent the hindsight conditions of the Trestle vineyard during the 2014 growing season, under the conditions present at that time. If the models are to be adapted to future use, more data is necessary to truth the accuracy of the by block Kc models with the true development of the vines. The models presented here for ETo and Degree Days have been shown to produce accurate results and maybe helpful in future planning or in the determination of vineyard water use from historical averages, as well as a offer a baseline for comparison.

Looking forward to the drought conditions of the future, and impending global climate change, droughts may only become worse. The availability of water may, for coastal farmers, if not all, become a limiting factor and supplemental irrigation a luxury. If this is the case, the ETo model developed in this project could be paired with the Kc curve developed, in the wake of a two year drought, and under non-ideal conditions to adapt the average water use of vines in the San Luis Obispo coastal area for a drought conditioned year. Therefore, while the data collected during this project may be limited in its scope, the conditions of the measurements may represent something of an indication of future developments in the wake of a changing global climate given the conditions of a one in 1200 year drought occurrence during their recording (Science Direct, 2014).

Below are photos of the project during the spring, summer and fall quarters 2014.

Planning and laying out the Paso Panel Design 5/21/14

One of the two Paso Panels, post fabrication, bolted together outside the engineering hangar. 6/5/2014

After completing measurements. 9/29/14

Shaded Area, after measurement, in the PNL block on 9/29/14.

Works Cited

Allen, R.A., Pereira, L.S., Raes D., Smith, M. 1998. “Crop evapotranspiration: guidelines for computing crop water requirements.” FAO Irrigation and Drainage Paper No. 56. FAO, Rome, Italy.

Ayars, J.E., Johnson, R.S., Phene, C.J., Trout, T.J., Clark, D.A., Mead, R.M., 2003. “Water use by drip irrigated late season peaches.” Irrig. Sci. 22, 187–194.

Battany, Mark. "Crop Coefficients - Paso Panel." *University of California Cooperative Extension, San Luis Obispo County*. University of California, n.d. Web. <http%3A%2F%2Fcesanluisobispo.ucanr.edu%2FViticulture%2FPaso_Panel%2F>.

Burt, Charles, and Stuart W. Styles. Drip and Micro Irrigation Design and Management: For Trees, Vines, and Field Crops: Practice plus Theory. San Luis Obispo, CA: Irrigation Training and Research Center, 2007. Print.

"California's Drought Is the Worst in 1,200 Years, Evidence Suggests." ScienceDaily. ScienceDaily, n.d. Web. 09 Dec. 2014. <http://www.sciencedaily.com/releases/2014/12/141205124357.htm>.

Coombe, B.g. "Growth Stages of the Grapevine: Adoption of a System for Identifying Grapevine Growth Stages." *Australian Journal of Grape and Wine Research* 1.2 (1995): 104-10. Web.

de Medeiros, G.A., Arruda, F.B., Sakai, E., Fujiwars, M., 2001. The influence of crop canopy on evapotranspiration and crop coefficient of beans (Phaseolus vulgaris L.) Agric. Water Manage. 49, 211–224.

Lorenz, D.h., K.w. Eichhorn, H. Bleiholder, R. Klose, U. Meier, and E. Weber. "Growth Stages of the Grapevine: Phenological Growth Stages of the Grapevine (Vitis Vinifera L. Ssp.

Vinifera)—Codes and Descriptions According to the Extended BBCH Scale." *Australian Journal of Grape and Wine Research* 1.2 (1995): 100-03. Web.

Peacock, W.L., Williams, L.E., and Christensen L.P. 2000. Water Management and Irrigation Scheduling (PDF). Pages 127-133 in: Raisin Production Manual. University of California, Agricultural and Natural Resources Publication 3393, Oakland, CA.

Peacock, W.L., and Christensen, L.P. 2000. Interpretation of Soil and Water Analysis (PDF). Pages 115-120 in: Raisin Production Manual. University of California, Agricultural and Natural Resources Publication 3393, Oakland, CA

Prichard, T. Vineyard Irrigation Systems (PDF). Pages 57 - 63 in: Raisin Production Manual. University of California Agricultural and Natural Resources Publication 3393, Oakland, CA.

Williams, L., and Araujo, F. 2002. "Correlations among Predawn Leaf, Midday Leaf, and Midday Stem Water Potential and their Correlations with other Measures of Soil and Plant Water Status in Vitis vinifera" *J. Amer. Soc. Hort Sci.* 127(3):448-454.

Williams, Larry. "Determination of Evapotranspiration and Crop Coefficients for a Chardonnay Vineyard Located in a Cool Climate." *Am. J. Enol. Vitic* 2014th ser. 65.2 (2014): n. pag. Print.

Williams, Larry E. "Interaction of Applied Water Amounts and Leaf Removal in the Fruiting Zone on Grapevine Water Relations and Productivity of Merlot." *Irrigation Science* 30.5 (2012): 363-75. Web.

Williams, L.e., and J.e. Ayars. "Grapevine Water Use and the Crop Coefficient Are Linear Functions of the Shaded Area Measured beneath the Canopy." *Agricultural and Forest Meteorology* 132.3-4 (2005): 201-11. Web.

Williams, L.E. 2000. Grapevine Water Relations (PDF). Pages 121-126 in: Raisin Production Manual. University of California, Agricultural and Natural Resources Publication 3393, Oakland, CA.

Williams, Larry E. 2014. “Determination of Evapotranspiration and Crop Coefficients for a Chardonnay Vineyard Located in a Cool Climate.” Am. J. Enol. Vitic. June 2014 65:159-169; published ahead of print January 23, 2014, doi:10.5344/ajev.2014.12104

Williams, L.E., Matthews, M.A., 1990. Grapevine, In: Stewart, B.A., Nielson, D.R. (Eds.), Irrigation of Agricultural Crops – Agronomy Monograph No. 30. ASA-CSSA-SSSA, Madison, WI, pp. 1019–1059.

Wright, J.L., 1985. Evapotranspiration and irrigation water requirements, In: Proceedings of the National Conference on Advances in Evapotranspiration, 16–17 December. ASAE, St. Joseph, MI, Chicago, pp. 105–113.

"XonGrid Interpolation Add-in." XonGrid Interpolation Add-in. N.p., n.d. Web. 11 Dec. 2014. <http://xongrid.sourceforge.net/>.