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Effect of deficit irrigation on yield quantity and quality, water productivity and economic returns of four cultivars of hops in the Yakima Valley, Washington State

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ABSTRACT

Hop production, like all other water uses in the area, is facing water availability concerns. Deficit irrigation may address water scarcity issues in hop production. This study quantifies the effect of deficit irrigation on hop yield, quality, water productivity and grower profitability. Mt. Hood, Columbus, Chinook and Willamette cultivars were grown under three irrigation levels; 60, 80 and 100% of the crop's irrigation requirement, using a sub-surface drip irrigation system. Results show that hop plants generally respond to water stress with yield reductions; compared to the 100% irrigation level, the 60% irrigation level caused reductions in total 2-year dry hop cone yield of 30%, 33%, 25%, and 19% for Mt. Hood, Willamette, Columbus and Chinook cultivars respectively, whereas, the 80% irrigation level caused total 2-year yield reductions of 14%, 10%, and 3% for Mt. Hood, Willamette and Chinook cultivars respectively. For Columbus, the 80% irrigation level gave 2% more dry hop cone 2-year total yield than the fully irrigated treatment. Hop cone quality was however not affected; the concentrations of alpha and beta acids were generally similar across all irrigation levels for cultivars for each year of study. The cost of water in Washington State does not vary with changes in water use; only water pumping costs vary with water use. Pumping costs are only 1.5% of the total cost of producing hops in an established yard. As such, savings in pumping costs due to using less water were minimal when compared to the resulting loss in revenue due to yield reductions. Deficit irrigating hops grown under sub-surface drip irrigation system in the Yakima Valley is therefore not economically viable. However, under conditions of water scarcity, high water prices or when there are more profitable alternative uses for the water, deficit irrigation may then be considered. Deficit irrigation though has potential to improve water productivity as observed from the 2012 results. Under the 60% irrigation level, water productivities were 0.42, 0.55, 1.02, and 0.44 kg/m^3 for Mt. Hood, Willamette, Columbus, and Chinook respectively. Under the 80% irrigation level, water productivities for Mt. Hood, Willamette, Columbus, and Chinook were 0.34, 0.41, 0.95, and 0.45 kg/m^3 respectively. For full irrigation, water productivities were 0.33, 0.31, 0.84, and 0.37 kg/m^3 for Mt. Hood, Willamette, Columbus, and Chinook respectively. This study provides production functions for the hop cultivars for forecasting yield quantities under various irrigation amounts.

1. Introduction

Hops (*Humulus lupulus* L.) are herbaceous perennial plants whose root systems are extensively branched. The crowns can survive for 50 or more years (Wample and Farrar, 1983), although hop yards are normally replanted every 10–20 years or less, due to reduced yields or when the market demands it (Turner et al., 2011). The harvested product on a hop plant is the fully mature female flower, commonly known as the hop cone. Hop cones contain a sticky golden yellow powder called lupulin that is used in the beer brewing process to provide the characteristic flavor and aroma to beers and ales (Kneen, 2002; Wang et al., 2008). Contained in the lupulin are resins containing alpha and beta acids (Kneen, 2002; De Keukeleire et al., 2003). Hop cone quality depends on its beer bit-

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tering power due to its concentrations of alpha and beta acids (Zepp et al., 1995; Čeh et al., 2007). In their pure state, the alpha and beta acids are only slightly bitter (De Keukeleire, 2000). During the beer brewing process, in the time of wort boiling, thermal isomerization of alpha acids to iso-alpha acids takes place (De Keukeleire, 2000; Danenhower et al., 2008). The extreme bitterness of the iso-alpha acids imparts the bitter taste to beer; as such, the bittering power of hop cones, and therefore the quality of hop cones, mainly depends on the alpha acids percent content of the hop cone and the extent of alpha acid isomerization (Beatson et al., 2003; Danenhower et al., 2008). Beta acids to a smaller extent also contribute to bittering of beer; they become more bitter through oxidation both in storage and during boiling (De Keukeleire, 2000; Kneen, 2002). An increase in concentration of either alpha acids or beta acids therefore suggests an increase in quality of that cultivar of hops. Different hop cultivars contain different concentrations of alpha and beta acids. Variations in alpha and beta acids concentrations in a particular cultivar are due to weather conditions and water availability during the growing season (De Keukeleire et al., 2007; Mozny et al., 2009). High temperatures inhibit the accumulation of alpha and beta acids in hops (De Keukeleire et al., 2007; Mozny et al., 2009). Alpha and beta acids start to accumulate from the beginning of the flowering stage (De Keukeleire et al., 2007). Water stress just before flowering and all through the flowering stage therefore can decrease alpha acids yields, and can also decrease hop cones yield (Evans, 2003; De Keukeleire et al., 2007; Srečec et al., 2008). However, the greatest accumulation of the alpha and beta acids occurs during the cone development stage (De Keukeleire et al., 2007). Thus, the hop cone development stage most critically influences hop cone yield and quality, and water stress during the hop cone development stage significantly affects hop cone yield and quality (Hnilickova and Novak, 2000; De Keukeleire et al., 2007; Srečec et al., 2008).

Approximately 75% of the United States hops are produced by Washington State growers (USDA, 2015) and almost all this hop production is done in the Yakima Valley. The Yakima Valley receives very little rainfall (Table 1), and crop production is therefore dependent on irrigation. In the Yakima Valley, most hop cultivars are reported to use about 610–712 mm of water per year during a normal growing season (George, 2001; Evans, 2003). Hop production faces competition from other increasing water demands in the region, including water and power needs for the growing urban areas, water for other agricultural uses, and ample water to provide in-stream flows in order to preserve native fish populations. There are also pressures in the valley to reduce water losses i.e. non-beneficial water uses including runoff and deep percolation from irrigated fields in order to reduce non-point pollution sources of nutrients to surface and ground water resources. The limited water supplies therefore call for innovations aimed at improving the crop's water productivity. One such innovation, deficit irrigation, requires scheduling for irrigations not based on full crop water requirement. Under deficit irrigation, plants are supplied with water below the crop's actual water requirement whenever irrigations are applied thereby allowing the plants to go through some extent of water stress (FAO, 2002; Fereres and Soriano, 2007; Geerts and Raes, 2009). Through deficit irrigation, water is saved but this should be done with minimal negative impacts on the crop yield and quality. The crop's response to different levels of water stress therefore needs to be known, if deficit irrigation is to be successfully implemented.

Water deficit along the hop growing season was found to cause reductions in yield of hop cones (Hnilickova and Novak, 2000; Delahunty and Johnston, 2011; Fandiño et al., 2015). Hnilickova and Novak (2000) compared hop yields between supplementally irrigated and non-irrigated plants in Chech Republic in years where precipitation received during the growing season was below the long time average. Delahunty and Johnston (2011) compared hop cones yields of four hop cultivars that were either supplementally drip-irrigated or not irrigated at all (i.e. depended on the received precipitation) in Maine, USA. Fandiño et al. (2015) reported that hop cone yields increased with increasing hop plant transpiration in both rainfed and irrigated hops. In arid and semi-arid areas like the Yakima Valley, hop production does not depend on the amount of rainfall received since very little rainfall is received during the growing period (Table 1). Studies on irrigation water management are thus needed to assess the potential of reducing water use in hop production without significantly affecting yields and net income. Evans (2003) noted that hops generally are fairly drought tolerant and if grown on deep soils, they would give fair yields when subjected to limited irrigation. This is because hop roots can grow to greater depths and will extract water from lower soil profiles, up to depths of 2.4 m or more.

The objectives of this study were therefore to (i) assess the effects of various levels of water stress applied throughout the growing season on the yield and quality of four cultivars of hops grown under sub-surface drip irrigation, and (ii) evaluate the potential to improve water productivity and economic profitability of hop production through deficit irrigation.

2. Materials and methods

2.1. Site description

The study was conducted for two years 2011 and 2012, in an already established experimental hop yard at the Washington State University Irrigated Agriculture Research and Extension Center (IAREC) near Prosser, WA (46.26°N, 119.74°W, and 265 m above sea level). The soil at the study site was classified as Warden Silt loam, 2–5% slopes, with average sand, silt and clay of 21, 68 and 8% respectively. The weather conditions for the site during the periods of experimentation were as presented in Table 1. Daily precipitation and average temperature are shown in Fig. 1. Daily grass reference evapotranspiration (ETo), calculated using Penman-Monteith equation (Allen et al., 1998) for both years for the periods of study are shown in Fig. 2.

2.2. Treatments and irrigation scheduling

The hop yard was established in 1991, with the hop plants planted in hills of 2.1 m by 2.1 m spacing. Some hills in the hop yard had plants missing at the beginning of this study. Hills with missing plants were filled in with transplants at the beginning of the 2011 growing season. The hop yard had a plant density of 2200 plants per hectare. The yard had four cultivars of hops laid out in two blocks per cultivar. Each block was divided into three plots (Fig. 3). Each plot was 5 rows of hop hills wide by 14 hills long, and each plot was independently irrigated via subsurface polyethylene drip tubing buried approximately 38–45 cm deep. An electrically operated valve controlled the flow of water to each plot. An Irritrol-MC-PLUS-B-Controller (Irritrol Systems, Riverside, CA, USA) was used to control the opening and closing of the valves. Three irrigation levels were randomly assigned to each of the three plots per block per cultivar; each irrigation level was therefore replicated twice for each cultivar. The subsurface drip line ran parallel to each row of hop vines. The drip lines all had emitters spaced 90 cm apart with emitter flow rate of 2 l h^{-1}. Weeding between rows in the hop yard was done mechanically whenever it was required. No mulch material covered the soil surface during the growing seasons in both years.

The four hop cultivars in the yard were Mt. Hood, Columbus (also known as Tomahawk), Willamette and Chinook. Mt. Hood is a triploid aroma-type cultivar used for its aromatic properties; its

Table 1
Monthly weather parameters during the periods of experimentation.

	March	April	May	June	July	August	September
	2011						
Rainfall (mm)	30.5	7.1	34.3	4.3	6.1	0	0
Mean max. temp (°C)	26.2	27.8	25.9	31.2	34.8	35.4	35.0
Mean min. temp (°C)	−3.3	−2.2	0.3	4.0	6.5	6.4	3.5
RH (%)	68.8	50.8	54.8	51.7	51.1	52.3	55.3
ETo (mm/day)	2.18	3.34	4.19	5.30	5.75	5.43	4.38
	2012						
Rainfall (mm)	19.8	24.5	6.6	41.4	7.4	1.3	0
Mean max. temp (°C)	21.8	30.7	32.4	31.2	38.4	37.8	30.8
Mean min. temp (°C)	−3.0	−2.2	0.3	4.0	6.5	6.4	3.5
RH (%)	57.5	57.2	47.1	57.0	52.7	51.1	57.2
ETo (mm/day)	2.29	3.60	4.75	4.95	6.25	5.80	4.38

alpha acids to beta acids ratio is about 0.8. Willamette is also a triploid aroma-type hop used for its aromatic properties and moderate bittering. Its alpha to beta ratio is about 1.1. Chinook is a bittering cultivar with aroma characteristics; it has a high bittering power due to the high content of alpha acids (12–14%). Its alpha to beta ratio is about 4.0. Columbus is also a high bittering hop. Among the four cultivars, Columbus has the highest content of alpha acids ranging between 14–18%. The alpha to beta ratio of Columbus is about 3.1 (Yakima Chief Inc., 2002).

Three irrigation levels were considered in this study; 60%, 80% and 100%. The 100% irrigation level indicates that the plants were fully irrigated (that is, the plants were not subjected to any water stress throughout their growth period). The fully irrigated plots (i.e. plots receiving 100% irrigation level) for each cultivar were used as controls to schedule irrigations for the other irrigation levels, 60% and 80%. Soil water content was measured twice every week throughout the growing season using an on-site calibrated neutron-probe (503DR hydroprobe, Campbell Pacific Nuclear, Concord, CA, USA) from each of the fully irrigated plots. At each of the days that soil water content was measured, the soil water deficit (i.e. soil water content at field capacity – current soil water content) in the 100% level plots was computed for each cultivar. Using an application efficiency of 95% for the sub-surface drip irrigation system (Howell, 2003), the 100% plots per cultivar were replenished back to field capacity i.e. the 100% plots received irrigation amounts = soil water deficit/application efficiency (0.95). The 60% and 80% irrigation level plots each then received only 60% and 80% respectively of the irrigation amount applied in the 100% irrigation level plots. Since the sub-surface drip application rate was the same for all plots, differences in volumes of irrigation water applied to each plot depending on the irrigation level assigned to it for each cultivar were achieved through programming the Irritrol-MC-PLUS-B-Controller for different watering durations for the various plots. For example, if the 100% irrigation level plots of Chinook needed 10 h of irrigation to bring the soil water back to field capacity, then the 80% and 60% irrigation level plots were programmed to receive water for only 8 and 6 h respectively. These irrigation levels were applied throughout the growing seasons for both years. All plots per cultivar and per irrigation level were always irrigated proportionately on the same day. Irrigations in the fully irrigated plots were scheduled such that the available soil water in the active root zone (active root zone depth for hops was considered to be about 1.2 m (Evans, 2003)) was never allowed to go below 50% (i.e. management allowed depletion (MAD)) of the total available soil water (the difference between soil water content at field capacity and that at permanent wilting point) (Allen et al., 1998) nor would it go above field capacity to ensure limited water losses to deep percolation. Fig. 4 shows a measured soil water content graph for Columbus for the 2012 growing season.

At the end of every growing season, the entire hop yard was fully irrigated to ensure that for the next year all plots started at field capacity and to also prevent winter freeze damage to roots.

Late March of 2011 when evapotranspiration was minimal, about 48 h after a heavy rainfall event, undisturbed soil core samples were taken at about 40 cm soil depth, from various spots in the hop yard. Soil water content of the samples was determined gravimetrically and averaged in order to obtain the water content of the hop yard at field capacity. The permanent wilting point was estimated to be about half of the water held by the soil at field capacity (Saxton and Rawls, 2006).

2.3. Field practices and harvesting

The hop growing seasons in both study years begun in April. Irrigation applications started in the first week of May. A spring application of nitrogen fertilizer at a rate of 100 kg/ha was done in first week of May, and another nitrogen fertilizer application at a rate of 100 kg/ha was done in the first week of July for all irrigation treatments. The hops bines were trained on two strings per hill in the second week of May. Hops were harvested once a year either in the last week of August or first week of September depending on the cultivar. During harvest, 10–14 hop bines were selected randomly per plot for each cultivar. Harvesting took four days during both years; one cultivar per day. These bines were manually cut at the ground level and at the overhead support wires as they fell on to a truck trailer. The bines were then transported to a stationary picking machine where the bines were hung upside down on hooks and carried into the picking machine where the cones and leaves were stripped from the vine. A series of cleaning devices separated the cones from the leaves, vines and other debris. The cones were then collected in plastic bags and weighed. Two 2.4 kg subsamples of hop cones from each plot were then put in wooden boxes with mesh bottoms and loaded in a drier and 60 °C air was forced through these freshly picked hops for about nine hours (George, 2001) to achieve a constant weight. After this drying time, the hop cones retained about 8–10% water content. The weight of the dried cones was then recorded and the weight of the dried cones per hectare computed. The dried cones were then baled and placed in cold storage awaiting alpha acids and beta acids composition analysis.

Analysis of the percent content of alpha and beta acids of the dried hop cones was done using spectrophotometric analysis. A composite sample (200–500 g), taken from hop bales, was prepared for analysis by grinding the sample using a universal no.3 grinder with a six-tooth cutter. Within one hour of grinding, a moisture detector (model G-34, Delmhorst Instrument Co., Towaco, NJ) was used to perform a rapid moisture determination on the ground hop sample to ensure that moisture content was within the range of

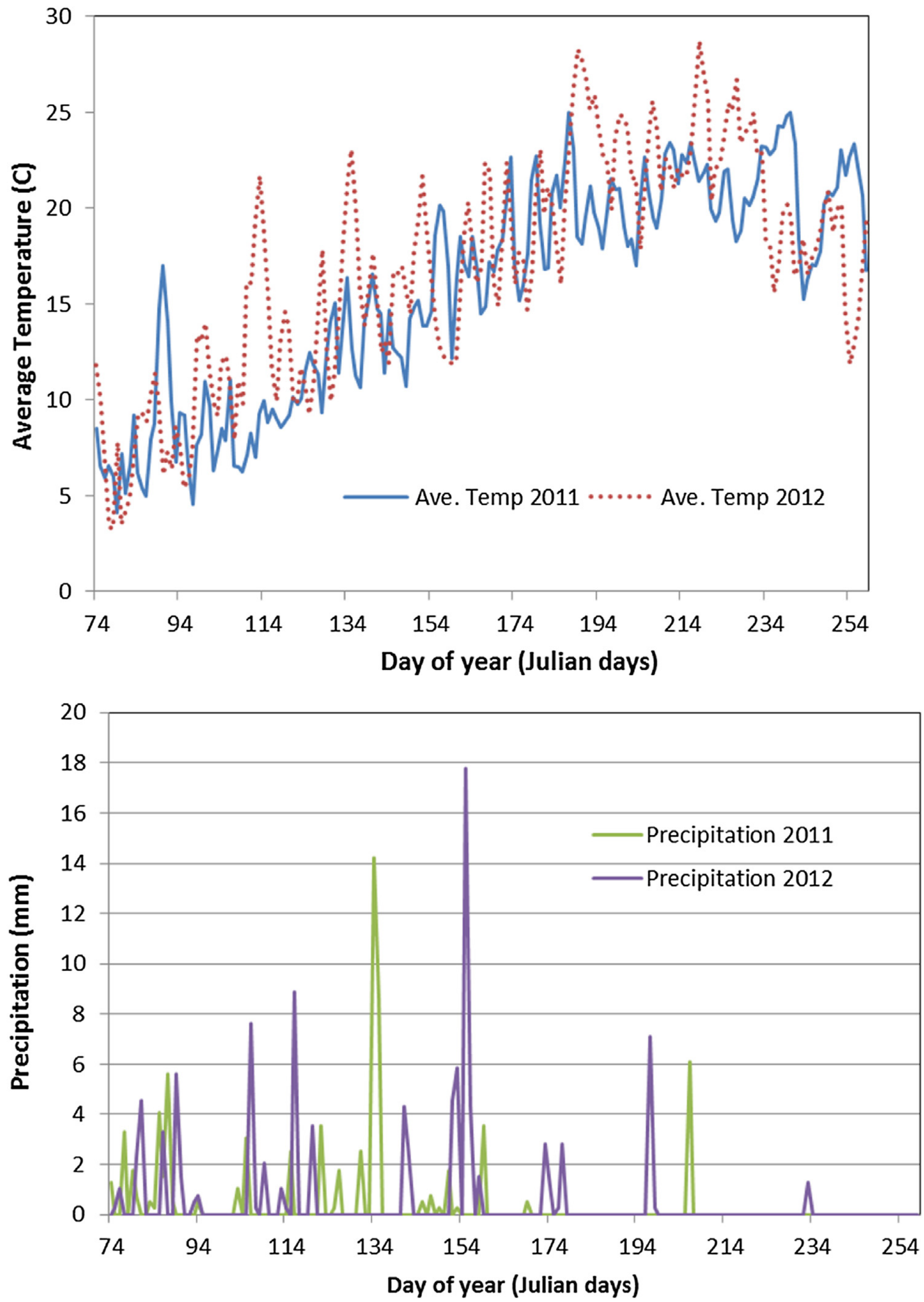

Fig. 1. Daily average temperature and precipitation during the study periods.

8–10%. Immediately following grinding, a 5-g aliquot of ground hop material was extracted with 100 ml of toluene for thirty minutes on a mechanical shaker. Each sample was then centrifuged at 2000 rpm for 5 min. A 5-ml aliquot of the clarified toluene extract was then diluted with 100 ml of methanol (dilution A). An alkaline methanol solution was used to further dilute dilution A such that absorbance measurements could be made within the range of 0.2–0.8 absorbance units at wavelengths corresponding to 355, 325, and 275 nm (American Society of Brewing Chemists, 1992). A set of equations was then used to calculate the α-acids concentration (%), and the β-acids concentration (%) (American Society of Brewing Chemists, 1992). All analyses were performed in duplicate.

2.4. Crop water use (crop ET)

The soil water budget shown below was used to determine actual crop evapotranspiration (crop ET) (Allen et al., 1998; Evett et al., 2009):

$$\text{CropET} = P + I \pm D - R + \Delta S \quad (1)$$

Where P is the total precipitation received throughout the hop growing season, I is the irrigation applied, D is deep percolation below the root zone (−) or capillary rise (+); the upward flow from a shallow water table to the root zone, R is runoff, and ΔS is the change in the soil profile's water storage during the growing season (i.e. soil water content at the start of the season minus soil water content at harvest for the root zone). For each plot, a begin-

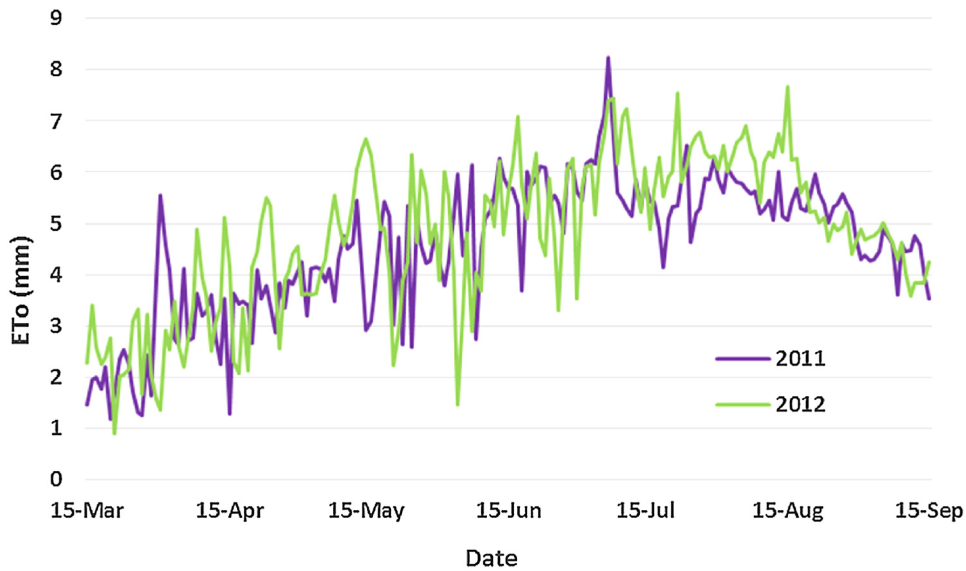

Fig. 2. Penman-Monteith grass reference evapotranspiration (ETo) calculated for the study periods of both years.

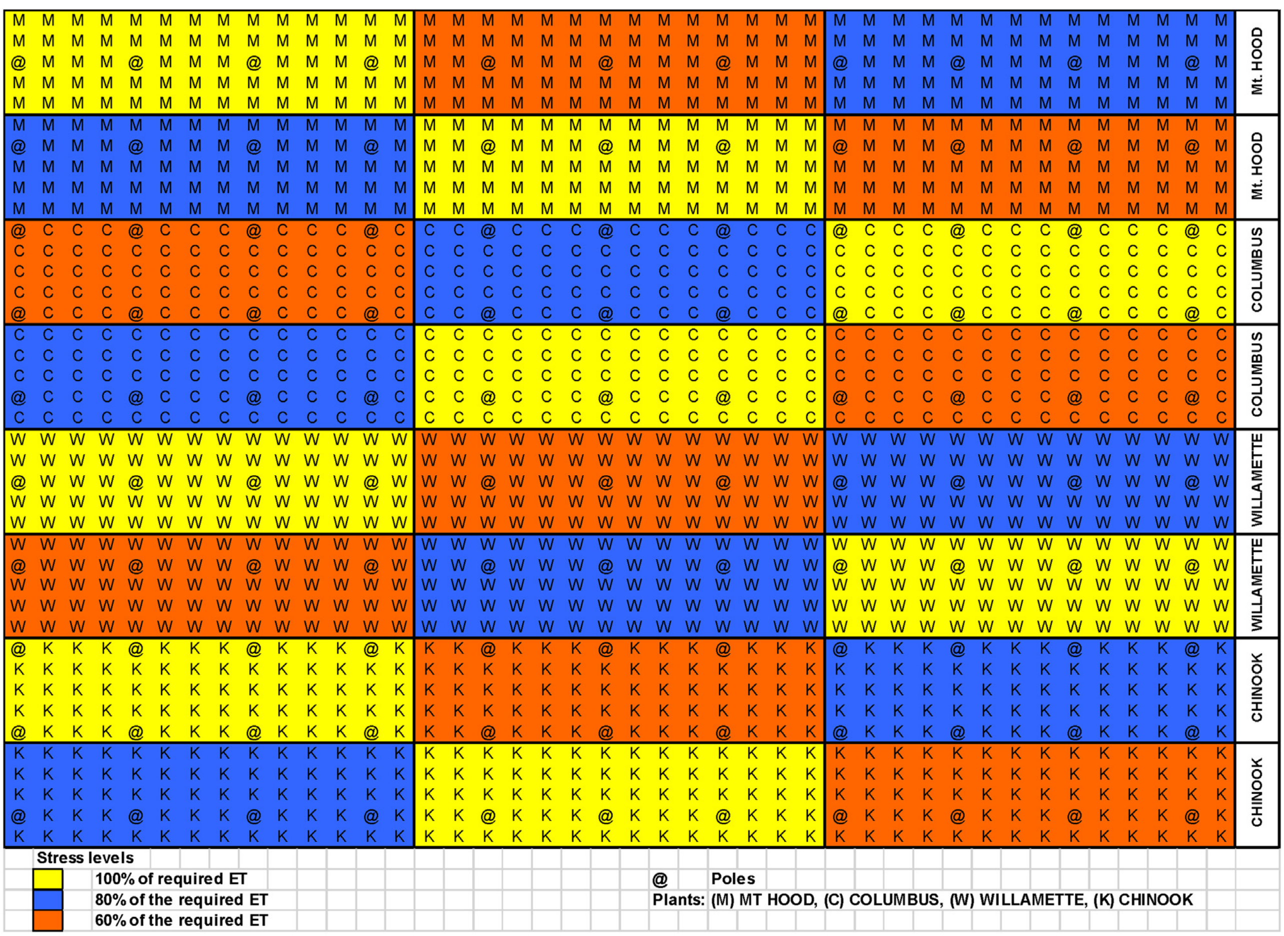

Fig. 3. Experimental plot design of the hop yard.

ning of hop season soil water content measurement was taken in April, and an end of season soil water content measurement taken on the harvest day after harvests were done for each cultivar in order to determine ΔS for the whole growing season. Upward flow of water to the root zone was of no concern in this study site since there are no shallow water tables (Soil Survey Staff, 2010). Deep percolation was considered to be negligible as care was taken to make sure that the amounts of water applied never brought soil water levels in the root zone to exceed field capacity as shown in Fig. 4. This ensured that the soil water in the root zone was always within limits that the soil could hold without significant leakages of water to the lower soil profile. The subsurface drip irrigation

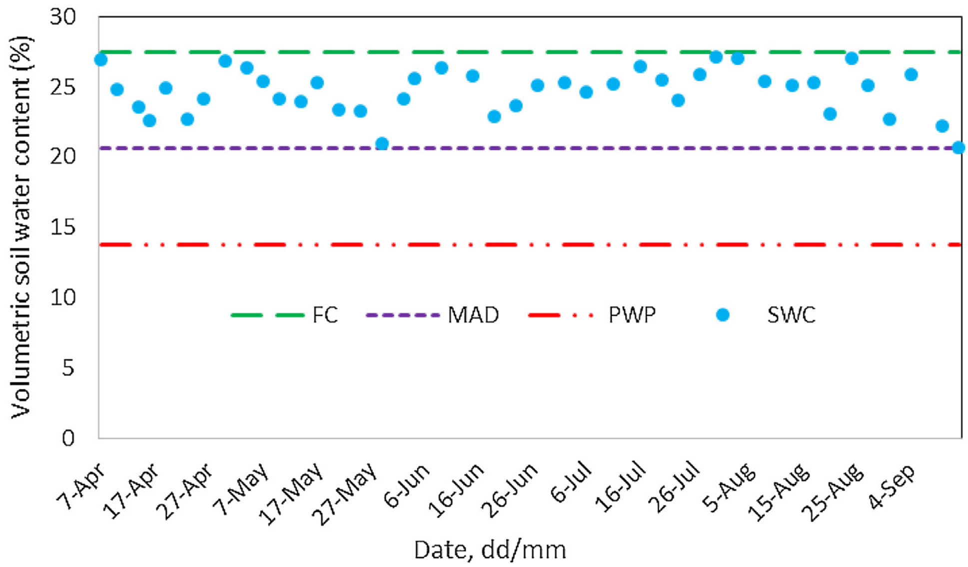

Fig. 4. Soil water content in the Columbus root zone during the 2012 growing season under the 100% irrigation level. SWC = Soil Water Content, FC = Field Capacity, MAD = Management Allowed Depletion, and PWP = Permanent Wilting Point.

system produced no runoff, and there were no precipitation runoff during the growing periods and thus R in Eq. (1) was taken to be zero for the determination of actual crop evapotranspiration. The precipitation amounts received throughout the hop growing seasons for both years are presented in Table 1. The two replications per treatment for each cultivar gave similar crop ET values; these were averaged to obtain a single seasonal crop ET value for each treatment per cultivar for each year as shown in Table 2.

2.5. Water productivity (WP)

Water productivity was determined as the mass (kg) of dried hop cones per cubic meter of crop ET (Pereira et al., 2012).

2.6. Statistical analysis

Data were analyzed by performing analysis of variance (ANOVA) and the Tukey's comparison of means test using the MINITAB 16.2.3 Statistical software (Minitab Inc. PA, USA). Statistically significant differences were determined at 5% significance level.

2.7. Economic analysis

The economic analysis was performed to determine how differences in amounts of irrigation water applied and the resulting yields affected the costs of production and the gross revenue. Costs of hop production (Galinato et al., 2011) were grouped into either fixed costs or variable costs. Fixed costs for this study are those costs that are not affected by amounts of irrigation water applied whereas variable costs are directly or indirectly affected by differences in the amounts of water applied. Fixed costs include costs for land rent; land and property taxes; hop yard establishment (including land preparation, field poles, anchor poles, anchor holes, anchor materials, wires and staples, irrigation system, hop roots, labor; these costs are only incurred during the establishment year); herbicide and fertilizer application; weeding; insecticide and fungicide application; irrigation labor; water charge; irrigation system repair and maintenance; trellis repair and maintenance; machinery repair, lubrication, and fueling; harvesting; hops cone drying and baling; market assessment; crop insurance; inspection fees; and management charge. Management charge is the opportunity cost of management the hop yard during the production year.

In Washington State, growers are given water rights that authorize them to use a predefined quantity of water every growing season. Water is then charged at a fixed rate per acre. Currently, the water is charged at about $222 per hectare. The cost of water per acre in the Yakima Valley is thus constant. The only variable cost that is impacted by the reduction in water applied in hop production is the cost of pumping the water. Electrical power (or fuel) for pumping water is saved when less water needs to be pumped as a result of deficit irrigation. The cost of pumping was assumed to reduce by the same proportion as the percentage reduction in the amount of irrigation water applied.

3. Results and discussion

3.1. Rainfall received, irrigation applied and crop water use

Total rainfall amounts received during the hop growing periods were 52 and 82 mm in 2011 and 2012 respectively; the monthly breakdown is as shown in Table 1. Irrigation amounts applied and crop evapotranspiration (crop ET) values for each irrigation level per cultivar per year are presented in Table 2. For each cultivar and year, irrigation amounts applied for the various irrigation levels were significantly different (p-value < 0.001). More irrigation water was applied in 2012 than in 2011 due to the evaporative demand in 2012 being higher than that in 2011 (Fig. 2). The differences in amounts applied for the various irrigation levels were able to maintain various water deficits in the soil as was required for this experiment. These various soil water deficits led to the various crop ET values for the various irrigation levels for each cultivar as shown in Table 2. Crop ET values were consistently higher than the applied irrigation for all treatments because the hop crop utilized stored water in the soil profile and the rainfall received during the growing period.

As mentioned earlier, the crop water requirement of most cultivars in the Yakima Valley is reported to range from 610 to 712 mm per year (Evans, 2003). Most hop growers in the area use either surface drip or furrow irrigation systems. The ETc values for full irrigation (100% irrigation level) ranged from 396 to 557 mm depending on the year's climatic conditions and cultivar (Table 2). These hop water use values are less than the reported values and are in agreement with a study that was carried out in the same hop yard from 1992 to 1995 to assess the seasonal water

Table 2
Effect of irrigation level on applied irrigation, hop cone yield, crop evapotranspiration, water productivity, and alpha and beta acids concentration for the four hop cultivars.

Cultivar	Year	Irrigation level (%)	Irrigation applied (mm)	Dry weight yield (kg ha^{-1})	Crop ET[a] (mm)	WP[b] (kg m^{-3})	Alpha acids (%)	Beta acids (%)
Mt. Hood	2011	**60**	169[a,*]	556[a]	288	0.19[a]	3.73[a]	5.33[a]
		80	222[b]	1037[a,b]	343	0.30[a]	3.52[a]	4.93[a]
		100	276[c]	1200[b]	397	0.30[a]	4.15[a]	5.50[a]
	stdev[c]		44	258	21	0.11	0.35	0.48
	p-value		*<0.001*	*0.033*		*0.073*	*0.095*	*0.326*
	2012	**60**	238[a]	1394[a]	332	0.42[a]	2.65[a]	5.04[a]
		80	307[b]	1356[a]	399	0.34[b]	3.31[a]	5.21[a]
		100	377[c]	1570[a]	479	0.33[b]	3.27[a]	5.28[a]
	stdev		57	183	60	0.04	0.48	0.22
	p-value		*<0.001*	*0.613*		*0.001*	*0.448*	*0.295*
Willamette	**2011**	**60**	174[a]	559[a]	312	0.18[a]	3.01[a]	2.12[a]
		80	230[b]	1413[a,b]	340	0.42[b]	2.46[a]	1.99[a]
		100	285[c]	1922[b]	396	0.49[b]	2.82[a]	2.06[a]
	stdev		45	521	28	0.18	0.64	0.34
	p-value		*<0.001*	*0.019*		*0.027*	*0.564*	*0.893*
	2012	**60**	243[a]	1742[a]	318	0.55[a]	3.64[a,b]	3.37[a]
		80	315[b]	1706[a]	421	0.41[b]	3.73[a]	3.45[a]
		100	386[c]	1536[a]	497	0.31[c]	3.43[b]	2.95[b]
	stdev		58	90	74	0.10	0.28	0.25
	p-value		*<0.001*	*0.551*		*0.001*	*0.019*	*0.002*
Columbus	**2011**	**60**	174[a]	2439[a]	327	0.75[a]	14.35[a]	4.64[a]
		80	230[b]	4192[b]	351	1.19[b]	13.01[a]	3.99[b]
		100	285[c]	3969[b]	407	0.98[c]	13.85[a]	4.38[a]
	stdev		45	699	32	0.40	1.25	0.42
	p-value		*<0.001*	*0.001*		*0.002*	*0.108*	*0.005*
	2012	**60**	254[a]	4041[a]	395	1.02[a]	16.71[a]	5.51[a]
		80	322[b]	4615[a]	486	0.95[a]	15.62[a]	5.27[a]
		100	395[a]	4685[a]	557	0.84[b]	17.66[a]	5.56[a]
	stdev		58	289	66	0.07	2.65	0.35
	p-value		*<0.001*	*0.713*		*0.001*	*0.470*	*0.619*
Chinook	**2011**	**60**	202[a]	1624[a]	360	0.45[a]	9.99[a]	2.65[a]
		80	266[b]	2027[a,b]	413	0.49[a]	11.71[b]	2.99[a,b]
		100	331[c]	2256[b]	444	0.51[a]	12.32[b]	3.22[b]
	stdev		52	247	35	0.03	1.31	0.29
	p-value		*<0.001*	*0.034*		*0.304*	*0.005*	*0.004*
	2012	**60**	249[a]	1768[a]	405	0.44[a]	12.57[a]	3.39[a]
		80	322[b]	2019[a]	447	0.45[a]	12.77[a]	3.25[a]
		100	395[c]	1921[a]	519	0.37[b]	13.46[a]	3.56[a]
	stdev		60	103	47	0.04	0.69	0.21
	p-value		*<0.001*	*0.803*		*0.001*	*0.073*	*0.054*

[*] Means that share a letter down the column are not significantly different by the Tukey test at 5% significancelevel.
[a] Crop ET = Actual crop evapotranspiration.
[b] WP = Water productivity.
[c] stdev = standard deviation.

use patterns for the same four hop cultivars (data not published). This implies that the subsurface drip irrigation (SDI) system (Camp, 1998) coupled with scientific irrigation scheduling based on rainfall and soil water data can substantially reduce water use in hop production even before deficit irrigation is considered. The SDI system saves water by delivering water directly to the root zone where it's needed at high efficiencies of 95% (Howell, 2003; Irmak, 2005). Buried drip lines minimize evaporation of irrigation water from the soil surface, there is no surface runoff and the low volume and high frequencies of irrigations of an SDI system minimize the movement of water below the crop root zone (Ayars et al., 1999; Yao et al., 2011; Martinez and Reca, 2014). The SDI system coupled with regular monitoring of soil water conditions and regular recording of climatic data like rainfall amounts received ensured timely applications of water directly to the root zone and eliminated irrigation applications that were not necessary (Lamm et al., 1995).

3.2. Dry weight hop cone yield

Hop yield is reported as weight per hectare of hop cones dried to about 10% water content. Mean dry weight yield of hop cones for the various irrigation levels for each cultivar for both years are summarized in Table 2. Columbus is clearly the highest yielding of all four cultivar followed by Chinook. Willamette and Mt. Hood are lower yielding cultivars. The effect of irrigation level on yield was highly significant in both years ($p < 0.001$). Generally across all the four cultivars, highest yield was obtained from the highest irrigation level (100%) for both years (Fig. 5); yield increased as the amount of irrigation applied increased. The 2012 season generally gave higher yields than the 2011 season across the irrigation levels for all the cultivars except for the 100% treatment in Willamette and Chinook (Fig. 5). This was because the new hop plants that were planted at the beginning of the 2011 season put most of their effort into establishing their extensive root system and not into above the ground growth for the 2011 growing season. This affected yield from these plants in 2011. Water stress further affected yield production of these plants as is shown by the results in Table 2; the

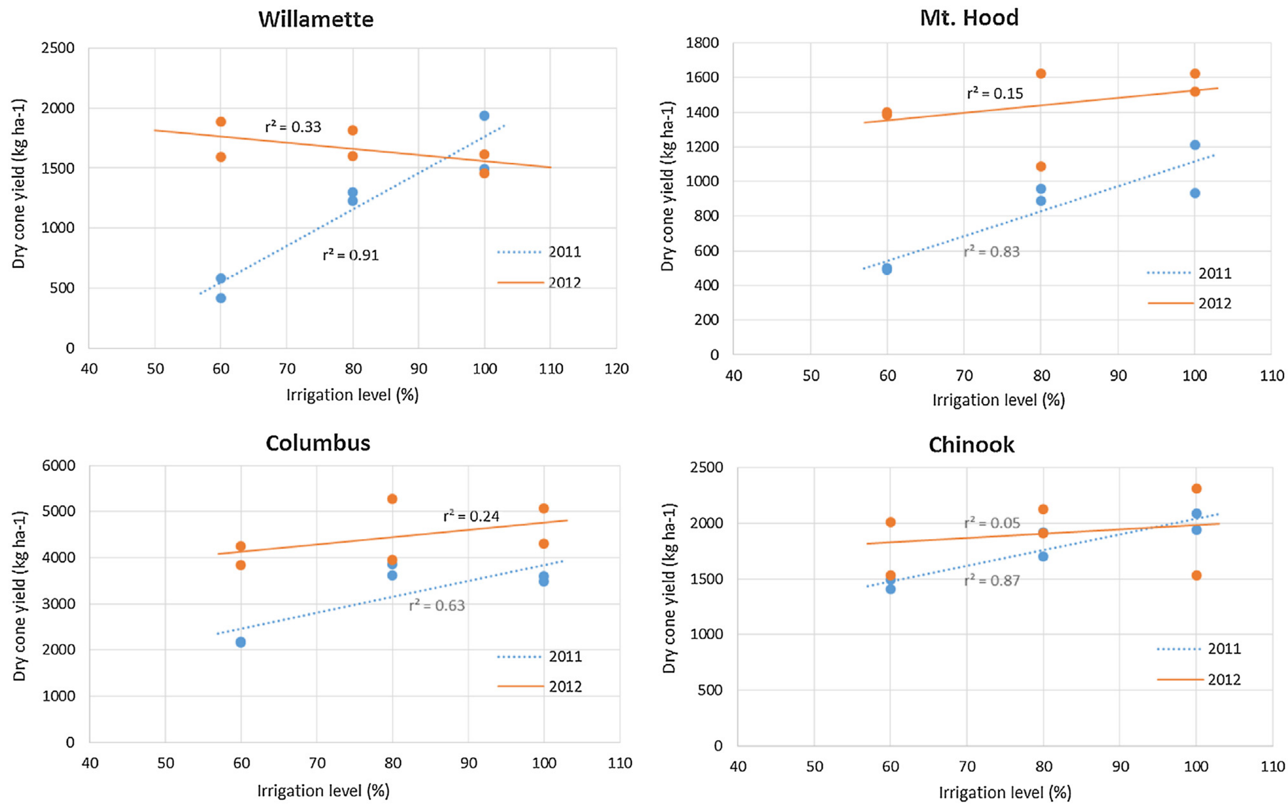

Fig. 5. Hop cone yield versus irrigation level for both years for the four cultivars.

lowest yields were obtained from the driest irrigation level, 60%, across all cultivars in the year 2011. With the root system developed in the second year of 2012, the plants were able to fair better and give better yields with water stress (Fig. 5). This is because their developed roots were now able to extract water from lower soil layers. The highest percentage decrease in yield by the driest irrigation level (60%) in the 2012 season was 14% across the cultivars; this suggests that yield reduction due to deficit irrigation may not be very significant when water stress is applied to hop plants with well-developed root systems. This also implies that when water is scarce and/or expensive, a grower may still be able to receive reasonable yield when he/she subjects moderate stress to hop plants.

When yield totals for the two years are compared to those of fully irrigated plots, the 60% irrigation level plots gave 30, 33, 25, and 19% less yield for Mt. Hood, Willamette, Columbus and Chinook cultivars respectively. The 80% irrigation level on the other hand decreased yields of Mt. Hood, Willamette and Chinook by 14, 10, and 3% respectively, whereas, Columbus yields increased by 2%. This suggests that Columbus and Chinook cultivars may have greater tolerance to water stress than Mt. Hood and Willamette cultivars.

Fig. 6 presents hop crop-water use production functions for the four cultivars. The functions were determined by averaging yield and crop ET values for both years for each irrigation level. These functions can be used by hop growers to optimize irrigation and estimate the reductions in yield that can occur under scenarios when water is scarce. Depending on the opportunity cost for water, a grower is then able to make an informed choice on the most economically profitable use of the water.

3.3. Water productivity (WP)

Table 2 presents the mean water productivities for all cultivars, water stress levels for both years. Irrigation levels had a significant effect on water productivity across all the cultivars. There were significant differences among water productivities for the irrigation levels for the various cultivars. Water productivity trends for the cultivars are presented in Fig. 7. Across all cultivars in 2011, water productivities for the 80% and 100% irrigation levels were not significantly different. However, the water productivities for the driest irrigation level (60%) decreased significantly. This as mentioned earlier was due to the newly established plants in this season that didn't produce optimally in this year and whose yield was further impacted by water stress. In 2012 however, water productivity increased as water stress increased (Fig. 7). This suggests that once a hop plant has established its extensive root system, deficit irrigating the plant moderately will improve efficiency of use of the water applied.

3.4. Yield quality

Alpha and beta concentrations for all the cultivars and irrigation levels for both years are presented in Table 2. The irrigation levels generally did not affect the concentrations of alpha and beta acids significantly as indicated in Table 2. Generally alpha and beta acids concentrations of the cultivars were not significantly different across irrigation levels for each of the two years. Deficit irrigation therefore had no significant effect on hop cone quality. Similar results are reported by Fandiño et al. (2015) who found that hop transpiration did not significantly affect concentrations of both alpha and beta acids. Alpha and beta concentrations however differed significantly across the two years. Except for Mt. Hood, both alpha and beta acids were significantly higher for the year 2012 than for 2011 (Table 3). Similarly as explained for dry matter hop cone yield quantity, in 2011, the newly established plants were establishing their root systems thus limiting above the ground growth including alpha and beta acids accumulation. In 2012, with

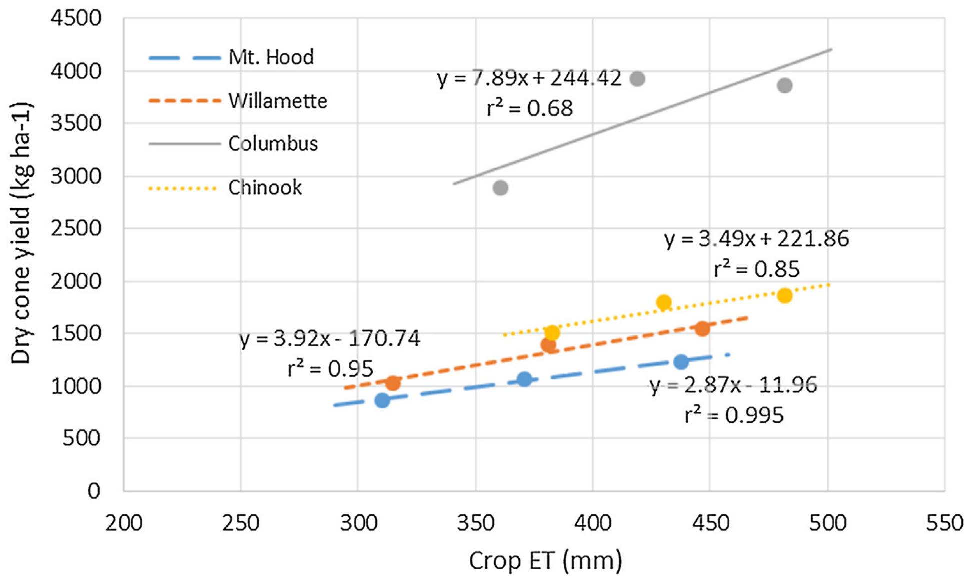

Fig. 6. Relationships between yield and actual crop evapotranspiration for the four cultivars. Values are averages of 2011 and 2012 ETc and yields.

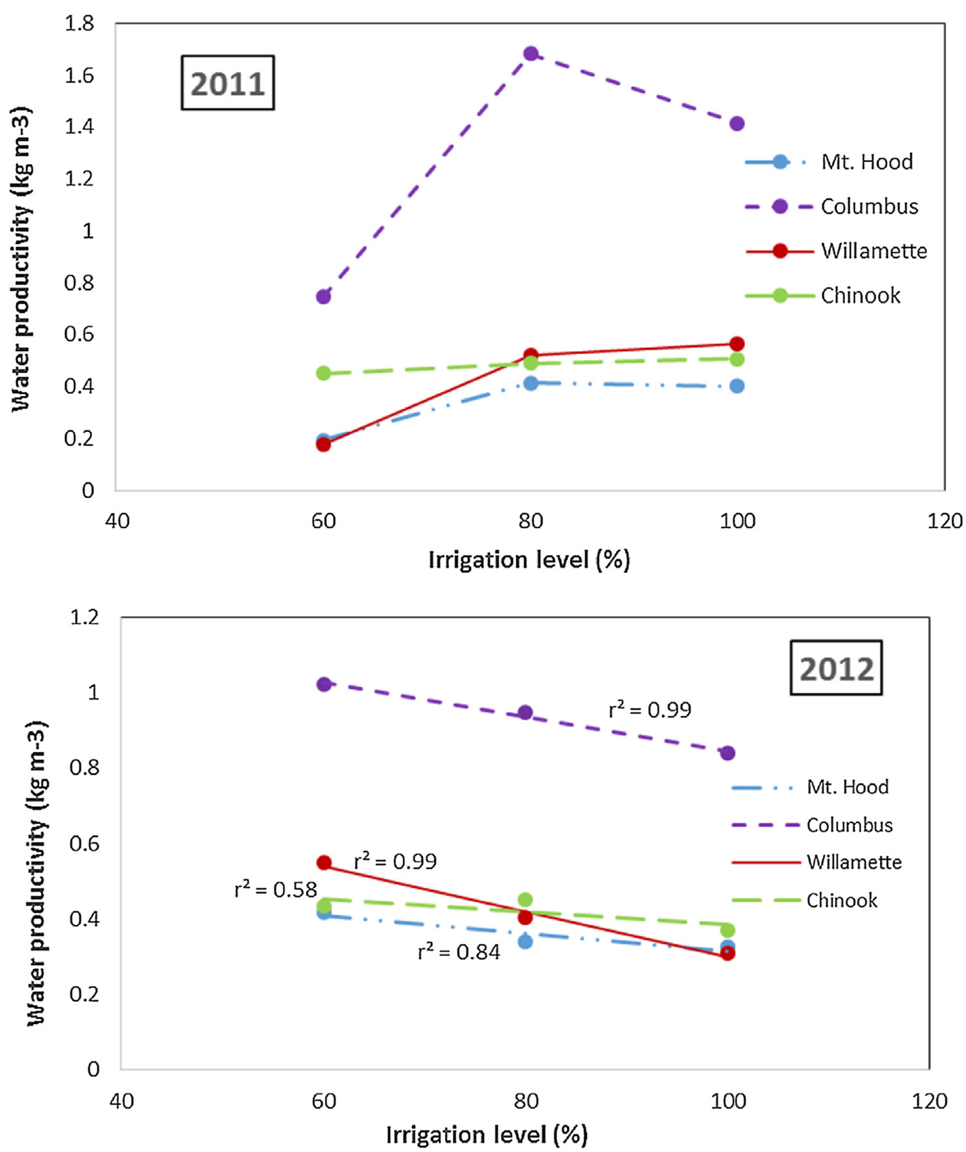

Fig. 7. Water productivity at the three irrigation levels for the four cultivars for 2011 and 2012.

Table 3
Effect of year of production on the concentrations of alpha and beta acids of the four hop cultivars.

Cultivar	Year	Average alpha acids (%)	Average beta acids (%)
Chinook	2011	11.29	2.95
	2012	12.93	3.40
	p-value	*<0.001*	*<0.001*
Columbus	2011	13.71	4.33
	2012	16.66	5.44
	p-value	*0.021*	*<0.001*
Mt. Hood	2011	3.81	5.25
	2012	2.99	5.18
	p-value	*<0.001*	*0.636*
Willamette	2011	2.77	2.06
	2012	3.62	3.26
	p-value	*0.003*	*<0.001*

the rooting system now established, alpha and beta acids accumulation then improved.

3.5. Economic analysis

The total establishment cost and the first year operation of a hop yard is approximately $14,514 per hectare (Galinato et al., 2011). The total cost of producing hops on an established yard is $15,374 (Galinato et al., 2011). The annual cost of pumping water was estimated to be only about US $225. Deficit irrigation causes reductions in water applied, thus reduction in pumping costs. However, the reduction in pumping costs due to deficit irrigation results into minimal reductions in total hop production costs. For Chinook for example; according to the production function generated in Fig. 6, 100% irrigation level gives a yield of 2131 kg/ha and the 80% irrigation level gives a yield of 1931 kg/ha. The reduction in yield is 202 kg. The price for 1 kg of hops in Washington State in 2012 was about $7.03 (USDA, 2012). This brings the loss in revenue to $1422. Assuming that the pumping cost reduce by the same proportion as the reduction in water needed to be pumped, the pumping cost will reduce by 20%. The reduction in pumping cost is therefore $45. The reduction in pumping costs is the overall reduction in the total hop production costs. Owing to this small decrease in hop production costs, the gross revenue reduces more than the production costs making deficit irrigation of hops under SDI system less profitable. However, in scenarios where water is scarce and/or expensive, a grower will be forced to make a decision on whether to concentrate the limited water over a smaller land area and irrigate it adequately or to irrigate the total area with levels below the full crop irrigation requirement (i.e. below 100% irrigation level). The optimum decision will be that where the overall net income is maximized.

4. Conclusions

In this two year study, hop yield increased with increase in irrigation level. The decrease in yield was less significant for hop plants after they had a well-developed root system. The yield reduction though caused a greater loss in revenue than the savings in total cost of production as a result of applying less water. When water is readily available, deficit irrigation of hops grown under SDI might not be an economically viable practice. However, during water short years, applying moderate stress to hop plants might be a practical choice to hop growers.

Water productivity decreased with increase in irrigation level. This implies that deficit irrigating hops can reduce water losses due to deep percolation and further increase the application efficiency of the SDI system. For each year of production, deficit irrigation maintained the quality of the hop cones across the various cultivars similar to those for fully irrigated hops. Like hop cone yield quantity, hop cone quality also improved in the second year of production due to the plants having a more developed root system. The production functions developed in this study (Fig. 6) are useful in forecasting the impact of different water stress levels on hop yield of the four cultivars under SDI.

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