Irrigation Monitoring and Evapotranspiration Modeling at the UBC Farm

Determining Crop Water Requirements of a Teggia Bean (*Phaseolus vulgaris*)

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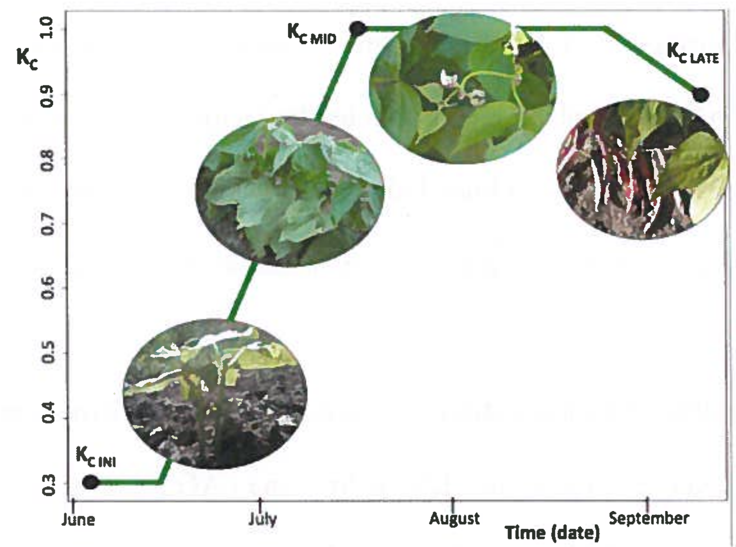
Executive Summary

The efficient use of agricultural water resources is a relevant concern because irrigated agriculture consumes 70% of the world's available freshwater (FAO Water, 2011). Different varieties of crops require different amounts of water to grow. This is known as the *crop water requirement*, and is generally equivalent to the quantity of the water lost through *evapotranspiration* (ET). ET the combined process of evaporation from the soil and transpiration from the plant, and is affected by factors like weather, crop characteristics, and environmental conditions. A knowledge of crop water requirements leads to a better understanding of specific irrigation needs, which allows crop production to be increased (Al-Kaisi, 1993).

The objective of this study was to compare current irrigation practices at the UBC Farm with calculated recommendations from the FAO 56, with an aim to improve irrigation practices and crop yields through more efficient water management. The crop water requirements of a teggia bean (*Phaseolus vulgaris*) field at the UBC Farm, located in B.C.'s Lower Fraser Valley, were determined using FAO guidelines (FAO 56 by Allen et al., 1998). The teggia bean is a horticultural bush bean that matures in approximately 100 days, producing red-yellow pods (Paulsrud, 2011). The teggia crop was planted on June 4th, and irrigated by the Farm staff until Sept. 3rd. Drip irrigation was used, a water-efficient form of irrigation which allows water to be applied directly to the root zone.

The crop water requirements of the teggia bean were calculated based on the FAO 56 Penman-Monteith equation, which requires climate data inputs. The climate data was obtained from the Totem Field Station on the UBC Campus (Black et al., 2011). This model produced a measure of the evaporative demand of the atmosphere, called *Reference ET*

(ET_0). This value of ET was adjusted for the teggia crop using a *crop coefficient* (K_C). K_C reflects the effects of crop characteristics and soil moisture in the root zone (Allen et al., 1998), and produces a measure of ET specific to the crop, called *Crop ET* (ET_C). K_C changes as a function of time as the teggia bean passes through four distinct stages of growth: Initial, Crop Development, Mid-Season, and Late Season (Figure below).



The calculated irrigation requirement was compared with the actual irrigation applied to the crop. According to this study, the crop experienced soil water (SW) deficits during 40% of the growing season. This meant that the crop did not have enough water and became *stressed.* Since wilting was rarely observed, it was concluded that the crop was only mildly stressed during these periods. In the remaining 60% of the crop's lifetime, SW surpluses were experienced, meaning the crop received adequate irrigation. Due to several uncertainties that affected the outcome of this study, further investigation would be required to accurately compare the Farm's irrigation practices with the calculated recommendations.

Recommendations include applying more irrigation during late June and July, when the crop was mildly stressed. Installing a timer on the drip line valve would make irrigation more precise, and decrease the probability of accidental irrigation events.

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List of Symbols, Abbreviations or Other

ET	Evapotranspiration (mm)
ET_0	Reference ET (mm)
K_C	Crop coefficient (unitless ratio)
ET_C	Crop evapotranspiration (mm)
FAO 56	Food and Agriculture Organization Irrigation and Drainage Paper 56
SW or SWS	Soil water storage (mm)
ΔSW	Change in soil water storage (mm)
SWS Capacity	Soil water storage capacity (mm/m)
I	Irrigation (mm)
P	Precipitation (mm)
PAW	Plant available water (mm)
R_n	Net radiation at the crop surface ($MJ/m^2/day$)
G	Soil heat flux density ($MJ/ m^2/day$)
T	Mean daily temperature at a 2 m height (°C)
u_2	Wind speed at a 2 m height (m/s)
e_s	Saturation vapour pressure (kPa)
e_a	Actual vapour pressure (kPa)
$(e_s - e_a)$	Saturation vapour pressure deficit (kPa)
Δ	Slope of the vapour pressure curve (kPa/°C)
γ	Psychrometric constant (kPa/°C)

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Chapter 1: Introduction

1.1 Introduction to Evapotranspiration

Different varieties of crops require different amounts of water to grow. In general, the crop water requirement is the quantity of the water lost through evapotranspiration (ET), the combined process of evaporation from soil and transpiration from plants (Figure 1). ET is

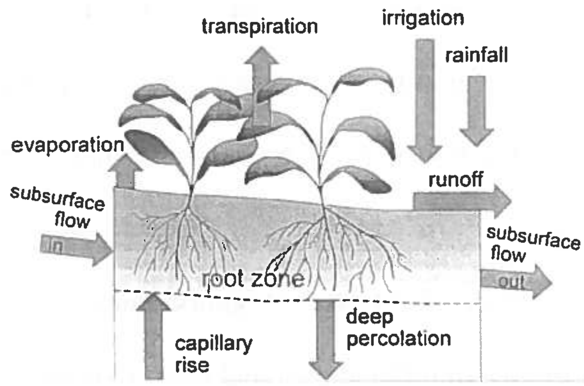

Figure 1. The forms of water transfer experienced by the crop, including evaporation from the soil and transpiration from the plant. (Allen et al., 1998).

controlled by energy exchange at the plant's surface, and is limited by the amount of energy available (Allen et al., 1998). The first component, evaporation, is the process of converting liquid water to water vapour. This vapour is then removed from the evaporating surface into the atmosphere. The heat energy required to change the state of the molecules is provided by solar radiation (Allen et al., 1998). Evaporation occurs from open water, soil, and vegetated surfaces (Ward, 2004). Transpiration occurs in the intercellular spaces of the plant leaf. Water is absorbed by the plant roots, travels up through the xylem, and diffuses into the atmosphere when the stomata open to capture carbon dioxide. The entire exchange is controlled by the stomata during photosynthesis (Allen et al., 1998). Transpiration from the stomata and evaporation from the soil are often combined because of the difficulty in distinguishing between the two forms of water transfer (Ward, 2004). Factors that affect ET include weather, crop characteristics, and environmental conditions.

1.2 Crop Water Requirements

A knowledge of crop water use helps establish a better understanding of specific irrigation requirements (Al-Kaisi, 1993). Growing food requires significant amounts of freshwater, which is why agricultural water management is important for environmental sustainability and efficient use of water resources. Of the total water in the world, only 3% is freshwater. On a world scale, irrigated agriculture is the largest consumer of available freshwater at 70% (FAO Water, 2011). Over-irrigation causes saturated soil conditions, and can result in increased surface runoff and overland flow. Excessive amounts of water can be damaging to the root zone and increase the possibility of root rot (FAO Water, 2011). On the other hand, insufficient irrigation during the initial stages of crop development can have a negative effect on the crop, retarding plant development and causing non-uniform growth (Köksal, 2008). By understanding specific crop water requirements, based on weather, crop characteristics and environmental conditions, irrigation practices can be adjusted accordingly. More efficient irrigation provides a means to optimize plant water use and increase crop production (Al-Kaisi, 1993).

1.3 Crop Development and Irrigation Practices

The teggia bean (*Phaseolus vulgaris*) is a horticultural bush bean that matures in approximately 100 days, producing red-yellow pods (Paulsrud, 2011). For a high percentage of germinating seeds, the soil must maintain a temperature of at least 15°C (FAO Water, 2011). The risk posed by low temperatures is that the beans could rot before germinating or emerge at different times, leading to non-uniform growth and a less efficient harvest (Morgan, 2011). According to Paulsrud (2011), it has a weak, shallow rooting system that is easily injured by close cultivation. Although the tap root may reach 1.0 to 1.5 m in depth, the majority of water uptake occurs in the first 0.5 to 0.7 m (FAO Water, 2011). This type of bean can be harvested green or dry, depending on the use. For fresh shelling, they are to be harvested green, when the pods are firm, crisp, and elongated (Paulsrud, 2011). Dry beans are harvested when the leaves turn yellow. The development of the bean can be divided into five stages: Establishment (10-15 days), Vegetative (25-30 days), Flowering (20-35 days), Yield Formation (5-10 days), and Ripening (0-2 days for green, 14-28 for dry) (FAO Water, 2011; Morgan, 2011).

Drip irrigation (or trickle irrigation/micro-irrigation) is water-efficient form of irrigation, and has a high uniformity of applied water when compared to furrow (Hanson, 1993). Drip lines allow water to be applied directly to the root zone, minimizing water loss due to runoff and deep percolation (Al-Kaisi, 1993). According to Morgan (2011), drip irrigation reduces fungal issues, including the colonization and spreading of fungi throughout the crop, often resulting from perpetual moisture in the foliage and/or fruit. This is especially important in the case of bean crops, which are prone to mildew in humid climates. Factors that influence the time and duration of irrigation include temperature, cloud cover, signs of wilting/turgid plants, symptoms of pest/disease pressure related to soil moisture, proximity of harvest, and soil moisture conditions to a depth of 50 mm (Morgan, 2011).

1.4 Study Objectives

This study focuses on how to improve irrigation practices and crop yields through more efficient water management. The crop water requirements of the teggia bean field will be determined using FAO guidelines (FAO 56 by Allen et al., 1998). The model is based on the FAO 56 Penman-Monteith equation and requires both climate and soil data inputs. The goal is to compare current irrigation practices at the UBC Farm with calculated recommendations from the FAO 56. At the end of the crop's growth, the calculated irrigation requirement will be compared with the actual irrigation applied to the crop by the Farm. This comparison is the key component of the study, because it will reveal the efficiency of the current irrigation methods as compared to FAO 56. The aim is to provide the Farm with additional knowledge about land and water interactions, and to generate new questions for future students interested in agricultural water management.

Chapter 2: Methodology

2.1 Site Description

The UBC Farm is located on UBC's South Campus in the B.C. Lower Fraser Valley (Figure 2). It is situated on the Point Grey plateau, at an elevation of 100 m above sea level (Masselink, 1991). This region of the Fraser Valley is classified by mild winter temperatures,

Figure 2. The UBC Farm on South Campus (blue arrow), the location of the teggia bean (*Phaseolus vulgaris*) crop on the southeastern plot (red circle), and the location of the Totem Field climate station (green arrow). Map of UBC Vancouver. Retrieved on July 28, 2011. http://maps.google.ca/maps

extremely high levels of precipitation, and loamy sand to sandy loam soils (Bertrand, 1991). According to Bertrand (1991), the lowest ever temperature recorded at YVR Airport was –17.8°C, and the average maximum July temperature recorded at UBC is 20.7°C. During the growing season, May to September, the greater part of the valley receives between 250 mm and 350 mm of precipitation (Bertrand, 1991). Despite the frequent rainfall events, there is a possibility of crop water deficiency as sandy soils have poor water retention. This type of soil tends to drain rapidly and to be well aerated (Bertrand, 1991). Most surface drainage occurs in a south to southwest direction along an average land slope of 4%. At the Farm, the majority of the soil is a Bose Podzol with a sandy loam texture (Morgan, 2011). To obtain good nutrient levels, Morgan (2011) states the soil must be well drained, have full sun exposure, and have adequate levels of organic matter (at the Farm, there is 13% - slightly higher than average). The soil must also be slightly acidic, have a balanced composition of micro- and macro- nutrients, and be watered regularly. Ideally, the soil should be kept moist at least 50 mm deep (Morgan, 2011). The crops are grown in rows with bed dimensions of 3 ft across and 1 ft in between rows. Each row extends a horizontal distance of 385 ft (Morgan, 2011).

2.2 Planting and Harvest

On June 4th, 2011 the teggia bean crop was planted in the Farm's southeastern plot (Figure 2) and harvested in mid-September. This planting was considered to be late in the season, and the delay was due to uncharacteristically cold temperatures and high levels of precipitation in the spring. During May, the average temperature was 10.7°C and the total precipitation was approximately 76.8 mm (Black et al., 2011). A single row was double seeded with a 4 to 6 inch drop (approximately 1400 plants), creating an optimal spacing of 2 to 3 inches between plants. The planting was accomplished using a precision seeding tool called the *Earthway Seeder*. This tool is a row crop planted that is pushed along well-tilled soil, allowing for accuracy and efficiency in planting (Rushmere, 2011). The neighbouring crop is onions and the adjacent bed is fallow. Initially the Farm planned to plant a neighbouring cover crop. Cover crops are close-growing forages that are grown to protect the minerals in the soil from leaching, the process of being pulled from the top layer of soil by percolation (Bertrand, 1991). The teggia bean has an expected 100-day development (Table 1). The Farm conducted two harvests, one for green beans and the second for dry beans. To facilitate the growth of the dry beans, irrigation was stopped entirely after September 3, 2011 (Morgan, 2011).

Table 1. Stages of development of teggia bean (*Phaseolus vulgaris*). (Morgan, 2011).

	Stages (number of days)	Green bean	Dry bean
0	Establishment (of plant)	10-15	10-15
1	Vegetative (up to first flower)	25-30	25-30
2	Flowering (including pod setting)	20-35	20-35
3	Yield formation (pod development and bean filling)	5-10	5-10
4	Ripening (of single bean)	0-2	14-28
	TOTAL	60-92 days	74-123 days

The process of harvesting began with initial pickings (Rushmere, 2011). According to Rushmere (2011), every week the ripe bean pods were selectively picked by hand from each plant along the length of the row. Beans that were not yet ripe enough were left on the plant. In the sessions following, more ripe beans were removed from the plant, until finally the entire plant was pulled up. The bean pods were stripped from the plant and the remaining plant material was composted. Each year the Farm staff may vary their harvesting practice, depending on the weather and other considerations.

2.3 Current Irrigation Practices

The teggia bean field was irrigated using drip irrigation, which is more water efficient than overhead irrigation. This type of water application is also called micro-irrigation or trickle irrigation, and allows a high degree of water control (Al-Kaisi, 1993). The teggia bean crop relies on surface drip, where the drip line is run along the length of the crop row, alongside plant stems. The water drips from the line and infiltrates slowly at closely placed intervals. The Farm uses the John Deere T-Tape drip line, of the 700 series, with a thickness of 6 mm and an emitter spacing of 20 cm (T-Tape Drip Tape, 2011). Water flows from the drip line at a rate of approximately 210 lph/100 m of drip line. As the length of the crop row is 117 m, this means that the flow rate of the entire drip line is 245.7 lph. The *wetting width* is the surface area of the soil wetted by the drip holes, and may be estimated as 2/3 of the total row width (0.9144 m). Thus, the *wetting area* becomes 71.32 m^2 and the velocity of flow from the line is 0.003445 m/hr. Total irrigation was obtained by multiplying flow velocity by irrigation duration. The Farm typically irrigates for 1 to 2 hours per day, once weekly in June. In July and August, mean daily temperatures peak around 17ºC (Masselink, 1991), when the Farm irrigates 2 to 3 times per week, typically in the early morning or evening.

The teggia crop was irrigated under the direction of the Farm staff. Factors that influence the time and duration of irrigation include temperature, cloud cover, signs of wilting/turgid plants, symptoms of pest/disease pressure related to soil moisture, proximity of harvest, and soil moisture conditions to a depth of 50 mm (Morgan, 2011). The system is turned on from the *irrigation pit*, a white-fenced section of the field beside the southeastern plot. Water flows from the main piping to all of the lines which feed various crop rows, the teggia beans included. The position of the holes allow the soil to be wetted uniformly in circular shapes that merge to ensure full wetting. The Farm staff recorded the details of the irrigation on a chart provided to them, which remained in a waterproof container beside the crop row. These details included date, time, start of irrigation, end of irrigation, irrigation duration, and other notes. See Appendix A for sample of the irrigation recording chart. This information, combined with the irrigation flow rate, allowed the calculation of the total water applied by irrigation per day.

2.4 Crop Evapotranspiration Calculations

2.4.1 Reference Evapotranspiration

ET is affected by factors like radiation, air temperature, air humidity, wind speed, and vapour pressure deficit. Vapour pressure deficit is the air pressure gradient that acts as the main driving force for evaporation (Ward, 2004). All of these components are combined in the Penmnan-Montheith equation to determine the ET rate. Reference ET (ET_0) is the amount of ET from a grass or alfalfa reference crop with the following specific criteria: an extensive surface of green, well-watered grass of uniform height, completely shading the ground (Allen et al., 1998). The result is a measure of the evaporative demand of the atmosphere, unaffected by soil and crop characteristics, called ET_0 (Figure 3). There are many methods for calculating ET_0, and it can be determined from meterological data or pan evaporation. In pan

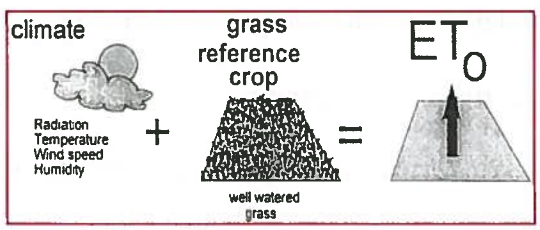

Figure 3. Climatic parameters are combined with grass reference crop characteristics to produce Reference ET. (Allen et al., 1998).

evaporation, the evaporation rate from water surface is estimated. The Food and Agriculture Organization of the United Nations Irrigation and Drainage Paper 56 (FAO 56) recommends the Penman-Monteith equation for its accurate performance in both arid and humid climates. The FAO 56 Penman-Monteith method allows the computation of ET_0 from meterological

$$ET_0 = \frac{0.408(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$$

Equation 1. FAO 56 Penman-Monteith equation.

data (Allen et al., 1998). See Equation (1). Using this method, ET_0 was calculated on 10-day averages. There are many components involved in this calculation. R_n is the net radiation at the crop surface ($MJ/m^2/day$), G is the soil heat flux density ($MJ/m^2/day$), T is the mean daily temperature at a 2 m height (°C), u_2 is the wind speed at a 2 m height (m/s), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), $(e_s - e_a)$ is the saturation vapour pressure deficit (kPa), Δ is the slope of the vapour pressure curve (kPa/°C), and γ is the psychrometric constant (kPa/°C). A complete list of sub calculations may be found in the FAO 56 guidelines. G was assumed to be zero for the daily time steps.

The data required for this calculation includes location (altitude and latitude), temperature, humidity, radiation, and wind speed. These were obtained from the Totem Field Weather Station on the southwest UBC Campus (Figure 2), courtesy of the Biomet Group (Black et al., 2011). The Totem Station has a variety of instruments used to measure various climate parameters. A complete list of the equipment used at the Station can be found in Appendix B. The data is recorded to a PC program using a data logger attached to a PC computer (Grant, 2011). In-house software is used to pull out the data in columns, average the data half-hourly, and write it to a database. According to Grant (2011), the data is cleaned manually, with spikes removed visually and gaps filled using data from YVR (Vancouver International Airport).

Pressure data was taken from Buckley Bay, Vancouver Island. At this location, just south of Courtenay, the Biomet personnel have a flux site which provided daily air pressure values. This data is also recorded on half-hour intervals. The pressure differences between Buckley Bay and YVR were assumed to be minimal because these sites are at a similar elevation and latitude.

Solar radiation increases during the day, and it is a key component of R_n, which appears in Equation (1). Minimal ET occurs without solar radiation, and thus night-time ET was assumed to be negligible. The data was manipulated in Microsoft Excel to eliminate pre-sunrise and post-sunset. This was done by selecting the average sunrise time (6:00) and sunset time (20:30) for the months of June to mid-September, and deleting all rows of values between 12:00 – 6:00 and 20:30 – 11:30 in a given day. This allowed most of ET to be captured, considering only the sunlight hours of the day when, on average, radiation levels reached higher than 0.001 MJ/m^2. Aquatics Informatics Aquarius version 2.7 was used for time series analysis. In Aquarius, important values such as maxima, minima, and means were calculated for certain climatic parameters. Data examined includes pressure, maximum and minimum air temperature, wind speed, max and min relative humidity, solar radiation, etc. See Appendix C for the completed climate data tables.

The now-simplified climatic data from Totem Station was combined with the FAO 56 guidelines to compute ET_0. These calculations were carried out through coding, using a program called *R for Statistical Computing* (R Development Core Team, 2011). See Appendix F for the complete version of the Reference ET code.

2.4.2 Crop Evapotranspiration

ET_0 is merely a measure of the evaporative demand of the atmosphere, and it does not represent the ET that would occur from a distinct crop, like the teggia bean. A common methodology is to adjust the Reference ET for a particular crop using a crop coefficient (K_C). The crop coefficient is an experimentally determined ratio that allows the estimate of ET for crops other than alfalfa at various stages of growth (Wright, 1982). These coefficients are used to simulate soil moisture in the crop root zone and to integrate the effects of characteristics that distinguish field crops from grass (Allen et al., 1998). They are used to estimate the actual water use for a particular crop, based on the Reference ET for a specific climate (Wright, 1982).

Crop coefficients for a specific crop change as a function of time, as the crop passes through various stages of growth (Wright, 1982). The teggia bean passes though four stages of growth that require different values of crop coefficient (Figure 4). These stages include Initial, Crop Development, Mid-Season, and Late Season (Allen et al., 1998). For the teggia

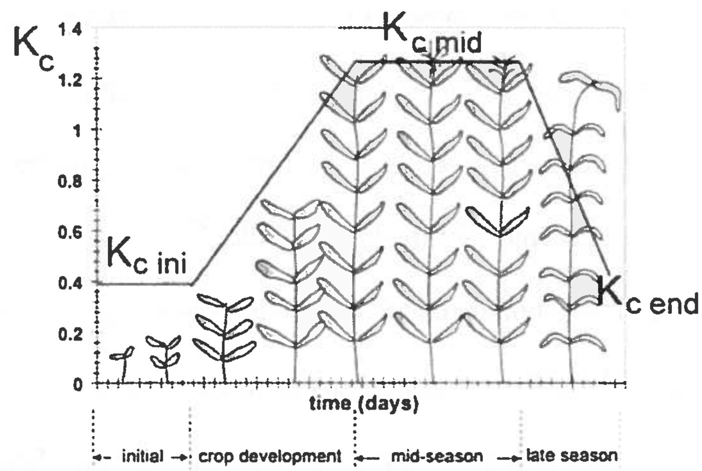

Figure 4. The value of Kc changes as a function of time over the crop's growth. FAO Water (2011).

crop, these stages were identified through bi-weekly observations. Every 3 to 4 days the Farm was visited and the crop characteristics were observed. These included plant height, number of leaves, fraction of flowering plants, number of pods, and other characteristics. See Appendix D for a copy of the chart used to record observations of the teggia crop. These observations allowed the distinct stages of growth of the teggia bean to be identified.

The values for the crop coefficients were taken from literature. There were several options, as no data could be found pertaining to this specific crop, climate, and soil characteristics. The FAO 56 provides crop coefficient values for the common bean for the climate of California (Table 3). The combination of the literature values and the observed growth stages allowed the construction of the K_C curve, specific to the teggia crop.

Table 2. Crop coefficient values from FAO 56 guidelines (California). (Allen et al., 1998).

	Stages of Development					Plant Date
Crop Characteristic	Initial	Crop Development	Mid-Season	Late Season	Total	Aug/Sept
Stage length (days)	15	25	25	10	75	
Rooting Depth (m)	0.3	>>	>>	1.0		
Crop Coefficient, K_C	0.5	>>	1.05	0.9		

Once the timeline of the crop's development was constructed, the appropriate K_C value was applied to the ET_0. The K_C operates on ET_0 to produce a measure of ET specific to the crop, the Crop ET (ET_C). See Equation (2).

$$ET_C = K_C ET_0$$

Equation 2. Crop ET is a product of Kc and ET_0.

As ET_O was calculated on a daily basis, ET_C was also calculated in daily time steps. For each successive stage of the crop's growth, the corresponding K_C value was applied. During the Crop Development stage, the value of K_C increases linearly over time from $K_{C.INI}$ to $K_{C.MID}$. Then, during the Late Season stage, the crop coefficient decreases linearly from $K_{C.MID}$ to $K_{C.LATE}$. Thus, ET_C is directly related to the development cycle of the crop. The result is a daily measure of how much water was lost from the teggia crop through ET.

2.5 Soil Water Balance

The soil water balance of a given area is determined by precipitation, ET, and the water-holding capacity of soil (Bertrand, 1991). When additional water was applied through irrigation, this was factored into the balance as a positive input (like precipitation). The soil water storage (SWS) is the total amount of water that is stored in the soil within the plant's root zone (Nyvall, 2002). Both the type of soil the crop is growing in and the mature rooting depth of the crop determine the SWS. Crops with deeper rooting depths penetrate further into the ground for water, giving the crop more water to draw upon between irrigation events (Nyvall, 2002). When the water applied to the crop exceeds the total SWS, the result may be water loss through surface runoff (if the soil is already saturated) or deep drainage.

For this study, a simplified soil water balance was considered, involving irrigation (I, mm), precipitation (P, mm), evapotranspiration (ET_C, mm), and the change in soil water content (ΔSW, mm). See Equation (3).

$$\Delta SW = I + P - ET_C$$

Equation 3. The soil water balance combines irrigation (mm), precipitation (mm), and ETc (mm).

Values for ET_C, I and, P were previously calculated/collected. The SWS was calculated according to water conservation guidelines presented by the B.C. Ministry of Agriculture, Food and Fisheries. Using this method, the SWS was equivalent to the rooting depth multiplied by the SWS capacity. See Equation (4).

$$SWS = Rooting\ depth * SWS\ capacity$$

Equation 4. The soil water storage (SWS) is a product of rooting depth (m) and SWS capacity (mm/m).

According to the B.C. Ministry of Agriculture (2002), the mature rooting depth of a common bean crop is 0.6 m, and the SWS capacity of sandy loam soil is 125 mm/m. This produced a value for SWS of 75 mm at maturity. This represents the total amount of water that can be stored in the crop's mature root zone, and any additional water may be lost to drainage. The balance was calculated on a daily basis using Microsoft Excel. See Appendix E for a complete version of the soil water balance.

2.6 Irrigation Analysis

The soil water balance provides a daily knowledge of crop water requirements. On days when the water applied (though P and I, as well as any remaining water in the soil, ΔSW) exceeded water lost (though ET_C) then it means the crop was well hydrated. As long as the amount of water in the crop's root zone did not exceed the total SWS (75 mm), then no water was lost to drainage and the plant was in a healthy condition. If the water applied was less than the water lost through ET_C, then the crop suffered from a water deficit on that given day.

Through this system of the soil water balance, results were obtained on a daily basis which indicate if the plant received an adequate amount of water. Days when the crop suffered from over-/under-watering were revealed, and the results produced by the balance may be indicators of the Farm's irrigation efficiency. Overall, the calculated crop water requirement was compared to the amount of water required by the Farm's irrigation practices. This comparison is the key component of the study because it allows the efficiency of the irrigation methods to be evaluated, and to explore ways of improving these methods.

Chapter 3: Results

The growing season of the teggia bean (green harvest) was taken to be June 4th to September 3rd (92 days), when irrigation was cut off. During this period, the maximum and minimum temperatures recorded were 27.17 °C and 10.43 °C, respectively, and occurred in mid-August (Figure 5). Mean air temperature increased gradually over the summer before falling sharply in early September. ET_C was generated in 10-day increments, and increased gradually until mid-July when the crop entered the Mid-Season stage.

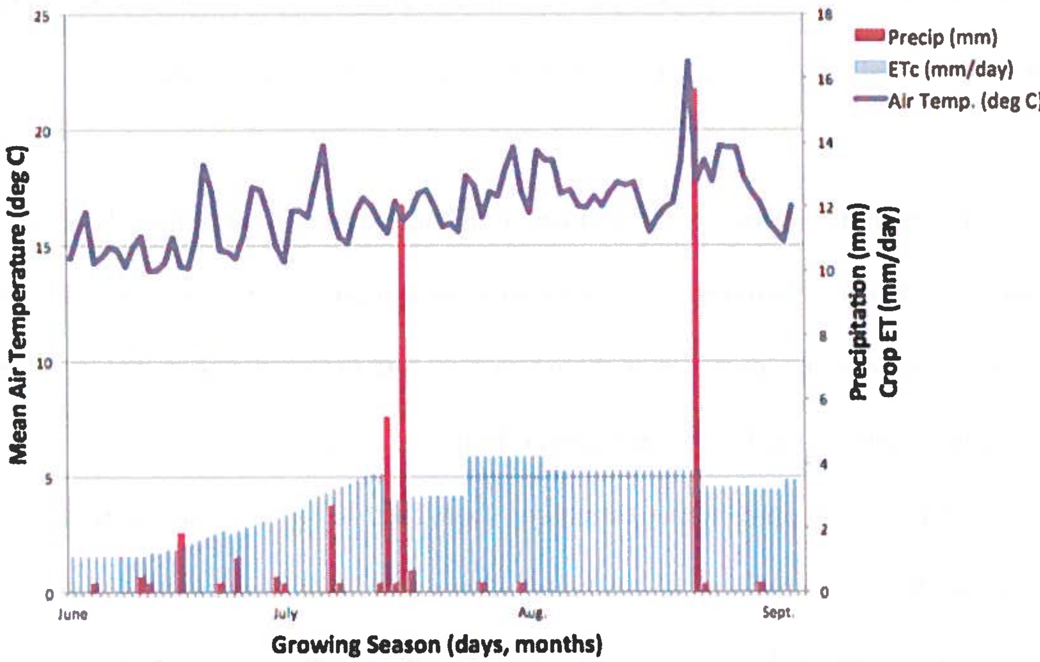

Figure 5. The mean air temperature, precipitation, and crop evapotranspiration (ET_C) over the 92-day growing season.

The solar irradiance ranged from 17.91 MJ/m^2 in early June, to 3.56 MJ/m^2 in late August. The maximum relative humidity (RH_{max}) of 97.4% occurred in late August and the minimum (RH_{min}), 36.3%, in early July. The pressure data was collected from the Buckley Bay climate station, on Denman Island, B.C. For the complete tables of climatic data, see Appendix C.

The K_C values for the common green bean may be found in Table 4. Together this data generated the K_C curve (Figure 6). During the Initial stage, the crop grew to a height of about 8 cm. During Crop Development, the crop grew to about 25 to 50 cm tall. The peak height of 75 cm was reached during the Mid-Season, when the flowering occured and yield formation began (FAO Water, 2011). Pod filling occured during the Late Season, and the plant drooped to about 70 cm in height.

Table 3. The Kc values and growth stage durations for the teggia bean (*Phaseolus vulgaris*) were estimated from FAO 56 data for common green beans.

Growth Stages	Stage Duration (days)	K_C
Initial	12	0.3
Crop Development	32	–
Mid-Season	40	1.0
Late Season	8	0.9
Total	92	–

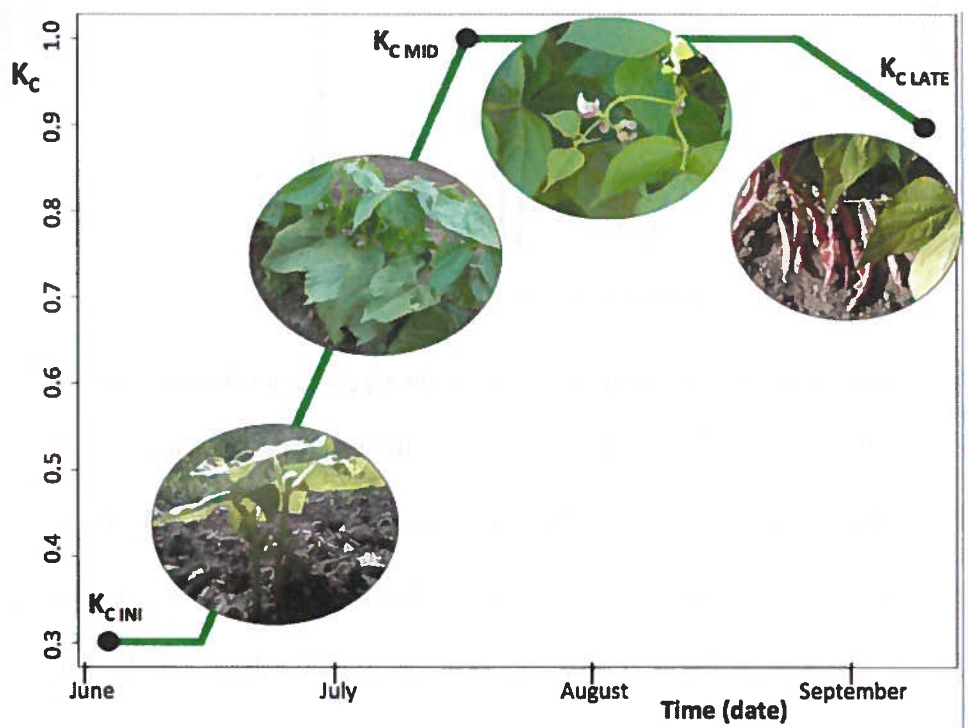

Figure 6. The K_C curve for the teggia bean (*Phaseolus vulgaris*) with images showing the plant development at each stage.

On August 6th, the irrigation was left on overnight for approximately 24 hours. This spike in irrigation may be noted in Figure 7. As well, two large rainfall events occurred with 12 mm of precipitation on July 16th, and 15.6 mm on August 22nd. These precipitation events are both smaller in magnitude than the irrigation spike. In Figure 7, the K_C curve is plotted against time along with irrigation (mm) and precipitation (mm). The crop was more heavily irrigated during the Mid-Season stage, during late July and August.

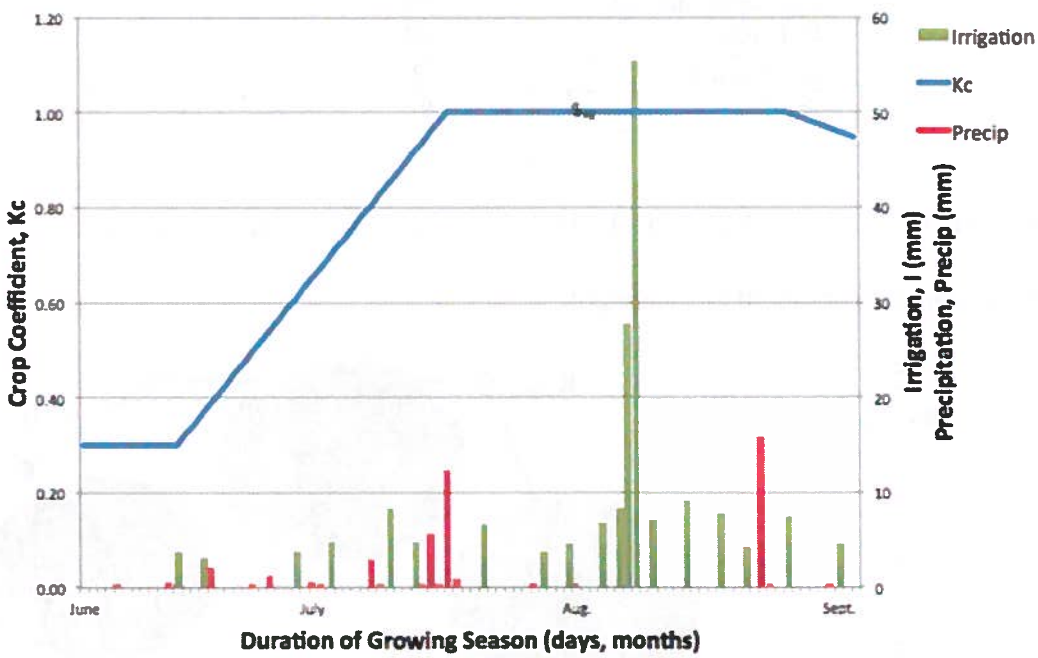

Figure 7. Irrigation and precipitation events during the teggia bean (*Phaseolus vulgaris*) growing season (92 days).

Small SWC deficits occured throughout the growing season, and were represented as negative values (Figure 8). From plant emergence (June 11th) onwards, these deficits corresponded to plant water stress conditions. This means that there was inadequate water available to the plant in the rooting zone, as determined by the methods in this study. SWC deficits were small during June and July, when the mean air temperature was low. Large spikes corresponded to the 24-hour irrigation incident, occurring on August 6th and 7th, and its effects on the SWC for the remainder of the growing season. This irrigation event caused a large amount of water to be added to the plant root zone. This corresponds to a large, positive increase in ΔSWC.

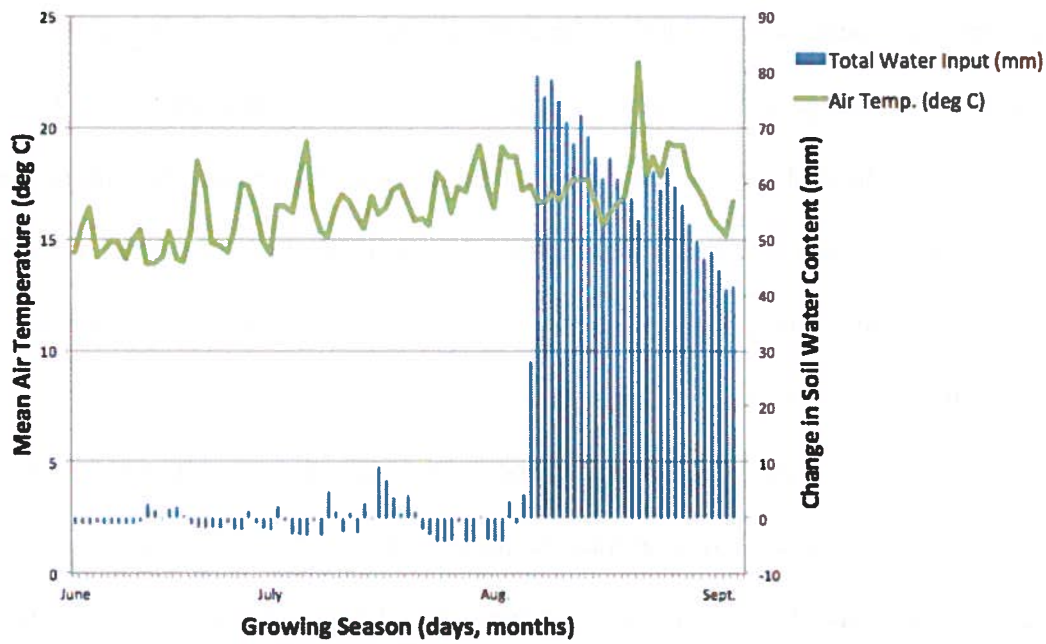

Figure 8. The change in soil water content, ΔSWC, and mean air temperature over the growing season.

Chapter 4: Discussion

The Soil Water Balance combined water input and output to determine if the teggia crop received adequate water during the growing season. In Figure 8, the ΔSW was examined to determine when periods of plant water stress exist. According to this study, the crop was classified as "stressed" on 36 days out of the 92 day growing season. This result implied that the plant did not receive enough water during 40% of its lifetime. Yet, there were other aspects to be considered, like *how stressed* was the crop? And, how does this result compare to the Farm's methods of identifying plant stress?

This study shows that SW deficits occured frequently, even though they were small in relation to SW surpluses. For example, the maximum recorded SW deficit was – 4.20 mm of water, which occured on 6 different days during late July and early August. The temperature ranged from 20.46°C to 22.80°C during this period, thus it was not surprising that a small SW deficit occured. If the effects of the accidental irrigation event are not considered, the maximum SW deficit was 45% of the maximum SW surplus (+9.10 mm, occurring on July 16th). Considering the accidental irrigation event, the largest SW deficit was only 5.30% of the maximum SW surplus (+79.31 mm, occurring on August 7th). Thus, the SW deficits were proportionally small when compared to the SW surpluses. According to this study, even though the plant was frequently classified as "stressed", the level of stress experienced was relatively mild. Since crop yields decline when the plant is stressed, the results of this study imply a marginally reduced crop yield.

Although it appears that the plant was "stressed" over a large portion of the growing season, it is important to consider the Farm's methods for identifying plant stress. According to Morgan (2011), the Farm aims to limit plant stress by irrigating depending on temperature, cloud cover, signs of wilting, among other factors. The most common symptom of plant water stress is wilt (Pearson et al., 2003), which was rarely observed for the teggia crop. This important observation implies that the crop was not stressed very frequently, and thus crop yields would not have been noticeably reduced.

The results of the comparison between the calculated irrigation requirements (in accordance with the FAO 56 guidelines) and the Farm's irrigation methods, were affected by several uncertainties. The main uncertainties lie in the calculation of the Soil Water Balance, caused by gaps in knowledge regarding soil drainage and crop rooting depth. A more accurate estimate of ΔSWC could be determined if the soil water drainage and the height of the water table was known. According to Evans (1996), the effective rooting depth increases as the crop grows, until the reproductive stage is reached. After this, the depth remains relatively constant (Evans, 1996). It was estimated that the rooting depth increased linearly from planting (June 4th) until flowering (July 18th). At this point it reached its mature rooting depth of 75 mm. These assumptions may have affected the plant water stress analysis. If the rooting depth was actually greater than calculated on a given day, the plant may have been classified as "stressed" when, in fact, there was enough plant available water (PAW). This estimation could be improved given more information about the teggia rooting depth behavior.

The FAO 56 K_C values taken for this study (Table 4) affect the results considerably, because K_C is used to adjust ET_0 for the teggia bean crop. The uncertainty associated with ET_C would have been decreased if this analysis was performed using closely tabulated K_C values, specific to the teggia bean in B.C. or Washington state. Daily ET_C is one of the primary components in the Soil Water Balance, and differences greater than ± 0.01 mm will affect the irrigation analysis.

The K_C curve for the teggia crop (harvested green) was terminated post-irrigation (Sept. 3rd). This may have affected the slope and length of the curve during the Late Season stage. The Late Season was estimated to have begun on August 27th, marked by the senescence of leaves, often beginning with the lower leaves of the plant (Allen et al., 1998). The curve would typically be extended until crop harvest, but this analysis does not consider the Soil Water Balance post-irrigation.

Totem Field station does not record atmospheric pressure, so pressure data was retrieved from Buckley Bay climate station, near Comox, B.C. The gaps in the data were filled using the FAO 56 equation for atmospheric pressure. The site elevation is about 26 m above sea level (Gladstone, 2011), while the elevation of Totem Field station is 104 m. Thus, there are minimal differences between sites in elevation and environment. To compare, the mean pressure recorded at Buckley Bay from June to Sept. 2011 was 99.82 kPa, and the 2010 equivalent from YVR (Vancouver Airport) was 100.07 kPa. As ET_C was only calculated to two significant figures, the effect of this discrepancy is very small. In general, air pressure is less sensitive to these differences than other climatic parameters. To alleviate this difference, pressure data could be taken instead from YVR for a cost of CAD$50 -100.

Even though Totem station is less than 2.0 km away from the UBC Farm, differences in elevation and environment between these sites may have affected other climatic parameters. During bi-weekly crop observations, it was noted that the teggia crop was downwind of another furrow-irrigated plot. The increased amount water in the air (or the increased RH) may have affected the air temperature, and thus the vapour pressure, in the proximity of the teggia crop. These fluctuations would not have been captured by Totem Field station, and thus ET_C was not adjusted during these periods. Again, the discrepancy is small because ET_C was calculated to two significant figures. This problem could be remedied by measuring all climatic parameters above the crop canopy. This would involve gages and sensors being installed along the crop row.

Chapter 5: Conclusion and Recommendations

Overall, the results of this study indicate that the teggia crop experienced SW deficits during approximately 40% of its growing season. During these periods, the water output exceeded the water input, and the crop did not have access to enough PAW. This indicated that the crop was "mildly stressed". Yet, when compared to the Farm's irrigation practices, it appears that the crop did not undergo observable stress, and that the crop yield was not noticeably affected.

Several uncertainties affected the outcome of this study, including gaps in knowledge regarding soil drainage, crop rooting depth, K_C values specific to crop and region, K_C curve trend during the Late Season, and spatial differences between the sites involved (UBC Farm, Totem Field, and Buckley Bay). Given these unknowns, it was difficult to compare the results of this study with the Farm's irrigation practices. Further investigation into these uncertainties would allow a more accurate comparison to be made, and may generate recommendations for future irrigation practices.

The results of this study, although associated with numerous uncertainties, indicate that in the future the Farm could apply more irrigation during late June and July, when the bulk of the SW deficits occured. This would alleviate the mild plant stress during these periods, according to the calculated model. Another recommendation is to use an alternative method to measure ET_0, like pan evaporation. A standardized pan could be placed in the field, and in the absence of rain, the amount of water evaporated corresponds to the decrease in pan water depth (Allen et al., 1998). A possible choice is the Class A pan, 120.7 cm in diameter and 25 cm deep, made of galvanized iron (Allen et al., 1998). This would provide an accurate measure of ET_0, as the pan could be mounted on the soil next to the teggia crop, reducing the effects of geographic differences between the Farm and Totem Station. A final recommendation is to improve irrigation efficiency by installing a timer on the drip line valve. This would allow precise irrigation durations to be selected and accidental irrigation events would be less likely to occur. This said, the irrigation event that occurred on August 6th and 7th appeared to benefit the crop, according to this study.

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Appendices

Appendix A Irrigation Recording Chart

irrigation system pressure – 96 psi

[0.27 gal/min per 100 ft] flow rate

Irrigation Monitoring at the UBC Farm - SUMMER 2011

Main contact: Michael [illegible]
Contact information: email [illegible] tel [illegible]

Objective: To track irrigation practices of a bean field over the growing season. Irrigation practices will then be compared to crop water requirements calculated from meteorological data.

Guidelines used: Food and Agriculture Organization, Irrigation and Drainage Paper 56
Available online: [illegible]

Steps:
1. Please fill in the necessary information (Date, time of day)
2. Turn on drip irrigation system, start timer or record time at which the irrigation was turned on
3. Turn off irrigation, stop timer or record time at which the irrigation was turned off
4. Record duration of irrigation
5. Make any observations regarding issues with irrigation if any (damage to lines, changes in flow rate)

Bean plant date: JUNE 4th/11

Shoot emergence: JUNE 11th/11 — Please note the date when majority of shoots emerge

GREEN CROP
JUNE 4th → SEPT 3rd

Date	Time	Start of irrigation	End of irrigation	Irrigation duration	Irrigation flow rate (enter units)	Notes (damage, issues, etc.)
JUNE 14	4:00	4:00	5:00	1h		
JUNE 17	3:00	3:00	3:50	50 min		
JUNE 28	11:00	11:00AM	12:00	1h		
JULY 2	1:25	1:25 PM	2:45 PM	1h 20 min		
JULY 9	2:00	2:00	4:20	2h 20 min		
JULY 12	3:00	3:00 PM	4:20	1h 20 min		
JULY 20	3:30	3:30 pm	5:20 p	1h 50 m		
JULY 27	2:30	2:30 PM	3:30 PM	1h		
JULY 30	3:25	3:25 PM	4:40 PM	1h 15 min		
AUG 3	3:15	3:15 PM	5:10 PM	1h 55 min		
AUG 5	10:00A	10:10 AM	12:30 PM	2h 20m		
AUG 7	4:00 p	?	4:00 PM	→		IRRIGATION WAS ON OVERNIGHT (unknown start)
AUG 9	2:20	2:20 pm	4:20 PM	2h		
AUG 13	2:10	2:10 pm	4:45 pm	2h 35m		
AUG 17	3:10	1:10 pm	3:20 pm	2h 10m		
AUG 20	2:45	2:45 pm	3:55 pm	1h 10 m		

Irrigation Recording Chart *cont…*

Date	Time	Start of irrigation	End of irrigation	Irrigation duration	Irrigation flow rate (L/min)	Notes (damage, issues, etc.)
AUG 25	4:45	2:10 ~~4:15~~	4:15	2h 5m		
AUG. 31	11:55	11:55	2:10	2h 15m		
SEPT. 3	10:35	10:35	11:45	1h 10m		

Appendix B List of equipment used at Totem Field Station

UBC Totem Climate Station					
Instrument	**Serial #**	**Parameter**	**Units**	**Height**	**Location**
Licor Solarimeter		Incoming Solar	W/m^2		Tower
RM Young Anemometer		Wind speed	m/s		Tower
		Wind direction	degrees		Tower
Vaisala HMP		Temp	deg C		S. Screen
		RH	%		S. Screen
SR50 Snow depth sensor		Snow depth	cm		Tower
Rain Gauge		Rain Fall	mm		Ground
Thermocouple Air	UBC	Air Temp	deg C		Tower
Thermocouple Air	UBC	Air Temp	deg C		S. Screen
Thermocouple Soil	UBC	Soil temp	deg C	-10 cm	Ground
Thermocouple Soil	UBC	Soil temp	deg C	-20 cm	Ground
Thermocouple Soil	UBC	Soil temp	deg C	-40 cm	Ground

Grant, N. (2011). Totem Field Station. In personal communication with B. Moore. Vancouver.

## Appendix C	Full table of climate data from Totem Station

Variable description: RH_{min} is the minimum relative humidity, RH_{max} is the maximum relative humidity, RH_{mean} is the mean relative humidity, T_{max} is the maximum air temperature, T_{min} is the minimum air temperature, $T_{air.mean}$ is the mean air temperature, R_n is the net solar radiation, u_2 is the wind speed at 2 m above ground surface, e_s is the mean saturation vapour pressure, e_a is the actual vapour pressure, Vap.deficit is the vapour pressure deficit (e_s - e_a), ET_0 is the reference ET, and Precip is the precipitation.

Date	RHmin	RHmax	RH.mean	Tmax	Tmin	Tair.mean	Rn	u2	es	ea	Vap.deficit	ETO	Precip
0011-06-04	64.29	85.4	74.8	17.59	11.31	14.4	17.91	4.43	1.67	1.22	0.45	3.76	0
0011-06-05	61.74	83.5	72.6	17.93	13.06	15.5	16.37	3.74	1.78	1.26	0.52	3.76	0
0011-06-06	67.85	86.5	77.2	18.74	14.04	16.4	17.8	2.68	1.88	1.42	0.46	3.76	0
0011-06-07	56.01	77.3	66.7	16.85	11.54	14.2	12.12	2.32	1.64	1.06	0.58	3.76	0.2
0011-06-08	61.44	84.3	72.9	17.79	11.24	14.5	13.8	3.14	1.68	1.19	0.49	3.76	0
0011-06-09	70.9	84.3	77.6	16.49	13.34	14.9	9.78	2.79	1.7	1.31	0.39	3.76	0
0011-06-10	63.55	86.7	75.1	16.75	12.76	14.8	10.65	2.86	1.69	1.24	0.45	3.76	0
0011-06-11	67.69	76.55	72.1	16.29	11.82	14.1	14.37	2.35	1.62	1.16	0.46	3.76	0
0011-06-12	58.66	81.1	69.9	17.91	11.82	14.9	15.32	2.61	1.72	1.16	0.56	3.76	0
0011-06-13	59.47	93.4	76.4	19.11	11.77	15.4	10.42	2.34	1.8	1.3	0.5	3.76	0.4
0011-06-14	58.59	82.2	70.4	16.05	11.77	13.9	9.04	2.48	1.6	1.1	0.5	3.9	0.2
0011-06-15	59.42	81.02	70.2	16.92	10.95	13.9	17.9	2.73	1.62	1.1	0.52	3.9	0
0011-06-16	53.92	76.3	65.1	17.53	10.94	14.2	16.9	2.27	1.66	1.04	0.62	3.9	0
0011-06-17	49.6	73.4	61.5	18.7	11.9	15.3	16.14	3.22	1.78	1.05	0.73	3.9	0
0011-06-18	72.14	95.2	83.7	16.56	11.56	14.1	9.89	2.58	1.62	1.33	0.29	3.9	1.8
0011-06-19	68.67	94.5	81.6	16.09	11.96	14	7.203	3.34	1.62	1.29	0.33	3.9	0
0011-06-20	63.72	87.4	75.6	17.95	12.89	15.4	11.76	1.68	1.78	1.31	0.47	3.9	0
0011-06-21	44.65	76.5	60.6	21.92	15.06	18.5	16.06	1.83	2.17	1.24	0.93	3.9	0
0011-06-22	59.23	81.8	70.5	20.51	14.13	17.3	16.78	3.68	2.01	1.37	0.64	3.9	0
0011-06-23	47.59	85.5	66.5	18.32	11.28	14.8	14.18	2.91	1.72	1.07	0.65	3.9	0.2
0011-06-24	58.91	81.95	70.4	16.78	12.67	14.7	14.65	1.72	1.69	1.16	0.53	3.66	0
0011-06-25	57.66	94.2	75.9	17.01	11.7	14.4	14.12	1.55	1.66	1.21	0.45	3.66	1
0011-06-26	49.01	84.9	67	18.98	11.82	15.4	15.78	1.37	1.79	1.13	0.66	3.66	0
0011-06-27	59.3	89.5	74.4	19.74	15.33	17.5	8.45	2.1	2.02	1.46	0.56	3.66	0
0011-06-28	68.24	87.37	77.8	18.8	15.99	17.4	7.811	2.21	2	1.54	0.46	3.66	0
0011-06-29	61.65	88.7	75.2	18.57	13.95	16.3	9.97	2.94	1.87	1.36	0.51	3.66	0
0011-06-30	53.62	77.4	65.5	17.48	12.26	14.9	11.59	1.88	1.72	1.09	0.63	3.66	0.4
0011-07-01	56.15	79.7	67.9	17.2	11.4	14.3	9.91	2.93	1.66	1.09	0.57	3.66	0.2
0011-07-02	40.4	85.03	62.7	21.56	11.35	16.5	15.76	1.84	1.96	1.09	0.87	3.66	0

Full table of climate data from Totem Station *cont…*

Date	RHmin	RHmax	RH.mean	Tmax	Tmin	Tair.mean	Rn	u2	es	ea	Vap.deficit	ET0	Precip
0011-07-03	54.16	93.3	73.7	19.16	13.76	16.5	16.79	2.03	1.9	1.33	0.57	3.66	0
0011-07-04	44.35	82.6	63.5	20.94	11.39	16.2	17.1	1.51	1.92	1.11	0.81	4.09	0
0011-07-05	36.3	80	58.2	22.71	12.74	17.7	16.92	1.31	2.11	1.09	1.02	4.09	0
0011-07-06	50.31	85.8	68.1	23.75	14.78	19.3	17.31	1.38	2.31	1.46	0.85	4.09	0
0011-07-07	66.85	93.6	80.2	18.85	13.86	16.4	8.016	1.36	1.88	1.47	0.41	4.09	2.6
0011-07-08	54.79	79.14	67	17.48	13.06	15.3	14.41	2.29	1.75	1.14	0.61	4.09	0.2
0011-07-09	53.02	77.6	65.3	18.54	11.71	15.1	17.14	2.16	1.76	1.1	0.66	4.09	0
0011-07-10	44.59	80.5	62.5	20.38	12.4	16.4	14.3	1.51	1.92	1.11	0.81	4.09	0
0011-07-11	46.01	78.3	62.2	20.07	14.03	17	12.33	1.48	1.98	1.17	0.81	4.09	0
0011-07-12	65.66	83.71	74.7	18.81	14.64	16.7	11.27	2.03	1.92	1.41	0.51	4.09	0
0011-07-13	67.12	92.35	79.7	18.36	13.71	16	10.11	3.12	1.84	1.43	0.41	4.09	0.2
0011-07-14	76.4	95.9	86.2	17.7	13.37	15.5	8.007	2.66	1.78	1.51	0.27	2.99	5.4
0011-07-15	62.73	89.6	76.2	19.31	14.44	16.9	8.03	2.89	1.94	1.44	0.5	2.99	0.2
0011-07-16	84.68	95.3	90	17.62	14.56	16.1	4.634	1.54	1.84	1.65	0.19	2.99	12
0011-07-17	74.9	94.44	84.7	17.86	14.89	16.4	8.41	1.51	1.87	1.57	0.3	2.99	0.6
0011-07-18	69.88	95.2	82.5	19.47	14.85	17.2	12.34	1.39	1.98	1.59	0.39	2.99	0
0011-07-19	59.66	93.7	76.7	20.61	14.21	17.4	13.55	1.95	2.03	1.48	0.55	2.99	0
0011-07-20	64.31	88	76.2	19.57	13.91	16.7	8.51	3.2	1.94	1.43	0.51	2.99	0
0011-07-21	65.81	95.7	80.8	18.25	13.4	15.8	13.2	1.74	1.82	1.43	0.39	2.99	0
0011-07-22	66.23	84.45	75.3	18.99	12.73	15.9	13.21	2.34	1.84	1.35	0.49	2.99	0
0011-07-23	54.89	89.3	72.1	19.92	11.26	15.6	15	1.82	1.84	1.24	0.6	2.99	0
0011-07-24	52.85	89.7	71.3	22.8	13.24	18	16.6	2.32	2.15	1.42	0.73	4.2	0
0011-07-25	65.56	81.85	73.7	19.89	15.37	17.6	13.27	4.21	2.04	1.48	0.56	4.2	0
0011-07-26	65.6	87	76.3	18.81	13.63	16.2	8.88	2.45	1.86	1.39	0.47	4.2	0.2
0011-07-27	52.31	85.68	69	20.22	14.36	17.3	14.36	1.65	2	1.32	0.68	4.2	0
0011-07-28	53.59	87	70.3	21.39	12.86	17.1	15.54	1.51	2.01	1.33	0.68	4.2	0
0011-07-29	54.96	86.9	70.9	21.77	14.88	18.3	13.45	1.93	2.15	1.45	0.7	4.2	0
0011-07-30	38.59	89.3	63.9	24.65	13.79	19.2	13.89	2.56	2.34	1.3	1.04	4.2	0
0011-07-31	61.45	95.6	78.5	20.19	14.42	17.3	13.93	1.95	2	1.51	0.49	4.2	0.2
0011-08-01	66.3	94.7	80.5	20.46	12.28	16.4	15.68	2.35	1.92	1.48	0.44	4.2	0

Full table of climate data from Totem Station *cont…*

Date	RHmin	RHmax	RH.mean	Tmax	Tmin	Tair.mean	Rn	u2	es	ea	Vap.deficit	ETO	Precip
0011-08-02	52.51	77.53	65	22.42	15.86	19.1	12.35	2.7	2.26	1.41	0.85	4.2	0
0011-08-03	64.51	83.03	73.8	21.9	15.42	18.7	14.53	2.11	2.19	1.57	0.62	3.82	0
0011-08-04	56.59	89.6	73.1	23.36	14.08	18.7	15.08	1.57	2.24	1.53	0.71	3.82	0
0011-08-05	68.01	91.2	79.6	20.35	14.12	17.2	13.75	3.04	2	1.55	0.45	3.82	0
0011-08-06	65.75	87.34	76.5	20.05	14.67	17.4	13.04	1.86	2.01	1.5	0.51	3.82	0
0011-08-07	62.31	91.6	77	20.55	12.84	16.7	14.76	1.83	1.95	1.43	0.52	3.82	0
0011-08-08	68.96	92.9	80.9	19.84	13.34	16.6	14.49	2.28	1.92	1.51	0.41	3.82	0
0011-08-09	63.92	81.5	72.7	19.69	14.53	17.1	11.53	3.14	1.97	1.4	0.57	3.82	0
0011-08-10	61.9	81.5	71.7	19.08	14.27	16.7	8.3	2.47	1.92	1.35	0.57	3.82	0
0011-08-11	63.9	84.67	74.3	19.72	14.89	17.3	12.16	1.91	2	1.45	0.55	3.82	0
0011-08-12	54.31	93.4	73.9	21.68	13.66	17.7	13.79	1.43	2.08	1.43	0.65	3.82	0
0011-08-13	53.14	79	66.1	20.11	15.11	17.6	12.22	3.93	2.04	1.3	0.74	3.84	0
0011-08-14	54.76	77.5	66.1	20.9	14.5	17.7	11.42	3.05	2.06	1.32	0.74	3.84	0
0011-08-15	51.9	88.8	70.4	20.12	12.98	16.6	12.97	1.81	1.93	1.28	0.65	3.84	0
0011-08-16	52.22	91.3	71.8	20.71	10.43	15.6	13.48	1.4	1.85	1.21	0.64	3.84	0
0011-08-17	55.54	84.5	70	20.05	12.42	16.2	13	1.57	1.9	1.26	0.64	3.84	0
0011-08-18	62.37	88.3	75.3	19.81	13.46	16.6	12.28	1.79	1.92	1.4	0.52	3.84	0
0011-08-19	60.18	94.3	77.2	21.54	12.01	16.8	13.23	1.83	1.98	1.43	0.55	3.84	0
0011-08-20	50.75	85	67.9	23.02	14.1	18.6	12.89	1.87	2.21	1.4	0.81	3.84	0
0011-08-21	41.47	72.64	57.1	27.17	18.7	22.9	10.52	3.6	2.88	1.53	1.35	3.84	0
0011-08-22	72.64	95.7	84.2	19.6	16.1	17.8	3.651	3.97	2.05	1.7	0.35	3.84	15.6
0011-08-23	60.9	93.6	77.2	21.57	15.79	18.7	10.93	2.59	2.18	1.62	0.56	3.33	0.2
0011-08-24	68.49	91.3	79.9	21.05	14.45	17.8	11.87	2.19	2.07	1.61	0.46	3.33	0
0011-08-25	61.88	93.5	77.7	21.9	16.63	19.3	12.5	2.92	2.26	1.7	0.56	3.33	0
0011-08-26	60.82	85.7	73.3	22.05	16.33	19.2	12.41	1.96	2.26	1.6	0.66	3.33	0
0011-08-27	61.86	92.8	77.3	22.93	15.55	19.2	12.24	1.81	2.28	1.69	0.59	3.33	0
0011-08-28	64.56	97.4	81	21.97	13.9	17.9	12.3	1.89	2.12	1.63	0.49	3.33	0
0011-08-29	64.55	85.5	75	20.29	14.25	17.3	7.57	3.39	2	1.46	0.54	3.33	0
0011-08-30	61.38	85.6	73.5	19.53	14.01	16.8	10.94	1.83	1.94	1.38	0.56	3.33	0.2
0011-08-31	64.54	84.8	74.7	18.24	13.81	16	9.16	2.12	1.84	1.35	0.49	3.33	0
0011-09-01	60.14	89.8	75	18.63	12.63	15.6	7.3	2.35	1.8	1.3	0.5	3.33	0
0011-09-02	62.02	85.05	73.5	17.73	12.58	15.2	10.43	2.82	1.74	1.25	0.49	3.72	0
0011-09-03	40.2	88.2	64.2	21.18	12.17	16.7	10.58	2.24	1.96	1.13	0.83	3.72	0

Appendix D Teggia bean observation chart

Monitoring Teggia Bean Growth at UBC Farm - Summer 2011

Date (2011)	Time	Average Plant Height (cm)	Average Number of Leaves	Average Diameter of Leaves (cm)	Number of Yellowing Plants	Fraction of Flowering Plants	Number of Pods	Average Pod Length (cm)	Observations
JUNE 9	Am	ø	ø	ø	ø	ø	ø	ø	seeds have begun to germin
JUNE 16	11:30	8	2	?	?	ø	ø	ø	~490 plants have emerged
JUNE 21	11:30	8-15	2	?	?	ø	ø	ø	some leaves have holes-pes ~560 plants have emerged
JUNE 23	16:30	10-16	2-3	6-10	5	ø	ø	ø	~580 plants have emerged baby leaf bundles growing 2 10cm gap ~2/3 way down ro
JUNE 28	15:00	10-25	4	6-12	7	ø	ø	ø	~1420 plants have emerged ~1/3 plants behind in develop. seeds sprouted in large gaps
JULY 2	15:00	10-30	5	8-15	8	ø	ø	ø	80-90% ground cover ~1/5 plants behind in develop
JULY 5	15:40	12-30	6	8-15	3	ø	ø	ø	small leaf bundles sprouting vertically ~1-3 leaf bundles per plant
JULY 9	15:30	20-40	12	8-15	6	~1/3	ø	ø	~1/3 plants flowering (small bu 90-95% ground cover ~1/20 plants with pest holes
JULY 13	16:20	25-50	15	9-15	4	~2/3	ø	ø	~2/3 plants have small flower buds (red-pink)
JULY 18	15:30	30-60	18	10-18	4	~3/4	ø	ø	~3/4 plants flowering bud stems extend 5-20cm above leaf canopy (*)
JULY 23	11:00	30-60	18	10-18	3	~3/4	ø	ø	tall bud shoots have fallen to ground, bees pollinating ladybugs present
JULY 27	14:00	40-60	24	12-16	1	~4/4	ø	ø	tall bud stems winding arou neighbouring stems for suppo

(*) ground cover 99%, soil moist due to rainfall

Teggia Bean Observation Chart *cont…*

Monitoring Teggia Bean Growth at UBC Farm - Summer 2011

Date	Time	Average Plant Height (cm)	Average Number of Leaves	Average Diameter of Leaves (cm)	Number of Yellowing Plants	Fraction of Flowering Plants	Number of Pods	Average Pod Length (cm)	Observations
JULY 30	15:00	50-75	30	13-18	3	~4/4	ø	ø	basically all plants have flower buds & flowers
AUG 4	11:45	50-80	/	13-18	2	~4/4	0-25	2-14	plants began growing pods ~1/3 flowers wilt and pods replace them → near tops/out on stems
AUG 6	15:00	50-70	/	13-20 *	1	/	0-25	2-16	photo of 70cm high plant beans weighting down what were once tallest plants
---------	-----	----	/	----	----	------	------	------	drip line reposition, end of row. * some top leaves above flower are younger, less than 13cm
AUG 10	13:00	50-70	/	13-20	1	/	0-25	3-16	
AUG 13	14:15	50-65	/	13-20	1	/	2-25	3-18	many slight yellowing – ½ beans pods weighing down some dropping to the ground
AUG 17	15:15	50-70	/	13-20	2	/	2-25	4-18	some late bloomers rise up and display 2.5cm pods typical max. height 65cm; now greener
AUG 20	14:45	55-75	/	13-20	4	/	4-25	4-18	many abt. 1/3 slight ylw. again late starters some 75cm high some bean pods reddening
AUG 24	16:10	55-70	/	13-20	5	/	5-25	5-18	fewer slight yellow 1/6 yellowing plants have some grn. long pods growing fatter
AUG 27	16:40	55-70	/	13-20	6	/	6-25	6-18	slight yellowing returns to 1/3 many plants slumping due to masses of pods
			/			/			
			/			/			

Appendix E Completed Soil Water Balance

Date	Growing Season	ET0	Kc	ETc	Precip	Irrigation Duration	Irrigation Total	Total Water Input	Drainage	Carry-Over Water	Rooting Depth	Total SWS	Stress Check
(yyyy/mm/dd)	(days)	(mm/day)	(unitless)	(mm/day)	(mm)	(hr)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	
0011-06-04	1	3.7	0.300	1.1	0	0.00	0.00	-1.10	0.00	0.00	0.6	1.7045	
0011-06-05	2	3.7	0.300	1.1	0	0.00	0.00	-1.10	0.00	0.00	0.6	3.409	
0011-06-06	3	3.7	0.300	1.1	0	0.00	0.00	-1.10	0.00	0.00	0.6	5.1135	
0011-06-07	4	3.7	0.300	1.1	0.2	0.00	0.00	-0.90	0.00	0.00	0.6	6.818	
0011-06-08	5	3.7	0.300	1.1	0	0.00	0.00	-1.10	0.00	0.00	0.6	8.5225	
0011-06-09	6	3.7	0.300	1.1	0	0.00	0.00	-1.10	0.00	0.00	0.6	10.227	
0011-06-10	7	3.7	0.300	1.1	0	0.00	0.00	-1.10	0.00	0.00	0.6	11.9315	
0011-06-11	8	3.7	0.300	1.1	0	0.00	0.00	-1.10	0.00	0.00	0.6	13.636	Stressed
0011-06-12	9	3.7	0.300	1.1	0	0.00	0.00	-1.10	0.00	0.00	0.6	15.3405	Stressed
0011-06-13	10	3.7	0.300	1.1	0.4	0.00	0.00	-0.70	0.00	0.00	0.6	17.045	Stressed
0011-06-14	11	3.8	0.300	1.2	0.2	1.00	3.45	2.45	0.00	0.00	0.6	18.7495	
0011-06-15	12	3.8	0.300	1.2	0	0.00	0.00	1.25	0.00	2.45	0.6	20.454	
0011-06-16	13	3.8	0.322	1.3	0	0.00	0.00	-0.05	0.00	1.25	0.6	22.1585	Stressed
0011-06-17	14	3.8	0.344	1.3	0	0.83	2.87	1.57	0.00	0.00	0.6	23.863	
0011-06-18	15	3.8	0.366	1.4	1.8	0.00	0.00	1.97	0.00	1.57	0.6	25.5675	
0011-06-19	16	3.8	0.388	1.5	0	0.00	0.00	0.47	0.00	1.97	0.6	27.272	
0011-06-20	17	3.8	0.409	1.6	0	0.00	0.00	-1.13	0.00	0.47	0.6	28.9765	Stressed
0011-06-21	18	3.8	0.431	1.7	0	0.00	0.00	-1.70	0.00	0.00	0.6	30.681	Stressed
0011-06-22	19	3.8	0.453	1.8	0	0.00	0.00	-1.80	0.00	0.00	0.6	32.3855	Stressed
0011-06-23	20	3.8	0.475	1.9	0.2	0.00	0.00	-1.70	0.00	0.00	0.6	34.09	Stressed
0011-06-24	21	3.6	0.497	1.8	0	0.00	0.00	-1.80	0.00	0.00	0.6	35.7945	Stressed
0011-06-25	22	3.6	0.519	1.9	1	0.00	0.00	-0.90	0.00	0.00	0.6	37.499	Stressed
0011-06-26	23	3.6	0.541	2	0	0.00	0.00	-2.00	0.00	0.00	0.6	39.2035	Stressed
0011-06-27	24	3.6	0.563	2.1	0	0.00	0.00	-2.10	0.00	0.00	0.6	40.908	Stressed
0011-06-28	25	3.6	0.584	2.2	0	1.00	3.45	1.25	0.00	0.00	0.6	42.6125	
0011-06-29	26	3.6	0.606	2.2	0	0.00	0.00	-0.96	0.00	1.25	0.6	44.317	Stressed
0011-06-30	27	3.6	0.628	2.3	0.4	0.00	0.00	-1.90	0.00	0.00	0.6	46.0215	Stressed
0011-07-01	28	3.6	0.650	2.4	0.2	0.00	0.00	-2.20	0.00	0.00	0.6	47.726	Stressed
0011-07-02	29	3.6	0.672	2.5	0	1.33	4.59	2.09	0.00	0.00	0.6	49.4305	
0011-07-03	30	3.6	0.694	2.6	0	0.00	0.00	-0.51	0.00	2.09	0.6	51.135	Stressed

Completed Soil Water Balance *cont…*

Date	Growing Season	ETO	Kc	ETc	Precip	Irrigation Duration	Irrigation Total	Total Water Input	Drainage	Carry-Over Water	Rooting Depth	Total SWS	Stress Check
0011-07-04	31	4	0.716	2.9	0	0.00	0.00	-2.90	0.00	0.00	0.6	52.8395	Stressed
0011-07-05	32	4	0.738	3	0	0.00	0.00	-3.00	0.00	0.00	0.6	54.544	Stressed
0011-07-06	33	4	0.759	3.1	0	0.00	0.00	-3.10	0.00	0.00	0.6	56.2485	Stressed
0011-07-07	34	4	0.781	3.2	2.6	0.00	0.00	-0.60	0.00	0.00	0.6	57.953	Stressed
0011-07-08	35	4	0.803	3.3	0.2	0.00	0.00	-3.10	0.00	0.00	0.6	59.6575	Stressed
0011-07-09	36	4	0.825	3.4	0	2.33	8.03	4.63	0.00	0.00	0.6	61.362	
0011-07-10	37	4	0.847	3.5	0	0.00	0.00	1.13	0.00	4.63	0.6	63.0665	
0011-07-11	38	4	0.869	3.6	0	0.00	0.00	-2.47	0.00	1.13	0.6	64.771	Stressed
0011-07-12	39	4	0.891	3.7	0	1.33	4.58	0.88	0.00	0.00	0.6	66.4755	
0011-07-13	40	4	0.913	3.7	0.2	0.00	0.00	-2.62	0.00	0.88	0.6	68.18	Stressed
0011-07-14	41	2.9	0.934	2.8	5.4	0.00	0.00	2.60	0.00	0.00	0.6	69.8845	
0011-07-15	42	2.9	0.956	2.9	0.2	0.00	0.00	-0.10	0.00	2.60	0.6	71.589	Stressed
0011-07-16	43	2.9	0.978	2.9	12	0.00	0.00	9.10	0.00	0.00	0.6	73.2935	
0011-07-17	44	2.9	1.000	3	0.6	0.00	0.00	6.70	0.00	9.10	0.6	74.998	
0011-07-18	45	2.9	1.000	3	0	0.00	0.00	3.70	0.00	6.70	0.6	75	
0011-07-19	46	2.9	1.000	3	0	0.00	0.00	0.70	0.00	3.70	0.6	75	
0011-07-20	47	2.9	1.000	3	0	1.83	6.31	4.01	0.00	0.70	0.6	75	
0011-07-21	48	2.9	1.000	3	0	0.00	0.00	1.01	0.00	4.01	0.6	75	
0011-07-22	49	2.9	1.000	3	0	0.00	0.00	-1.99	0.00	1.01	0.6	75	Stressed
0011-07-23	50	2.9	1.000	3	0	0.00	0.00	-3.00	0.00	0.00	0.6	75	Stressed
0011-07-24	51	4.1	1.000	4.2	0	0.00	0.00	-4.20	0.00	0.00	0.6	75	Stressed
0011-07-25	52	4.1	1.000	4.2	0	0.00	0.00	-4.20	0.00	0.00	0.6	75	Stressed
0011-07-26	53	4.1	1.000	4.2	0.2	0.00	0.00	-4.00	0.00	0.00	0.6	75	Stressed
0011-07-27	54	4.1	1.000	4.2	0	1.00	3.45	-0.76	0.00	0.00	0.6	75	Stressed
0011-07-28	55	4.1	1.000	4.2	0	0.00	0.00	-4.20	0.00	0.00	0.6	75	Stressed
0011-07-29	56	4.1	1.000	4.2	0	0.00	0.00	-4.20	0.00	0.00	0.6	75	Stressed
0011-07-30	57	4.1	1.000	4.2	0	1.25	4.31	0.11	0.00	0.00	0.6	75	
0011-07-31	58	4.1	1.000	4.2	0.2	0.00	0.00	-3.89	0.00	0.11	0.6	75	Stressed
0011-08-01	59	4.1	1.000	4.2	0	0.00	0.00	-4.20	0.00	0.00	0.6	75	Stressed
0011-08-02	60	4.1	1.000	4.2	0	0.00	0.00	-4.20	0.00	0.00	0.6	75	Stressed
0011-08-03	61	3.8	1.000	3.8	0	1.92	6.61	2.81	0.00	0.00	0.6	75	
0011-08-04	62	3.8	1.000	3.8	0	0.00	0.00	-0.99	0.00	2.81	0.6	75	Stressed

Completed Soil Water Balance *cont…*

Date	Growing Season	ET0	Kc	ETc	Precip	Irrigation Duration	Irrigation Total	Total Water Input	Drainage	Carry-Over Water	Rooting Depth	Total SWS	Stress Check
0011-08-05	63	3.8	1.000	3.8	0	2.33	8.03	4.23	0.00	0.00	0.6	75	
0011-08-06	64	3.8	1.000	3.8	0	8.00	27.56	27.99	0.00	4.23	0.6	75	
0011-08-07	65	3.8	1.000	3.8	0	16.00	55.12	79.31	0.00	27.99	0.6	75	
0011-08-08	66	3.8	1.000	3.8	0	0.00	0.00	75.51	4.31	79.31	0.6	75	
0011-08-09	67	3.8	1.000	3.8	0	2.00	6.89	78.60	0.51	75.51	0.6	75	
0011-08-10	68	3.8	1.000	3.8	0	0.00	0.00	74.80	3.60	78.60	0.6	75	
0011-08-11	69	3.8	1.000	3.8	0	0.00	0.00	71.00	0.00	74.80	0.6	75	
0011-08-12	70	3.8	1.000	3.8	0	0.00	0.00	67.20	0.00	71.00	0.6	75	
0011-08-13	71	3.8	1.000	3.8	0	2.58	8.89	72.28	0.00	67.20	0.6	75	
0011-08-14	72	3.8	1.000	3.8	0	0.00	0.00	68.48	0.00	72.28	0.6	75	
0011-08-15	73	3.8	1.000	3.8	0	0.00	0.00	64.68	0.00	68.48	0.6	75	
0011-08-16	74	3.8	1.000	3.8	0	0.00	0.00	60.88	0.00	64.68	0.6	75	
0011-08-17	75	3.8	1.000	3.8	0	2.17	7.48	64.56	0.00	60.88	0.6	75	
0011-08-18	76	3.8	1.000	3.8	0	0.00	0.00	60.76	0.00	64.56	0.6	75	
0011-08-19	77	3.8	1.000	3.8	0	0.00	0.00	56.96	0.00	60.76	0.6	75	
0011-08-20	78	3.8	1.000	3.8	0	1.17	4.03	57.19	0.00	56.96	0.6	75	
0011-08-21	79	3.8	1.000	3.8	0	0.00	0.00	53.39	0.00	57.19	0.6	75	
0011-08-22	80	3.8	1.000	3.8	15.6	0.00	0.00	65.19	0.00	53.39	0.6	75	
0011-08-23	81	3.3	1.000	3.3	0.2	0.00	0.00	62.09	0.00	65.19	0.6	75	
0011-08-24	82	3.3	1.000	3.3	0	0.00	0.00	58.79	0.00	62.09	0.6	75	
0011-08-25	83	3.3	1.000	3.3	0	2.08	7.17	62.66	0.00	58.79	0.6	75	
0011-08-26	84	3.3	1.000	3.3	0	0.00	0.00	59.36	0.00	62.66	0.6	75	
0011-08-27	85	3.3	0.993	3.3	0	0.00	0.00	56.06	0.00	59.36	0.6	75	
0011-08-28	86	3.3	0.987	3.3	0	0.00	0.00	52.76	0.00	56.06	0.6	75	
0011-08-29	87	3.3	0.980	3.2	0	0.00	0.00	49.56	0.00	52.76	0.6	75	
0011-08-30	88	3.3	0.973	3.2	0.2	0.00	0.00	46.56	0.00	49.56	0.6	75	
0011-08-31	89	3.3	0.967	3.2	0	1.25	4.31	47.66	0.00	46.56	0.6	75	
0011-09-01	90	3.3	0.960	3.2	0	0.00	0.00	44.46	0.00	47.66	0.6	75	
0011-09-02	91	3.7	0.953	3.5	0	0.00	0.00	40.96	0.00	44.46	0.6	75	
0011-09-03	92	3.7	0.947	3.5	0	1.17	4.03	41.49	0.00	40.96	0.6	75	

Appendix F R Code for ET_0

```
##REFERENCE EVAPOTRANSPIRATION

## This code was adapted by Brenda Moore from Michael Lathuilliere, UBC Vancouver Campus,
June 2011
## It applies to the UBC Farm and requires data input from UBC Totem Field Weather Station

## A special acknowledgement to the UBC Totem Field Station:
## Black, A., Brown, M., Chouhan, L., Grant, N., Hawthorn, I., Jassal, R., Ketler, R.,
Nesic, Z., Novak, M., Leitch, A., Lessard, D. (2011).
## Biometeorology and Soil Physics Group of UBC. Data Retrieved July 20, 2011, from
http://www.landfood.ubc.ca/biomet/index.htm

## Calculation of reference ET (ET0) as per FAO guidelines Irrigation and Drainage Paper 56
## Data should have first been analyzed and manipulated using Aquarius or other program, then
exported as .csv

## Link to the FAO 56 guidelines: http://www.fao.org/docrep/x0490E/x0490e00.htm#Contents

## File containing the following headings (stdev = standard deviation):

## Date: month/day/year
## Tair.mean: mean air temperature calculated as (Tmax + Tmin)/2, in deg.C
## Tair.stdev: standard deviation of mean air temperature
## RH.mean: mean relative humidity calculated at (RHmax + RHmin)/2, in %
## RH.stdev: standard deviation of the relative humidity
## P.mean: mean atmospheric pressure, in kPa
## P.stdev: standard deviation of atmospheric pressure
## Wspeed.mean: mean wind speed (record height of sensor), in m/s
## Wspeed.stdev: standard deviation of wind speed
## Tmax: maximum temperature over 24hr period, in deg.C
## Tmin: minimum temperature over 24hr period, in deg.C
## Precip: total precipitation over a 24hr period, in mm
## RHmax: maximum relative humidity
## RHmin: minimum realtive humidity

## All equations are numbered according to the FAO guidelines, irrigation and drainage paper
56

##------------------------------------------------------------

## Clear the workspace
rm(list = ls())

## Input file location of .csv for climate station data (using MacBook Pro)
Station <- read.table("/Users/brenda1/Documents/UBC/Courses/EOSC 448/R
Files/Aquarius/2011AquariusData-Rconfig.csv", header=TRUE, sep=",", na.strings="NA",
dec=".", strip.white=TRUE)

## Input file location of .csv for climate station data (using PC at AERL)
##Station <- read.table("C:/Users/m.lathuilliere/Documents/EOSC448/2011AquariusData-
Rconfig.csv", header=TRUE, sep=",", na.strings="NA", dec=".", strip.white=TRUE)

##------------------------------------------------------------

## Input altitude, latitude and name of climate station
Location = c("Totem Station")
#Altitude (above sea level) of Totem Station, UBC Vancouver Campus, in m
```

R Code for ET_0 *cont…*

```
Z = 104.42
#Latitude of Totem Station, in decimal degrees
lat = 49.26
#Height above ground of the sensor measuring wind speed, in m
Wheight = 10

##------------------------------------------------------------

#Attach database to R search path
attach(Station)

##Date conversions from .csv file
Date <- as.character(Date)
Date <- as.Date(Date, "%m/%d/%Y")

#Conversion to julian day
J <- as.numeric(format(Date, "%j"))

##List of variables and constants used in calculation

#Rename mean wind speed, in m/s
uz <- Wspeed.mean

#Calculate mean air temperature, in deg C
Tair.mean1 = (Tmax + Tmin)/2
#Round to 3 significant figures
Tair.mean = signif(Tair.mean1, digits = 3)

#Calculate mean relative humidity, in %
RH.mean1 = (RHmax + RHmin)/2
#Round to 3 significant figures
RH.mean = signif(RH.mean1, digits = 3)

#Temperature-dependent latent heat of vapourization (MJ/kg)
lambda <- ifelse(is.na(Tair.mean), 2.45, 2.501 - (2.361*0.001)*Tair.mean)

#Specific heat capacity at constant P (MJ/kg.degC)
Cp <- 1.013*10^-3

#Boltzmann constant in MJ/K^4m^2day
sigma <- 4.903*10^-9

#Wind speed at 2m height calculated from uz, equation (47)
u21 <- uz*(4.87/(log(67.8*Wheight-5.42)))
#Round to 3 significant figures
u2 <- signif(u21, digits = 3)

##------------------------------------------------------------

##Calculation of psychrometric constant 'gamm' (kPa/degC), equation (8)

gamm <- (Cp*P.mean)/(0.622*lambda)

##------------------------------------------------------------

##Calculating saturation vapour pressure 'es', in kPa, equation (11)
```

R Code for ET_0 *cont...*

```
eo.Tmax <- 0.6108*exp(17.27*Tmax/(Tmax+237.3))
#Round to 3 significant figures, due to Tmax
eoTmax <- signif(eo.Tmax, digits = 3)

eo.Tmin <- 0.6108*exp(17.27*Tmin/(Tmin+237.3))
#Round to 3 significant figures, due to Tmin
eoTmin <- signif(eo.Tmin, digits = 3)

#Calculating mean saturation vapour pressure
#If Tmax or Tmin are missing, 'es' is calculated using Tair.mean, eq(12)
es1 <- ifelse(is.na(eoTmax)|is.na(eoTmin),0.6108*exp(17.27*Tair.mean/(Tair.mean+237.3)),
   (eoTmax+eoTmin)/2)
#Round to 3 significant figures, due to temperature values
es <- signif(es1, digits = 3)

##Calculating actual vapour pressure 'ea', in kPa, equation (13) and equation (48)

ea1 <- ifelse(is.na(eoTmax)|is.na(RHmax)|is.na(RHmin), eoTmin,((eoTmin*RHmax/100)
   +(eoTmax*RHmin/100))/2)
#Round to 3 significant figures, due to RH
ea <- signif(ea1, digits = 3)

#If Tmax, RHmax, RHmin are missing, assume Tmin = dewpoint temperature
#RHmean is determined by RHmax and RHmin, so eq(19) cannot be used

#Option 2 for calculating 'ea' using RHmax (absence of RHmin) with equation (18)
#ea1 <- ifelse(is.na(eoTmax), (eoTmin*RHmax)/100,
#   ((eoTmin*RHmax/100)+(eoTmax*RHmin/100))/2)
##Round to 2 significant figures (due to RH)
#ea <- signif(ea1, digits = 2)

##Calculating vapour pressure deficit (es - ea), in kPa
Vap.deficit1 <- ifelse((es - ea)<0,0,(es-ea))
#Round to 3 significant figures, due to ea
Vap.deficit <- signif(Vap.deficit1, digits = 3)

##-------------------------------------------------------------

##Calculating slope of saturated vapour pressure curve, Delta (kPa/degC)

Delta1 <- 4098*(0.6108*exp((17.27*Tair.mean)/(Tair.mean+237.3)))/((Tair.mean+237.3)^2)
#Round to 3 significant figures, due to temperature values
Delta <- signif(Delta1, digits = 3)

##-------------------------------------------------------------

##Calculating incoming radiation to determine ET0 using data from climate station

#Input latitude (lat) in decimal degrees and convert to radians (fi), equation (22)
fi1 <- (pi/180)*(lat)
#Round to 3 significant figures, due to latitude
fi <- signif(fi1, digits = 3)
#Input solar constant, in MJ/m^2/min
Gsc <- 0.0820

#Calculating inverse relative distance Earth-Sun, equation (23)
dr <- 1+0.033*cos(2*pi*J/365)
```

```
#Calculating solar declination, equation (24)
delta <- 0.409*sin(-1.39+(2*pi*J/365))

#Calculating sunset hour angle in rad, equation (26)
ws1 <- acos(-tan(fi)*tan(delta))
#Round to 3 significant figures, due to fi
ws <- signif(ws1, digits = 3)

#Calculating extraterrestial radiation, in MJ/m^2/day, equation (28)
Ra1 <- (24*60/pi)*Gsc*dr*(ws*sin(fi)*sin(delta)+cos(fi)*cos(delta)*sin(ws))
#Round to 3 significant figures, due to fi
Ra <- signif(Ra1, digits = 3)

#Calculating clear sky solar radiation, in MJ/m^2/day, equation (37)
Rso1 <- (0.75+Z*2*10^-5)*Ra
#Round to 3 significant figures, due to Ra
Rso <- signif(Rso1, digits = 3)
#Equation (37) is chosen because as and bs of equation (36) are unavailable

##If the incoming solar radiation (Rs) is known, skip the following:
#Calculating incoming solar radiation using Tmax and Tmin, in MJ/m^2/day, equation (50)
#Hargreaves radiation formula using adjustment coefficient of 0.16 for interior regions
#Rs1 <- 0.16*Ra*(Tmax-Tmin)^0.5
#Round to 3 significant figures, due to temperature
#Rs <- signif(Rs1, digits = 3)

#Calculating net solar radiation from land surface albedo, in MJ/m^2/day, equation (38)
#Using albedo of 0.23 for reference surface, the hypothetical grass crop
Rns1 <- (1-0.23)*Rs
#Round to 3 significant figures, due to Rs
Rns <- signif(Rns1, digits = 3)

#Calculating net outgoing longwave radiation, in MJ/m^2/day, equation (39)
#Following formula requires temperature values be converted to Kelvin
#Convert temperatures from deg.C to Kelvin
Tmax.K <- Tmax + 273.16
Tmin.K <- Tmin + 273.16
#Calculating Rnl
Rnl1 <- sigma*(((Tmax.K^4)+(Tmin.K^4))/2)*(0.34-0.14*(ea^0.5))*(1.35*(Rs/Rso)-0.35)
#Round to 3 significant figures, due to ea
Rnl <- signif(Rnl1, digits = 3)

#Calculating net shortwave radiation, in MJ/m^2/day, equation (40)
Rn <- Rns - Rnl

##------------------------------------------------------------

#Calculating reference ET, in mm/day, equation (6)
#For daily measurement periods, soil heat flux (G) is negligible
ref.ET1 <- (0.408*Delta*(Rn-0)+ gamm*(900/(Tair.mean+273))*u2*Vap.deficit)/(Delta +
 gamm*(1+0.34*u2))
#Round to 3 significant figures, due to ea
ref.ET <- signif(ref.ET1, digits = 3)

#Create new data frame
Reference.Evap <- data.frame(Date, RH.mean, Tmax, Tmin, Tair.mean, eoTmin, eoTmax, ea,
 ref.ET, Precip)
```

R Code for ET_0 *cont…*

```
#Attach database to R search path
attach(Reference.Evap)

#Enter number of decades based on available data
decades <- 10
#Replicate 1 to 10, 10 times each
decade <- rep(1:decades, each=10)
#Create vector length based on number of entries
vector.length = length(J)
#Reduce vector length to correct number of elements
length(decade) <- vector.length

#Split reference ET data into subsets and apply aggregate function to all
df1 <- aggregate(ref.ET, list(decade), mean, na.omit = TRUE)

ET0.1a <- rep(df1$x, each = 10)
#Round to 3 significant figures
ET0 <- signif(ET0.1a, digits = 3)
#Reduce length to 119 elements
length(ET0) <- 99

df2 <- aggregate(ref.ET, by = list(decade), sd, na.rm = TRUE)
ET0stdev.1a <- rep(df2$x, each = 10)
#Round to 3 significant figures, due to ET0
ET0stdev.1 <- signif(ET0stdev.1a, digits = 3)

detach(Reference.Evap)

#--------------------------------------------------------------------------------

##Creating new data frame and graphing data
Reference.ET <- data.frame(Date, RHmin, RHmax, RH.mean, Tmax, Tmin, Tair.mean, Rn,
   u2, es, ea, Vap.deficit, ET0, Precip)

## Exporting data frame as table to My Documents

##For when using MacBook Pro
write.table(Reference.ET, file="/Users/brenda1/Documents/UBC/Courses/EOSC 448/R
 Files/UBC_ET0.csv", sep = ",", na = "", dec = ".",
   row.names = FALSE, col.names = TRUE )

##For when using PC at AERL
#write.table(Reference.ET, file="C:/Users/m.lathuilliere/Documents/EOSC448/UBC_ET0.csv", sep
 = ",", na = "", dec = ".",
   #row.names = FALSE, col.names = TRUE )

#--------------------------------------------------------------------------------

##Plotting data to check for calculation errors
par(mfrow=c(3,1), mar=c(2,2,2,2), oma=c(1.5,2,1.5,1))
plot(Date, Rn, ylab = "", main="Incoming Radiation, albedo = 0.23", col="red")
plot(Date,Vap.deficit, ylab = "", main="Vapour Pressure Deficit (kPa)", col="blue")
plot(Date,ET0, ylab = "", main="ET0 (mm/day), albedo = 0.23")
title(Location, cex = 1.5, outer = TRUE)
par(mfrow=c(1,1))

##Export graph of time series of Rn, Vap.deficit, ETO
```

R Code for ET_0 *cont…*

```
##For when using MacBook Pro
dev.print(pdf, file = "/Users/brenda1/Documents/UBC/Courses/EOSC 448/R
 Files/Rn_Vap_ET0_Graph.pdf",
   width=7.5, height=10, pointsize=5)

##For when using PC at AERL
#dev.print(pdf,
  #file="C:/Users/m.lathuilliere/Documents/EOSC448/Rn_Vap_ET0_Graph.pdf",
   #width=7.5, height=10, pointsize=5)


##Plotting reference ET alone
plot(Date, ET0, main = "Reference ET (mm/day)", col = "red")

##Export graph of ET0

##For when using MacBook Pro
dev.print(pdf,
  file="/Users/brenda1/Documents/UBC/Courses/EOSC 448/R Files/ET0_Graph.pdf",
   width=7.5, height=10, pointsize=5)

##For when using PC at AERL
#dev.print(pdf,
  #file="C:/Users/m.lathuilliere/Documents/EOSC448/ET0_Graph.pdf",
   #width=7.5, height=10, pointsize=5)

detach(Station)

#--------------------------------------------------------------------------------

#### END ####
```