Washington State Grape and Wine Research Program

FINAL REPORT
2017-21 FUNDING CYCLE

1. **Summary**:

Project title: Influence of cultivar, environment and management on grape yield components and quality
Principal investigator: Markus Keller

Vineyard management for optimum wine quality and low labor input is a top industry priority in Washington and elsewhere. This includes tailoring irrigation practices to produce premium-quality fruit according to winery specifications. Irrigation management is the most powerful tool available in arid eastern Washington to maximize fruit quality, but there is little knowledge regarding optimum irrigation amounts and timing for white wine grape varieties. This is in part because most irrigation trials have been conducted with relatively few red varieties. We studied the response of Riesling wine grapes to different irrigation practices, namely regulated deficit irrigation (RDI), partial rootzone drying (PRD), as well as full (no stress) irrigation. Full irrigation was based on replacing 100% of the water evaporated from the vineyard during the growing season. A key outcome from this study is the recommendation to avoid excessive water deficit in the production of white wine grape, and especially aromatic grapes like Riesling. Imposing RDI between fruit set and veraison tended to result in smaller canopies that were associated with high sun exposure of the fruit. By contrast, PRD from fruit set through harvest led to similar, or occasionally more, shoot growth compared with full irrigation and showed little difference in fruit composition. Thus PRD may be an interesting alternative irrigation strategy considering its potential for higher white wine quality compared to RDI despite similar irrigation water savings. The irrigation scheduling decision for PRD was easy to make based on soil moisture on two sides of a vine: irrigation was initiated on the drying side of the rootzone and withheld on the wet side whenever the soil moisture of the drying side fell below 12%. The "switching threshold" could be adapted to different soil types for integration in automated irrigation decision-support tools. Our results are being communicated to industry end users and other stakeholders during field days, workshops, industry meetings (e.g. WWA, WAVE), and other means as appropriate. This work will place valuable information in the hands of grape growers, enabling them to make better, science-based decisions regarding application and conservation of limited irrigation water. It will also lay the foundation for the development of more effective irrigation strategies for the wine industry, which will permit improvements in fruit and wine quality through the judicious application of deficit irrigation strategies with a focus on white wine grapes.

2. **Annual or Final Report**: Final.

3. **Project Title**: Influence of cultivar, environment and management on grape yield components and quality

4. **Principal Investigator/Cooperator(s)**:
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Cooperator: James Harbertson, WSU Wine Science Center, Richland WA 99352

5. **Objective and Experiments Conducted to Meet Stated Objective**:
Optimize irrigation strategies for high-quality white wine grape production.
Note: This report differs from the original proposal submitted in 2017. Only Objective 1 (as outlined above) from that proposal is considered here. A final report for Objective 2 (Determine responses to water deficit of different wine grape cultivars) was submitted in 2019, and Objective 3 (Support other research projects and graduate students) is ongoing.

6. **Summary of Major Research Accomplishments and Results by Objective:**
In 2017 we established a field trial with Riesling in the IAREC Roza research vineyard that was planted in 2010. Irrigation regimes or strategies include a non-stress control (full replacement of crop evapotranspiration, ET_c, after control of shoot growth is achieved), regulated deficit irrigation (RDI, moderate water deficit from fruit set through veraison), and partial rootzone drying (PRD, alternating irrigation between two sides of each vine from fruit set through harvest). All regimes were applied in four randomly replicated blocks of 55-60 vines each. The scope of this study was expanded in 2019 with NSF/USDA funding to develop "smart" irrigation practices based on remote sensing of plant water status; 2021 marks the last field season for that project. Measurements include soil moisture (θ_v), midday leaf water potential (Ψ_l), canopy growth and density, yield components, and fruit and wine composition. Wines were made at the WSU Wine Science Center from three of the four field replicates with grapes from each irrigation regime in 2018 and 2019, but all 2020 musts were discarded due to press equipment malfunction. Moreover, no formal sensory evaluation has been conducted on any of the wines to date.

Irrigation management in 2017 was somewhat challenging due to high amounts of winter snowfall and spring rainfall that led to vigorous shoot growth and large canopies. The non-stress control was associated with the highest θ_v and Ψ_l, while PRD was often similar to RDI (Table 1). Also, Ψ_l was well correlated with θ_v in the control and RDI regimes ($r = 0.80$, $P < 0.001$), but much less so in PRD ($r = 0.33$, $P < 0.001$) as expected. The goal of PRD is to conserve irrigation water while avoiding plant water stress, whereas RDI also conserves water but always results in some plant water stress. The control had the highest yield and RDI the lowest, with PRD intermediate (Table 1). Cluster weights were similar among irrigation regimes, but the deficit irrigation treatments were associated with lower cluster numbers, even though all treatments were irrigated the same until after fruit set. Berry weight, total soluble solids (TSS), and pH were similar among irrigation regimes, but grapes from the control had higher titratable acidity (TA) than those from RDI.

Table 1. Performance of field-grown Riesling under different irrigation regimes in 2017. Different letters within rows indicate significant differences by Fisher's LSD test ($P < 0.05$).

Parameter	**Irrigation treatment**		
	Control	RDI	PRD
θ_v (% v/v) (fruit set – veraison)	13.3 a	10.8 b	11.5 b
(veraison – harvest)	15.0 a	13.8 ab	12.8 b
Ψ_l (MPa) (fruit set – veraison)	-0.97	-1.11	-1.00
(veraison – harvest)	-0.70 a	-0.83 ab	-1.05 b
Pruning weight (kg/vine)	1.0	1.0	1.0
Cane number	44	43	40
Weak canes (<6 nodes)	9	8	7
Yield (tons/acre)	9.6 a	8.2 b	8.6 ab
Clusters per vine	110 a	93 b	90 b
Cluster weight (g)	100	101	109
Berry weight (g)	1.10	1.07	1.15
Berry TSS (Brix)	19.0	18.4	18.5
Berry pH	3.19	3.22	3.22
Berry TA (g/L)	9.1 a	8.4 b	8.8 ab

In 2018, RDI reduced θ_v and Ψ_l between fruit set and veraison, but not thereafter, while PRD was often similar to the non-stress control (Table 2). Like in 2017, Ψ_l was better correlated with θ_v in the control and RDI regimes ($r = 0.62$, $P < 0.001$) than in PRD ($r = 0.33$, $P < 0.05$). Shoots were rather vigorous in 2018. Although the irrigation treatments did not alter shoot length, RDI reduced vigor as indicated by fewer lateral leaves per shoot, lower pruning weight, more weak canes (i.e., canes with fewer than six nodes), higher sunlight exposure of the fruit zone, and markedly higher proportion of sun-exposed clusters (Table 2). The control had higher yield than RDI and PRD. The cluster number was lower, but the cluster weight was higher, in PRD than in the other treatments (Table 2). Berry weight, TSS, and pH were similar among irrigation regimes, but fruit from the control had higher TA than that from PRD (Table 2). Across berry samples collected at harvest, TA declined as TSS increased ($r = -0.85$, $P < 0.001$), and the pH increased with increasing TSS ($r = 0.78$, $P < 0.01$) and decreasing TA ($r = -0.79$, $P < 0.01$).

At the beginning of the 2019 growing season the soil water content was unusually high due to high spring snowpack and rainfall. Moreover, the RDI plots started the season with higher θ_v than the other plots. This situation delayed the onset of soil water deficit in the vineyard, delaying and compressing the target deficit period and inducing high plant vigor. Nevertheless, RDI (7.6") and PRD (8.3") received 38% and 32%, respectively, less seasonal irrigation water than did full irrigation (12.2"), which was based on replacing 100% of the evaporated water once shoot growth had stopped. All irrigation regimes resulted in similar shoot growth, crop yield, berry size, and fruit composition (Table 3). A subtle treatment effect was noticed in canopy architecture, with PRD reducing lateral shoot growth and canopy density (number of leaf layers). Clearly, the brief preveraison water deficit period of the RDI regime was insufficient to alter vine growth, yield formation, and fruit composition. The seasonal changes in midday Ψ_l matched the changes in θ_v ($r = 0.7$, $P < 0.01$).

Table 2. Performance of field-grown Riesling under different irrigation regimes in 2018. Different letters within rows indicate significant differences by Fisher's LSD test ($P < 0.05$).

Parameter	Irrigation treatment		
	Control	RDI	PRD
θ_v (% v/v) (fruit set – veraison)	14.3 ab	13.0 b	14.8 a
(veraison – harvest)	14.8	14.9	13.6
Ψ_l (MPa) (fruit set – veraison)	-0.77 a	-0.91 b	-0.83 ab
(veraison – harvest)	-0.71	-0.77	-0.83
Shoot length at harvest (cm)	175	140	176
Lateral leaves/shoot	36 a	39 a	24 b
Leaf layers across canopy	2.8	2.7	2.7
Fruit zone sun exposure (%)	22 b	28 a	26 ab
Pruning weight (kg/vine)	1.00 a	0.77 b	0.93 ab
Cane number	32 a	32 a	25 b
Weak canes (<6 nodes)	5 b	7 a	3 c
Yield (tons/acre)	8.7 a	7.4 b	7.4 b
Clusters per vine	75 a	69 a	58 b
Cluster weight (g)	133 ab	121 b	144 a
Berry weight (g)	1.48	1.49	1.63
Berry TSS (Brix)	19.2	20.1	20.0
Berry pH	3.10	3.10	3.14
Berry TA (g/L)	7.78 a	7.04 ab	6.96 b

Table 3. Performance of Riesling wine grapes grown under different irrigation regimes in 2019. Different letters within rows indicate significant differences by Fisher's LSD test ($P < 0.05$).

Parameter	Irrigation treatment		
	Control	RDI	PRD
θ_v (% v/v) (fruit set – veraison)	12.6	12.2	11.2
(veraison – harvest)	13.5	13.1	12.2
Ψ_l (MPa) (fruit set – veraison)	-0.93	-1.07	-1.06
(veraison – harvest)	-1.2	-1.1	-1.3
Shoot length at harvest (cm)	128	135	135
Lateral leaves/shoot	19 a	20 a	16 b
Leaf layers across canopy	3	3	2
Fruit zone sun exposure (%)	21	21	20
Pruning weight (kg/vine)	0.87	0.84	0.88
Cane number	37	37	35
Weak canes (<6 nodes)	6	5	5
Yield (tons/acre)	9	8	8
Clusters per vine	102	98	100
Cluster weight (g)	98	97	90
Berry weight (g)	1.1	1.1	1.2
Berry TSS (Brix)	20.0	18.6	19.1
Berry pH	3.3	3.3	3.3
Berry TA (g/L)	7.5	7.8	7.4

In 2020, we increased the water supply in the control regime to avoid any potential vine water stress. Consequently, the RDI regime led to significantly lower θ_v between fruit set and veraison than did the other irrigation regimes. Equipment malfunction prevented us from collecting reliable data on irrigation water use by treatment, but the seasonal changes in midday Ψ_l roughly reflected the changes in θ_v ($r = 0.6$, $P < 0.01$). This planned difference resulted in lower midday Ψ_l, as well as reduced shoot growth, crop yield, and berry size, and higher fruit-zone light exposure in RDI vines (Table 4). We hedged the more vigorous shoots of control and PRD vines at veraison to avoid excessive fruit-zone shading. However, overall yields were lower in 2020 than in previous years, and basic fruit composition remained unaffected by the irrigation regime. Thus, the PRD irrigation strategy was able to maintain larger canopies and higher yields compared with RDI, with no apparent change in fruit composition (Table 4).

Table 4. Performance of Riesling wine grapes grown under different irrigation regimes in 2020. Different letters within rows indicate significant differences by Fisher's LSD test ($P < 0.05$).

	Irrigation treatment		
Parameter	Control	RDI	PRD
θ_v (% v/v) (fruit set – veraison)	17.0 a	12.4 b	15.8 a
(veraison – harvest)	17.1	17.8	15.9
Ψ_l (MPa) (fruit set – veraison)	-0.81 a	-1.06 c	-0.94 b
(veraison – harvest)	-0.75	-0.78	-0.86
Shoot length at harvest (cm)	116 a	89 b	124 a
Lateral leaves/shoot	24	17	24
Leaf layers across canopy	2 b	2 b	3 a
Fruit zone sun exposure (%)	38 b	48 a	37 b
Pruning weight (kg/vine)	0.48 ab	0.37 b	0.53 a
Cane number	23	22	24
Weak canes (<6 nodes)	1	2	1
Yield (tons/acre)	5.2 a	3.2 b	5.0 a
Clusters per vine	52	47	49
Cluster weight (g)	113 a	77 b	114 a
Berry weight (g)	1.25	1.12	1.25
Berry TSS (Brix)	21.3	21.6	21.4
Berry pH	3.03	3.03	3.02
Berry TA (g/L)	9.4	8.9	8.8

Across all four years of this study, RDI reduced shoot growth ($P < 0.001$) as indicated by the lower pruning weight (0.75 kg/vine) compared with PRD (0.85 kg/vine) and the fully-irrigated control (0.87 kg/vine). Though the overall difference was small, it confirms that PRD had the intended effect of achieving a somewhat larger canopy compared with RDI. The low pruning weight and yield in 2020 compared with the previous three years was a result of excessive shoot thinning, which led to low cluster numbers. Across the four years, the crop level of control vines was 14% higher (8 tons/acre) than that of either PRD vines (7.1 tons/acre) or RDI vines (6.9 tons/acre; $P < 0.001$). Perhaps somewhat surprisingly, this yield difference was mostly caused by higher cluster numbers (+13%) on the control vines ($P < 0.001$). Irrigation regime effects on bud fruitfulness may not be the culprit here, since differences in cluster numbers were already noted in year one. The cluster weight, however, was 9% lower in RDI vines than in either control vines or PRD vines ($P = 0.01$). Overall, the cropping year had a much greater effect ($P < 0.001$) on average berry weights than did the irrigation strategy ($P = 0.051$). Across years, the PRD vines produced larger berries than the RDI vines, while the berries of non-stress control vines were intermediate in weight. Year ($P < 0.001$) but not irrigation strategy ($P = 0.75$) affected juice TSS at harvest. Similarly, while the vintage effect was highly significant ($P < 0.001$) for pH, there was only a trend ($P = 0.08$) for irrigation strategy, with full irrigation leading to marginally lower pH (3.14) than RDI (3.19) but not PRD (3.18). Nonetheless, both year ($P < 0.001$) and irrigation strategy ($P = 0.004$) altered TA. Across years, the fruit from control vines had slightly higher TA (8.54 g/L) than the fruit from either RDI vines (7.93 g/L) or PRD vines (8.09 g/L).

Basic wine chemistry data measured at the WSU Wine Science Center for the 2018 and 2019 wines indicate no effect of either vintage or irrigation strategy on wine pH. However, even though the 2019 wines had less malic acid (0.97 g/L) than the 2018 wines (1.47 g/L), the 2019 wines had 1 g/L higher TA compared with 2018 ($P = 0.01$). Across the two years, moreover, control wines had slightly but significantly ($P < 0.001$) more malic acid (1.33 g/L) than RDI wines (1.21 g/L) and PRD wines (1.13 g/L). In 2019, but not in 2018, the control wines also had somewhat higher acetic acid (0.14 g/L) than the wines from the deficit irrigation regimes (0.1 g/L). Neither the year ($P = 0.27$) nor the irrigation effect ($P = 0.08$) was significant for wine residual sugars; however, the much greater variation in the control wines may have masked their tendency to contain more residual sugar. Wine alcohol levels were similar between the two years ($P = 0.98$), but control wines had higher ($P = 0.045$) alcohol (12.5%) than either PRD wines (11.6%) or RDI wines (11.2%). No formal sensory analysis has been conducted on the wines made from this field trial. However, informal (non-blind!) tasting notes for the 2018 and 2019 wines suggest greater perceived bitterness of the RDI wines than either the PRD wines or the control wines.

Confirming our results from an earlier field trial with Riesling and Chardonnay (see our 2017 final report to WSGWRP), a key outcome from this study is the recommendation to avoid excessive water deficit in the production of white wine grapes, and especially aromatic grapes like Riesling. Imposing RDI between fruit set and veraison tended to result in smaller canopies that were associated with high sun exposure of the fruit, which might increase bitterness or astringency in wine. With similar or occasionally more canopy growth compared with full irrigation and little difference in fruit composition, PRD may be an interesting alternative irrigation strategy considering the similar irrigation water savings (30-40%) with the two deficit strategies. Also, the irrigation scheduling decision for PRD was easy to make based on soil moisture of two separate rootzones: irrigation was initiated on the drying side of the rootzone and withheld on the wet side whenever the soil moisture of the drying side fell below 12%. The "switching threshold" could be adapted to different soil types for integration in automated irrigation decision-support tools.

7. **Outreach and Education Efforts - Presentations of Research**:

Results from this project are being communicated to industry end users and other stakeholders during field days, workshops, industry meetings (e.g. WAVE, WWA, WSGS), and other means as appropriate. Novel scientific findings will be published in peer-reviewed journals. The following list is a selection of research presentations relevant to this project.

Interviews
Kate Prengaman, Good Fruit Grower, June 7, 2021
Glenn Vaagen, Washington Ag Network and KONA-AM (Pasco, WA), April 19, 2021
Ross Courtney, Good Fruit Grower, February 16, 2021
Lee Allen, Western Farm Press, January 7, 2021
Glenn Vaagen, Washington Ag Network and KONA-AM, January 5, 2021
Kate Prengaman, Good Fruit Grower, October 21, 2020
Kathie Zipp, American Fruit Grower, September 14, 2020
Sydney Brown, Daily Evergreen, September 14, 2020
Brandon Schrand, WSU Insider, September 8, 2020
Kate Prengaman, Good Fruit Grower, July 24, 2020
Glenn Vaagen, Washington Ag Network and KONA-AM, June 11, 2020
Lauren Paterson, WSU Voice of the Vine, March 16, 2020
Glenn Vaagen, Washington Ag Network and KONA-AM, January 22, 2020
Kate Prengaman, Good Fruit Grower, September 27, 2019
Michael Alberty, The Oregonian, September 17, 2019
Ross Courtney, Good Fruit Grower, April 18, 2019
Brandon Schrand, WSU Voice of the Vine, January 24, 2019
Anna King, National Public Radio, August 21, 2018
Christina Mangiapani, WSU Voice of the Vine, July 24, 2018
Glenn Vaagen, Washington Ag Network and KONA-AM, May 7, 2018
Andy Perdue, Seattle Times, February 27, 2018
Glenn Vaagen, Washington Ag Network and KONA-AM, February 2, 2018
Rachel Becker, The Verge, January 30, 2018

Website
http://wine.wsu.edu/extension/weather: Weekly updates of growing degree days, precipitation, and evapotranspiration for each of Washington's AVAs throughout the growing season.

Presentations
Diverres G. and M. Keller. 2021: Irrigation for white wine grapes. Washington State University/Washington State Grape Society Viticulture Field Day, Prosser, WA, July 29, 2021.
Keller M. 2021: Using rootstocks with deficit irrigation. Walla Walla Vit Tech Group Webinar, Walla Walla, WA, June 2, 2021.
Keller M. 2021: Thirsty vines: of stresses and varieties. Napa Valley Grapegrowers Sustainable Vineyard Practices Webinar, Napa, CA, March 11, 2021.
Hernández-Montes E. 2020: Efecto del estrés por calor y el estrés hídrico sobre el crecimiento, la fisiología de la vid y la composición del mosto. Unified Symposium, Sacramento, CA, February 4-6, 2020.
Hernández-Montes E. 2020: Results of different vineyard practices on acidity from academic vineyard trials. Washington Winegrowers Association Convention, Kennewick, WA, March 2-5, 2020.

Keller M. 2020: Irrigation for grape yield and quality and coping with heat stress. Webinar, 42nd South African Society for Enology and Viticulture Virtual Conference, Stellenbosch, South Africa, November 3-5, 2020.

Keller M. 2020: Irrigation management by grape variety. Webinar, Sun World International, Rutigliano, Italy. October 29, 2020.

Keller M. 2020: Turning up the heat: consequences and mitigation of heat and drought stress. Webinar, California State University, Fresno, CA, October 28, 2020.

Keller M. 2020: Vine water use by variety in a changing climate. WAVE Webinar 2020, Washington Advancements in Viticulture and Enology, April 1, 2020.

Keller M. 2020: The heat is on: consequences and mitigation of heat and drought stress. 9th International Table Grape Symposium. Santiago, Chile, February 16-21, 2020.

Thapa S., C. Kang, Z. Zhou, G. Diverres, U. Bhattarai, M. Karkee, Q. Zhang and M. Keller. 2020: Understanding water stress in vineyards using ground-based hyperspectral and 3D imagery. ASABE 2020 Annual International Meeting, Virtual, July 12-15.

Hernández-Montes E., Y. Zhang, N. Barkat and M. Keller. 2019. Heat waves and drought stress impact grapevine growth and physiology. 21st International GiESCO Symposium. Thessaloniki, Greece, June 23-28, 2019.

Hernández-Montes E., Y. Zhang, N. Barkat and M. Keller. 2019: Grapevine growth and physiology during heat and drought stress and recovery. American Society for Enology and Viticulture National Conference, Napa, CA, June 17-20, 2019.

Keller M. 2019: Water and grape ripening: myth meets reality. Seminar, CONICET and Universidad Nacional de Cuyo, Chacras de Coria, Mendoza, Argentina, May 9, 2019.

Keller M., J. Martinez, E. Hernández-Montes, Y. Zhang and B.M. Chang. 2019: Staying hydrated – not easy when it's hot. 21st International GiESCO Symposium. Thessaloniki, Greece, June 23-28, 2019 (keynote presentation).

Keller M. 2018: Irrigation for wine and juice grapes: differences and similarities. Washington State Grape Society Annual Meeting. Grandview, WA, November 15-16, 2018.

Keller M. 2018: Water and grape ripening: facts and fiction. Enoforum. Zaragoza, Spain, May 31 – June 1, 2018 (keynote presentation).

Keller M. 2018: Viticulture research. National Viticulture and Enology Extension Leadership Conference. Prosser, WA, May 22, 2018.

Keller M. 2018: Vineyard irrigation practices. Colorado Wine Industry Development Board Online Conference. May 7, 2018.

Keller M. 2018: Vineyard practices for crop yield and quality. Montana Grape and Winery Association Conference. Kalispell, MT, April 5-7, 2018.

Keller M. 2018: Water and grape ripening: facts and fiction. Ohio Grape and Wine Conference. Columbus, OH, February 19-20, 2018.

Keller M. 2018: Growing grapes for white wine production: do's and don'ts in the vineyard. Washington Winegrowers Association Convention. Kennewick, WA, February 6-8, 2018.

Keller M. 2018: Managing phenolics in the vineyard. Unified Wine and Grape Symposium. Sacramento, CA, January 23-25, 2018.

Zhang Y. and M. Keller. 2018: Irrigating white wine grape varieties. WAVE 2018, Washington Advancements in Viticulture and Enology. Prosser, WA, April 4, 2018.

Posters

Chang B.M. and M. Keller. 2021: Grape leaves may be more vulnerable to heat waves in cool than in warm seasons. 72nd American Society for Enology and Viticulture Annual Meeting. Virtual Conference, June 21-24, 2021.

Diverres G. and M. Keller. 2021: Tailoring smart irrigation strategies for white wine grapes in eastern Washington. 72nd American Society for Enology and Viticulture Annual Meeting. Virtual Conference, June 21-24, 2021.

Diverres G., S. Thapa, C. Kang, M. Karkee, Q. Zhang and M. Keller. 2021: Tailoring smart irrigation strategies for white wine grapes in eastern Washington. Washington Winegrowers Convention, Virtual, March 15-18, 2021 (also flash talk).

Chang B.M., J. Harbertson, T. Collins and M. Keller. 2020: Heat stress in wine grapes: acclimation and potential mitigation. Northwest Center for Small Fruits Research Virtual Conference, December 14-16, 2020.

Diverres G., S. Thapa, C. Kang, M. Karkee, Q. Zhang, M. Keller. 2020: Evaluating deficit irrigation strategies in Washington state. Washington Winegrowers Convention, Kennewick, WA, March 2-5, 2020 (also flash talk).

Barkat N., E. Hernández-Montes, P. Lehr and M. Keller. 2019: Heat stress and water stress impact grapevine growth, physiology and berry development. Washington Winegrowers Association Convention, Kennewick, WA, February 11-14, 2019.

Bondada B., G. Stahl, R. Smithyman and M. Keller. 2019: Stomatal conductance as a guide to scheduling irrigation in grapevine. 70th American Society for Enology and Viticulture Annual Meeting. Napa, CA, June 17-20, 2019.

Diverres G. and M. Keller. 2019: Irrigation strategies for white wine grapes in eastern Washington. Washington State Grape Society Annual Meeting, Grandview, WA, November 14-15, 2019.

Hernández-Montes E., Y. Zhang, N. Barkat and M. Keller. 2019: Heat waves and drought challenge grapevine growth and productivity. Washington Winegrowers Association Convention, Kennewick, WA, February 11-14, 2019.

Hernández-Montes E., B.M. Chang, N. Shcherbatyuk, G. Diverres, L.J. Mills, A. Kawakami and M. Keller. 2019: Sunlight buffet: a look at photosynthesis. WSU-IAREC Centennial, Prosser, WA, October 5, 2019.

Barkat N., E. Hernández Montes, P. Lehr and M. Keller. 2018: Effects of water stress and heat stress on shoot growth, grape berry size, and weight in grapevine. Washington State Grape Society Annual Meeting. Grandview, WA, November 15-16, 2018.

Bondada B., G. Stahl, R. Smithyman and M. Keller. 2018. Evaluation of plant-based measurement as an irrigation scheduling tool in grapevine. American Society for Enology and Viticulture National Conference. Monterey, CA, June 19-21, 2018. pp. 123.

Hernández Montes E., Y. Zhang, H. Medrano and M. Keller. 2018: Big changes at veraison: acidity and respiration. International Congress on Grapevine and Wine Sciences. Logroño, La Rioja, Spain, November 7-9, 2018.

Zhang Y. and M. Keller. 2018. Grapevines hit with a double-whammy: effects of water stress during heat waves on growth and physiology. American Society for Enology and Viticulture National Conference. Monterey, CA, June 19-21, 2018. pp. 135.

Zhang Y. and M. Keller. 2018. Grapevines hit with a double-whammy: effects of water stress during heat waves on growth and physiology. Washington Winegrowers Convention. Kennewick, WA, February, 6-8, 2018.

Publications

Hernández-Montes E., Y. Zhang, B.M. Chang, N. Shcherbatyuk and M. Keller. 2021: Soft, sweet and colorful: Stratified sampling reveals sequence of events at the onset of grape ripening. Am. J. Enol. Vitic. 72: 137-151.

Hoff R.T., B.R. Bondada and M. Keller. 2021: Onset and progression of the berry shrivel ripening disorder in grapes. Aust. J. Grape Wine Res. 27: 280-289.

Chang B.M., Y. Zhang and M. Keller. 2020: Grape berry splitting is not limited to humid climates. Acta Hort. 1276: 155-161.

Galat Giorgi E., M. Keller, V.O. Sadras, F.A. Roig and J. Perez Peña. 2020: Temperature during the budswell phase of grapevines drives shoot vigor by altering water transport capacity. Agric. For. Meteorol. 295: 108173.

Keller M. 2020: The Science of Grapevines. 3rd Edition. Elsevier Academic Press, London, UK.

Martinez J. and M. Hansen. 2020: Irrigating winegrape varieties. Wine Business Monthly, October 2020: pp. 54-59.

Peña Quiñones A.J., G. Hoogenboom, M.R. Salazar-Gutiérrez, C. Stöckle and M. Keller. 2020: Comparison of air temperature measured in a vineyard canopy and at a standard weather station. PLOS One 15: e0234436.

Blanquaert E. and M. Keller. 2019: Berry weight loss in *Vitis vinifera* (L.) cultivars during ripening. Proc. 21st International GiESCO Symposium, Thessaloniki, Greece, pp. 797-798.

Chang B.M. and M. Keller. 2019: Diffuse light due to wildfire smoke enhances gas exchange of shaded leaves. Proc. 21st International GiESCO Symposium, Thessaloniki, Greece, pp. 805-806.

Hernández-Montes E., Y. Zhang, N. Barkat and M. Keller. 2019. Heat waves and drought stress impact grapevine growth and physiology. Proc. 21st International GiESCO Symposium, Thessaloniki, Greece, pp. 264-267.

Keller M., J. Martinez, E. Hernández-Montes, Y. Zhang and B.M. Chang. 2019: Staying hydrated – not easy when it’s hot. Proc. 21st International GiESCO Symposium. Thessaloniki, Greece, pp. 371-374.

Peña Quiñones A.J., M. Keller, M.R. Salazar Gutierrez, L. Khot and G. Hoogenboom. 2019: Comparison between grapevine tissue temperature and air temperature. Sci. Hort. 247: 407-420.

Badr G., G. Hoogenboom, M. Abouali, M. Moyer and M. Keller. 2018: Analysis of several bioclimatic indices for viticultural zoning in the Pacific Northwest. Clim. Res. 76: 203-223.

Badr G., G. Hoogenboom, M. Moyer, M. Keller, R. Rupp and J. Davenport. 2018: Spatial suitability assessment for vineyard site selection based on fuzzy logic. Precision Agric. 19: 1027-1048.

Molitor D. and M. Keller. 2018: Wie beeinflusst die Witterung den Ertrag? Das deutsche Weinmagazin 2018(1): 32-35.

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8. **Research Success Statements**:

Research on optimum irrigation strategies for white wine grapes is important because most of these grapes are grown in arid eastern Washington, where highly efficient drip irrigation is the principal management tool to impact yield, quality, and sustainability of premium grape production. The outputs generated from this project have been and continue to be shared widely with wine industry stakeholders, which will contribute to the long-term economic and environmental sustainability of the Washington wine industry and will enhance the industry's competitiveness in both domestic and global markets. Knowledge generated from our research has placed valuable information in the hands of growers to help them make science-based decisions regarding irrigation approach and scheduling. More specifically, it has laid the foundation for the development of alternative and more effective deficit irrigation strategies for the production of white wines, which will permit improvements in fruit and wine quality. In addition, this knowledge will also help growers to conserve the state's dwindling water resources. Key findings from this project continue to be communicated to growers and to be integrated in the PI's classroom and certificate program teaching materials.

9. **Funds Status**:

Funds were spent in accordance with the originally proposed budget. We received a 1-year, no-cost extension for the NSF/USDA-funded irrigation study, which allowed us to add an extra year of data collection and winemaking in 2021.