Estimating green and water footprint of a pistachio orchard in Madera County, California

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Abstract

Water scarcity is a growing concern across the world as freshwater resources are increasingly coming under pressure to meet rising demand from a growing population. Global agriculture production is projected to be heavily affected by future water shortages as it currently accounts for about 70% of global freshwater use each year (OECD, 2022). In California, droughts are projected to increase in frequency and intensity, which will put additional on farmers to produce more food with less water. The passage of the Sustainable Groundwater Management Act (SGMA) in 2014 established groundwater sustainability agencies (GSAs) in medium and high priority basins that were responsible for achieving groundwater sustainability by 2040. The Madera County GSA has assigned allocations of evapotranspiration of applied water (ETaw) to all farmers located in the basin. Agri-World Co-op, a 3,000-acre pistachio orchard, was interested in studying their water usage and how they can comply with the new regulations. The objectives of this study were to: (i) estimate the applied water (AW) for the orchard using (i) remote sensing and (ii) crop coefficient approach; (ii) estimate the blue and green water footprints for the pistachio orchard and assess whether the orchard would have exceeded its 2021 allocation for groundwater and, if so, by how much. The applied water was estimated using both a crop coefficient (CIMIS) and a remote sensing (OpenET) approach. The average annual applied water for the pistachio orchard from 2016 – 2021 ranged from 9041-9910 AF/yr, with OpenET providing estimates 10% higher than CIMIS. The average WFg was 0.14 AF/ton and WFb was 2.17 - 2.37 AF/ton. For 2021, the pistachio orchard (Agri-World Co-op) would have exceeded their ETaw allocation by 0.63 – 0.69 AF/acre, resulting in a penalty of $1.1 - $1.2 million, which would have equated to about 6 – 7% of their income from sales in 2021.

Introduction

Water scarcity is a growing concern across the world as freshwater resources are increasingly coming under pressure to meet growing demand. This has already led to a nearly seven-fold increase in freshwater withdrawals globally in the past century (Gleick, 2000). This trend is expected to further increase as agricultural production increases to feed a global population of nine billion by 2050 (Strzepek & Boehlert, 2010). California is already experiencing the effects of water scarcity due to recent droughts. As a result, farmers have had to rely more heavily on groundwater pumping to irrigate their crops. The unsustainable levels of groundwater pumping led to the passage of the Sustainable Groundwater Management Act (SGMA) in 2014 to combat the negative impacts of groundwater overdraft.

SMGA set the ambitious goal to achieve groundwater sustainability by 2040. To achieve this goal, groundwater sustainability agencies (GSAs) were established for the high and medium priority basins that were responsible for developing and implementing groundwater sustainability plans (GSPs) that act as a roadmap to how groundwater basins will achieve long-term sustainability (CDWR, 2022). There are three subbasins located within Madera County: the Chowchilla subbasin, the Madera subbasin, and a portion of the Delta-Mendota Subbasin (MCWNR, 2022). To manage groundwater pumping over the next five years, the Madera County GSA established allocations of groundwater pumping for farmers in the subbasin. The allocations set limits to inches of allowed per acre, with small reductions each year (~4% over a five years) (Figure 1).

Madera County GSA 5-Year Allocation Schedule

Madera County GSA:	Inches of ETAW		
Year	Madera Subbasin	Chowchilla Subbasin	Delta-Mendota Subbasin
2021	28.3	26.7	19.8
2022	28.0	26.3	19.6
2023	27.7	25.9	19.3
2024	27.4	25.5	19.1
2025	27.1	25.1	18.9

Figure 1: Madera County GSA 5-Year allocation schedule from 2021-2025

The County GSA plans on using remote sensing technology (Irriwatch) to track how much water farmers are pumping by monitoring applied water via evapotranspiration (ET) and evapotranspiration of applied water (ETaw). Applied water is the volume of water delivered by an irrigation system while ETaw is the volume of applied water that is lost via evapotranspiration (ET). If farmers exceed their allocation, they receive two penalties: (1) a penalty for exceeding the allocation and (2) the cost to replace the amount of water that was overdrafted. The proposed penalty fee structure (Figure 2) show that the fee will increase over time. This will hopefully incentivize some farmers take the appropriate steps necessary to adjust to their allocations.

Draft Penalties and Replacement Water Charge (for Exceeding Allocation)

Allocation Year	Charge Year	Replacement Water ($/AF)	Penalty ($/AF)	Total
2022	November 2023	$600	$0	$600
2023	November 2024	$600	$100	$700
2024	November 2025	$600	$200	$800
2025	November 2026	$600	$300	$900
2026	November 2027	$600	$400	$1000

Figure 2: Penalties for exceeding water allocation from 2022-2026 for the Madera County GSA.

Research Questions and Objectives

There were three main research questions for this report: (1) what is the applied water (AW) for the pistachio orchard using a remote sensing approach (OpenET) and a crop coefficient approach (CIMIS); (2) what is the blue and green water footprints for the orchard; and (3) did the orchard overuse its 2021 allocation and, if so, by how much.

Methods

The process used to estimate applied water (AW) is shown in Figure 3 below. The initial step was to calculate effective crop evapotranspiration (ETc(eff)), which consists of the crop evapotranspiration (ETc) minus the amount of water provided by precipitation. To calculate ETc, I used two separate methods to compare results. The first method was using OpenET, a free and easily accessible online tool that provides ETc estimates using satellite-based technology. The second, more traditional method is to calculate ETc using reference evapotranspiration (ETo) and crop coefficients (Kc) following the below equation:

$$ET_c = ET_o \ x \ K_c$$

The final step is to subtract precipitation from ETc to calculate ETc(eff), which is seen as the amount of water supplied by irrigation. The ETc(eff) is then multiplied by the number of acres of the orchard and an acreage factor, which accounts for the percentage of land used by pistachio trees and divided by the application/irrigation efficiency to arrive at the applied water (AW) for the orchard. The acreage factor (AF) and application efficiency factor were both assumed to be 0.8 to simplify calculations.

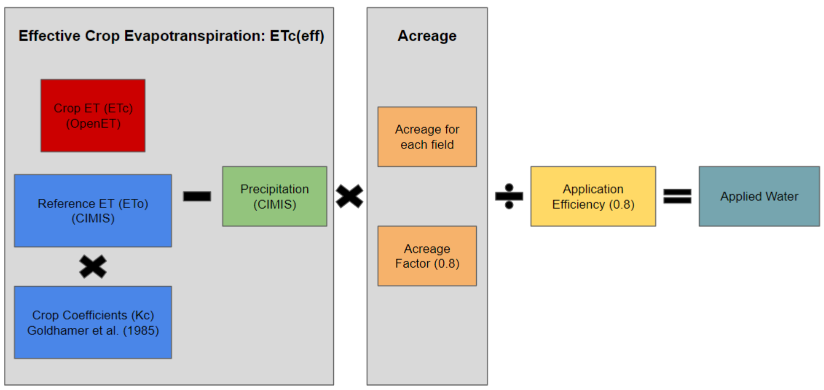

Figure 3: Methodology to calculate applied water using effective crop evapotranspiration (ETc(eff)), acreage information, and irrigation efficiency.

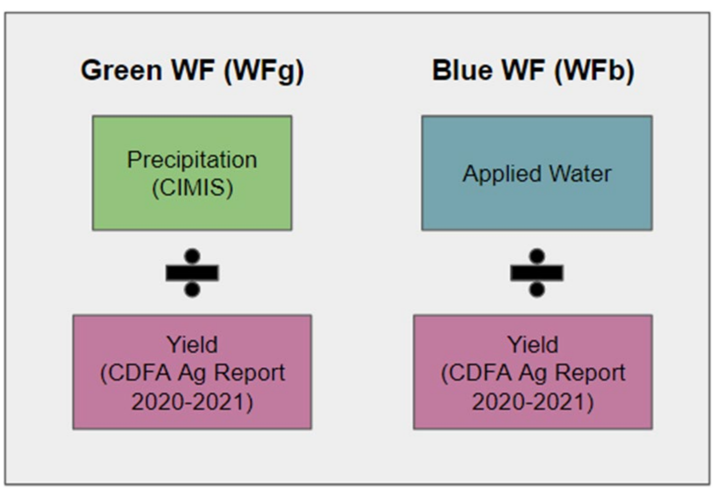

Figure 4: Calculations for green and blue water footprints.

With the AW for the orchard, the next step would be to calculate the green and blue water footprints. The green water footprint (WFg) estimates the amount of water provided via precipitation while the blue water footprint (WFb) estimates the amount of water provided via irrigation. In this case, precipitation data provided through CIMIS was used to calculate WFg while the AW was used to calculate WFb. Yield data for pistachios (e.g., yield per acre and $/lbs) was gathered from the California Department of Food and Agriculture's (CDFA) California Agricultural Statistics review 2020-2021 report.

Data sources

The pistachio orchard studied in this report is the Agri-World Co-op, a 3,000-acre pistachio orchard located near Madera, California (Figure 5). The orchard relies 100% on groundwater pumping to supply water for its orchard and is composed of pistachio trees of various ages.

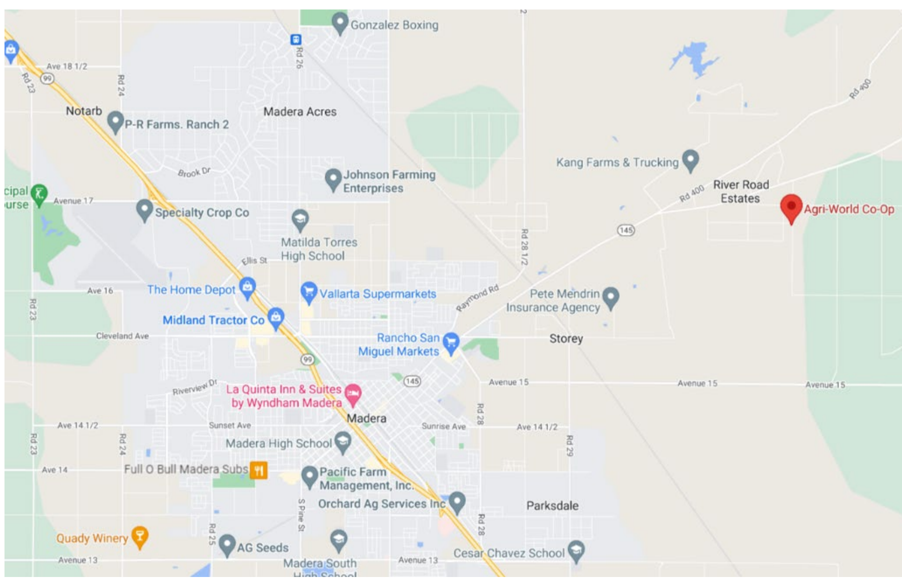

Figure 5: Location of Agri-World Co-Op.

OpenET provides ETc measurements using a variety of different remote sensing-based models at a plot-sized scale (Figure 6). There were 22 separate plots that covered the pistachio orchard. ETc measurements from the Ensemble model was chosen for the study and data 2016 – 2021 was downloaded from the website in an excel spreadsheet.

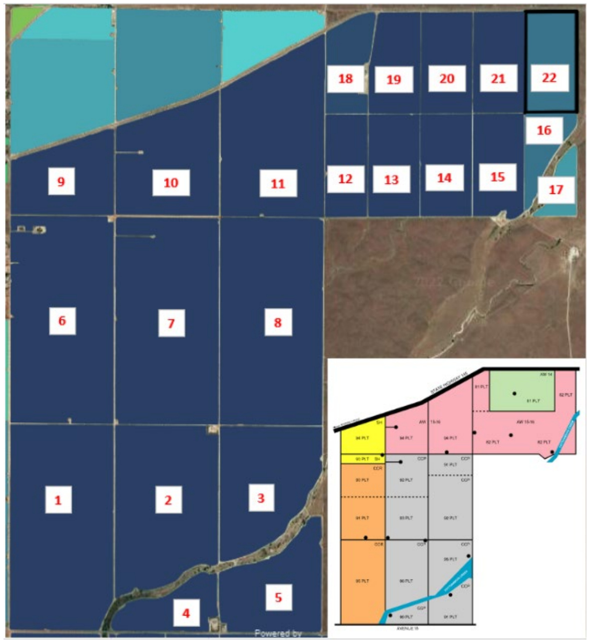

Figure 6: Map of Agri-world Co-op pistachio orchard in OpenET (orchard is broken up into 22 separate smaller fields).

To calculate ETc(eff), I used the reference evapotranspiration (ETo) data provided from a nearby weather station managed by the California Irrigation Management Information System (CIMIS). CIMIS operates a network of weather stations throughout California that collect climate data (e.g., max and min temperature, solar radiation, precipitation) and provides ETo estimates using the Penman-Monteith equation. The closest weather station to the orchard was the Fresno State weather station as shown in Figure 7. Daily ETo and precipitation data from 2016 – 2021 was collected from the weather station to use to calculate AW and water footprints.

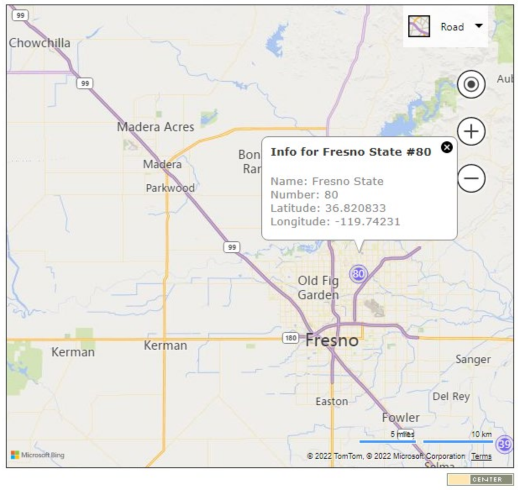

Figure 7: Location of Fresno State weather station (CIMIS)

Crop coefficients for pistachio trees were taken from Goldhamer et al. (1985), which provided Kc values for two-week periods during the growing season from April to mid-November (Table 1). Monthly ETc values were determined by first calculating the ETc for the two-week periods in each month using the ETo and Kc values and then adding the values from both periods to get the monthly Kc value.

Table 1: Crop coefficients for pistachio trees for each stage of the growing season provided by Goldhamer et al. (1985).

Growth Stage	Approx. Phenology	Period	Crop Coeff. (Kc)
Stage 1	Bloom	4/1 - 4/15	0.07
	Leafout	4/16 - 4/30	0.43
	Shell Expansion	5/1 - 5/15	0.68
Stage 2	Shell Hardening	5/16 - 5/31	0.93
		6/1 - 6/15	1.09
		6/16 - 6/30	1.17
Stage 3	Nut Fill	7/1 - 7/15	1.19
		7/16 - 7/31	1.19
	Nut Fill/Shell Split	8/1 - 8/15	1.19
	Shell Split	8/16 - 8/31	1.12
	Hull Slip	9/1 - 9/15	0.99
Harvest	Harvest	9/16 - 9/30	0.87
Post-Harvest	Post-Harvest	10/1 - 10/15	0.67
		10/16 - 10/31	0.5
		11/1 - 11/15	0.35

The crop yield data was gathered from the 2020-2021 California Agricultural Statistics Review report. It is an annual report prepared by the California Department of Food and Agriculture (CDFA) that provides an overview of the state's agricultural production for a given year. The reports include data, such as yield per acre, value per unit, and bearing/non-bearing acres for each crop grown in the state. The pistachio statistics from the report is provided in Figure 8 below.

Tree Nut Acreage, Production and Value, 2011 2020

Crop	Crop Year	Bearing	Non-Bearing [1]	Yield Per Acre	Marketable In-Shell	Production Shelling Stock	Total	Value Per Unit	Total Value
		Acres	*Acres*	*Pounds*		*1,000 Pounds*		*$/Pound*	*$1,000*
Pistachios					*Sold In-Shell*	*Sold Shelled*			
(In-Shell Basis)	2011	153,000	NA	2,900	341,000	103,000	444,000	1.98	879,120
	2012	182,000	NA	3,030	464,000	87,000	551,000	2.61	1,438,110
	2013	203,000	NA	2,320	379,000	91,000	470,000	3.48	1,635,600
	2014	221,000	NA	2,330	408,000	106,000	514,000	3.57	1,834,980
	2015	233,000	NA	1,160	203,600	66,400	270,000	3.29	888,300
	2016	239,000	NA	3,750	666,700	229,800	896,500	1.68	1,506,120
	2017	250,000	NA	2,400	460,600	139,700	600,300	1.69	1,014,507
	2018	264,000	NA	3,740	742,000	245,000	987,000	2.65	2,615,550
	2019	340,000	NA	2,180	576,500	164,500	741,000	2.81	2,082,210
	2020	372,000	NA	2,810	865,000	180,000	1,045,000	2.75	2,873,750

Figure 8: Pistachio statistics from the 2020-2021 California Agricultural Statistics Reviews report (CDFA, 2022b)

Results and Discussion

Applied Water (AW)

The average AW for the orchard from 2016 – 2021 ranged from 9041 (CIMIS) – 9910 (OpenET) AF/yr. In 2018, when precipitation was low (314 AF/yr), AW was highest (9352 and 10585 AF/yr) while in 2019, when precipitation was low (742 AF/yr), AW was low (8730 and 9456 AF/yr) (Table 2). This is to be expected as years with higher precipitation means farmers must irrigate less to ensure trees received sufficient water (Figure 10). Overall, OpenET AW estimates were, on average, 10% higher than CIMIS (Figure 9) across all years.

Table 2: Applied Water estimates using crop coefficients (CIMIS) and OpenET data for 2016 – 2021.

Year	Precipitation (AF/yr)	CIMIS AW (AF/yr)	OpenET AW (AF/yr)
2016	693	9159	9937
2017	539	9080	10123
2018	314	9352	10585
2019	742	8730	9456
2020	493	8814	10073
2021	536	9114	9285
Average	553	9041	9910

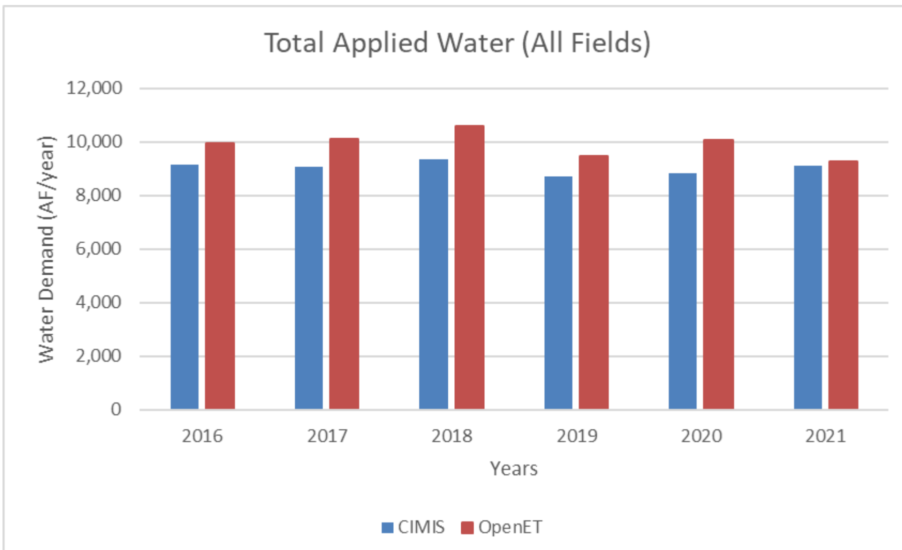

Figure 9: Total applied water estimates from CIMIS and OpenET from all 22 fields in the orchard

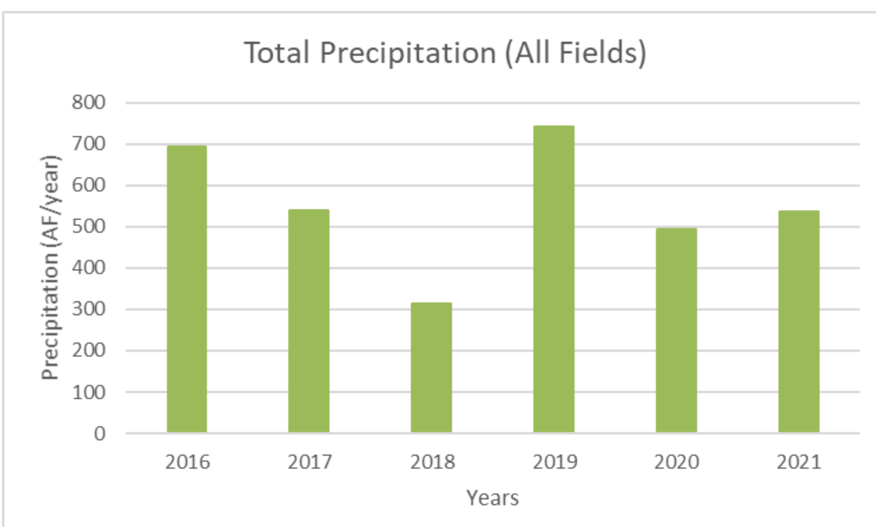

Figure 10: Total precipitation estimates from CIMIS from all 22 fields in the orchard.

Water Footprints

The yields from from 2016 – 2020 were taken from the 2020-2021 California Agricultural Statistics Overview report and used to calculate WFg and WFb for the orchard. Since 2021 data was unavailable, I assumed the 2021 yield to be 1.15 ton/acre because pistachio trees follow an "on/off" cycle, in which following a year with high yields, the next year will have low yields. This trend can be seen between 2017-2020, where 2017 had a low yield of 1.2 ton/acre, followed by a jump to 1.87 ton/acre in 2018, then another drop to 1.09 ton/acre in 2019, and lastly, an increase back up to 1.41 ton/acre in 2020. I chose 1.15 ton/acre since it was a middle ground between the low yields in 2017 and 2019.

The "on/off" cycle for pistachio trees impacted both the WFg and WFb from year to year. The water footprints have an inverse relationship with yield: years with higher yields corresponded with lower WFg and WFb, while years with lower yields corresponded with higher WFg and WFb. For example, in 2017, a year with low yield (1.2 ton/acre), the WFg was 0.15 AF/ton while the average of the OpenET and CIMIS WFb was 2.62 AF/ton (Table 3). This is in contrast to 2018, which had a higher yield (1.87 ton/acre), but resulted in a lower WFg (0.06 AF/ton) and WFb (1.64 AF/ton). The average WFg for the orchard from 2016-2021 was 0.14 AF/ton, which accounted for around 6% of the total water footprint (Figure 12). The average WFb, on the other hand, was ranged from 2.17 – 2.37 AF/ton, which composed the remaining 96% of the water footprint for the orchard (Figure 11). This is expected as the orchard relies 100% on groundwater pumping to sustain their orchard. With limited precipitation, the orchard has to rely heavily on irrigation to meet the pistachio tree's water needs.

Table 3: Estimated green and blue water footprints for the orchard from 2016 – 2021.

Year	Yield (ton/acre)	Precip. WFg (AF/ton)	CIMIS WFb (AF/ton)	OpenET WFb (AF/ton)
2016	1.88	0.12	1.6	1.74
2017	1.2	0.15	2.48	2.77
2018	1.87	0.06	1.64	1.86

2019	1.09	0.22	2.63	2.85
2020	1.41	0.12	2.06	2.35
2021	1.15	0.15	2.61	2.66
Averages	1.43	0.14	2.17	2.37

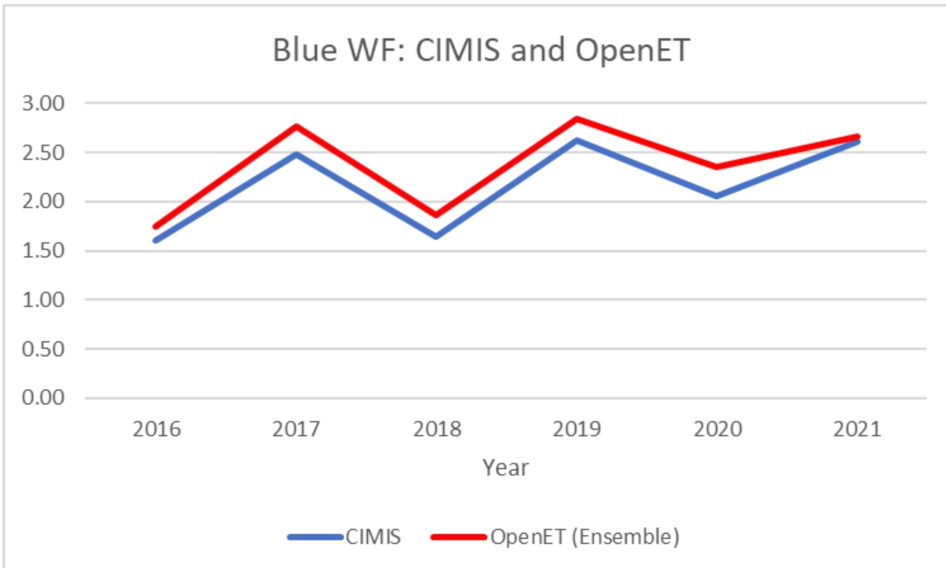

Figure 11: Estimated blue water footprint using OpenET and CIMIS methods for 2016 – 2021.

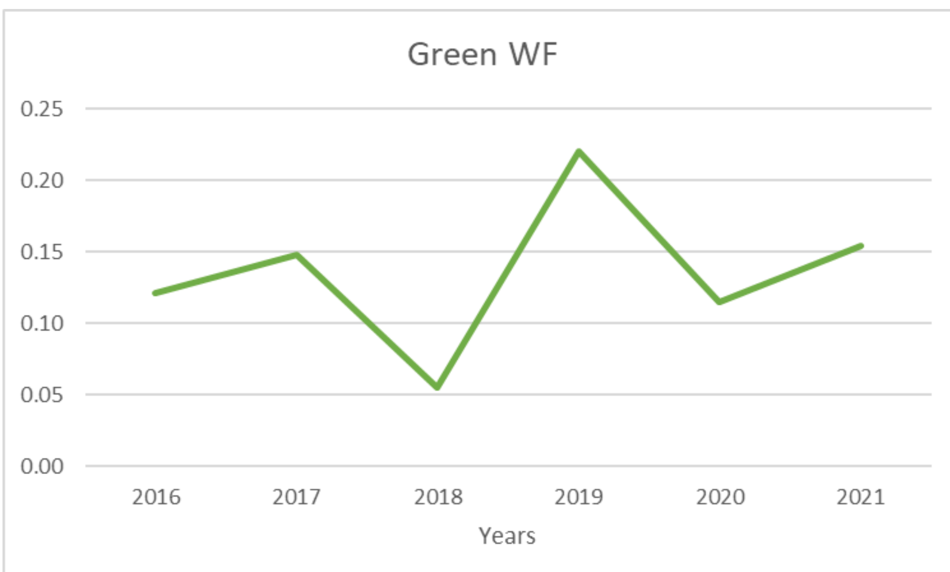

Figure 12: Estimated green water footprint for the orchard from 2016 – 2021.

2021 Allocation

To understand how the pistachio orchard's performance regarding its allocation, I ran a simulated scenario where I used the 2021 allocation of ETaw (28.3 in ETaw) but applied the combined 2022 penalty of $600/AF if they went above their allocation. The result of the simulation is provided in Table 4. From the calculations, the orchard would have exceeded its ETaw allocation in 2021 by 0.63 ft and 0.69 ft for the CIMIS and OpenET methods. Across their entire orchard (3046 acres), this would have resulted in a $1.1 ~ 1.2-million-dollar penalty in 2021, which would have accounted for about 6-7% of the income generated from the sale of pistachios using the 2021 per unit value from the Ag report. Projecting ahead, if they exceeded their 2026 allocation by the same amount, the amount for the penalty would have almost doubled.

Table 4: Estimated ETaw for 2021 using CIMIS and OpenET methods and potential penalties.

2021 Allocation: 2.36 ft ETaw	**CIMIS**	**OpenET**
2021 ETaw	2.99	3.05
Difference	0.63	0.69
Penalty ($600/AF)	$379	$412
Total Penalty (3046 acres)	$1,154,795	$1,257,386
Penalty % of Total Income	6%	7%
2026 Penalty	$2,259,719	$2,430,705

Conclusion

The applied water for the orchard ranged from 9,000 – 10,000 AF/year using both OpenET and crop coefficient method. Overall, OpenET estimations of applied water were about 10% higher compared to the crop coefficient method. AW levels followed a predictable trend during years of high precipitation (lower AW levels) and low precipitation (higher AW levels) as more AW was needed to make up for the lack of precipitation. This resulted in shifts in WFg and WFb from year to year as years with low yields resulted in higher WFg and WFb. The average WFg was 0.14 AF/ton and WFb was 2.27 AF/ton, which means that AW accounted for about 94% of pistachio production for the orchard. Looking back at 2021, the orchard would have overused its 2021 allocation by about 0.63 – 0.69 AF/acre, resulting in roughly $1.2 million in fines when using the 2022 fine of $600/AF. This would have accounted for about 6-7% of the total income from pistachio sales based on 2021 value per pound.

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