**Methods**

*Crops*

Background information on the data used for crop distribution on the landscape, Kcb values used in the model, and crop growth curve assumptions are available in Devine (2018). Basal crop coefficients (Kcb std) were assumed from several sources and chosen to reflect high density production except for wine grapes (insert 2 citations) (Figure Kcb curves by crop). Kcb std values for alfalfa were chosen to represent three different cutting cycles depending on the region of California: intermountain; Central Valley; and Imperial Valley. Grapes located in coastal California and foothills, including Sonoma and Napa Valleys, were assumed to be for higher quality wine production and lower Kcb values represented intentional crop water stress after veraison to help control canopy growth. Basal crop coefficient curve timing was based on the California specific, crop coefficient calendars in Goldhamer and Snyder (1989).

*Growth curve sensitivity test*

A sensitivity analysis was conducted for 4 of the 12 scenarios for almonds and walnuts growth assumptions. First, with respect to crop growth timing, we also ran -20, -10, 10, and 20 days from the initial assumed bloom time of February 15th for almonds and April 1st for walnuts. Second, we tested the effect of the winter Kcb value at 0.1 and 0.2, in addition to the commonly assumed 0.15 and to represent deep, diffusive “background” evaporation from the surface. We ran this test to examine coefficient sensitivity to winter time water balance for effects in almonds and walnuts.

*Surface wetting sensitivity test*

Finally, a sensitivity analysis of irrigation surface coverage assumptions for almonds and walnuts was done by running 4 of the 12 scenarios for these crops as drip (fw = 0.35) or surface/sprinkler irrigated (fw = 1).

**Results**

*Green water utilization and water balance implications by cro*

The proportion of precipitation utilized as green water varied by crop, especially between alfalfa growing year-round and the orchard and vine crops with dormant seasons and assumed wintertime bare soil conditions. Central and Imperial Valley alfalfa showed 64, 80, and 91% of precipitation utilized as green water in each of the 3 scenarios (shallow, moderate, and deep; see Figure 7B for moderate scenario), due to alfalfa’s year-round growth and coverage of the soil. This causes generally lower soil evaporation of precipitation and no dormant season ET loss seen in the other crops (Tables 3-5). The orchard and vine crops show generally lower amounts of green water utilized (Figure 7A-E). These crops have periods of dormancy and periods of exposed bare soil frequently wetted by precipitation. For instance, almonds show 36, 52, and 61% of precipitation utilized as green water for each of the shallow, moderate, and deep scenarios, respectively, with 26-28% of precipitation lost as dormant season ET across all scenarios. Actively growing alfalfa limits energy available for evaporation at the soil surface, limiting evaporative loss of precipitation at the soil surface, so that 15.6% of the total ET is soil surface evaporation in the moderate scenario for almonds but is only 7.3% in Central Valley alfalfa, which includes the wintertime evaporation as part of the growing season for alfalfa. In the shallow soil reservoir scenario, the difference is starker: the cumulative soil evaporation is 27.3% under almonds but only 13.1% under Central Valley alfalfa.

Pistachios had the lowest green water utilization in the simulation (Figure 7D), due to a combination of inherently low precipitation growing region and a relatively late bloom time (April 25th), such that the growing season begins after the end of the rainy season. Interestingly, 75-80% of annual precipitation was lost as dormant season ET in pistachios. While walnuts are grown in generally wetter climates (424 mm yr-1 average) compared to almonds (284 mm yr-1 average), almonds have greater green water utilization than walnuts in the shallow-moderate scenarios (Figure 10). The earlier bloom times of almonds allow for 36-52% of precipitation to be utilized as green water in the shallow-moderate scenarios (Tables 3-4). Soil water storage limitations and the shorter growing season affect green water utilization in walnuts where only 20-32% of annual precipitation is utilized in the shallow-moderate scenarios (Tables 3-4). However, when the rooting depth is increased to 2.0 m, the greater winter soil storage gains of walnuts overcome the lower number of growing season days that overlap the rainy season and utilization increases to 44%, compared to 61% in almonds (Table 5). The coast and foothills grape growing region is a generally wetter climate than walnuts’ growing region, so that the green water resource sees the fastest rate of gain with increases in allowable depletion of the shallow-to-moderate-to-deep scenarios, though there are some limiting areas owing to relatively shallow root restrictive contacts (Table 1; Figures 9 and 10).

Within a given crop, the range in mean green water availability is wide, with inner 80% percentile intervals spanning several hundred millimeters, except for pistachios (Figure 7A-E). This shows that each crop spans wide climatic and soil water holding capacity gradients and their growing conditions are not monolithic. Deeper scenarios lead to greater variability in green water availability, as more combinations of soil storage properties, climate, and crop are added to the mix on the landscape (**check this)**.

The effects of the dormant season crop coefficient (Kcb = 0.15) was explored in 4 of the 12 scenarios for both almonds and walnuts. This is the recommended value, though Huntington et al. 2014 used 0.12. It is actually meant to represent “background” evaporation, mostly deep diffusive evaporation that can occur the whole year [citation?]…

The effects of the surface irrigation coverage was also explored in 4 of the 12 scenarios for both almonds and walnuts. This was to test the extent to which the soil surface evaporation estimate is tied to the assumption about the fraction of the soil wetted by irrigation in a given crop…

Finally, the effects of crop growth curve timing assumptions (Table 1) was explored in 4 of the 12 scenarios, again for both almonds and walnuts. This was to test the extent to which the proportion of annual P utilized by green water is tied to how much the growing season overlaps the rainy season.

*Irrigation (blue water) demand by crop*

Blue water demand was highest for alfalfa in the Imperial Valley with 1.84 m irrigation demand yr-1 needed to maintain crop ET year-round in this warm, dry climate in the moderate scenario. This compares to 1.17 m irrigation demand yr-1 in Central Valley alfalfa moderate scenario. This is due to the Central Valley’s higher P and lower ET environment compared to the Imperial Valley (Figure 4A-C) with no winter irrigations regardless of soil moisture conditions (see Methods, section ???). Intermountain alfalfa’s irrigation demand of 0.82 m yr-1 was even lower with a clear winter dormancy and thus shorter growing and irrigation season. Almonds, grapes in the Central Valley, pistachios, and walnuts had similar blue water demands to Central Valley alfalfa with 1.26, 1.27, 1.21, and 1.16 m yr-1 needed, respectively. Differences in growing season reference ET for these crops, which should produce differences in irrigation water demand, were offset by differences in precipitation, crop growing season length and canopy coverage assumptions, which helped equalize irrigation water demand (Tables 1, 3-5). Grapes in coastal California and the foothills, where high quality wine grape irrigation management was assumed, had by far the lowest blue water demand of 0.51 m yr-1, partly due to intentional crop water stress of 0.15 m yr-1 but also due to lower assumed canopy coverage, lowering basal crop coefficients (Table 1) and transpiration demand. While this had the effect of increasing soil surface evaporation to 28% of growing season ET, the highest of all crops in the moderate scenario, growing season green water utilization was highest in wine grapes, offsetting 23% of growing season ET in the moderate scenario, much higher than the 10% for all crops combined.

Year-to-year differences in climate also affected annual variability of irrigation water demand across crops. Variability in irrigation water demand was greatest where the green water resource was the greatest. In the moderate scenario, irrigation water demand ranged 1.07-1.40 m yr-1 (8.6% C.V.) in almonds, 0.99-1.32 m yr-1 in Central Valley alfalfa, 1.73-1.90 m yr-1 in Imperial Valley alfalfa, 0.69-0.89 m yr-1 in intermountain alfalfa, 1.11-1.39 m yr-1 in Central Valley grapes, 0.42-0.57 m yr-1 in (9.6% C.V.) coast and foothill grapes, 1.06-1.32 m yr-1 in pistachios, and 1.00-1.27 m yr-1 in walnuts.

*Crop water stress results*

The much lower blue water demand for the 80% allowable depletion scenarios is largely due to lack of available soil water and accumulation of crop water stress, which the study assumes to occur when the soil water depletion reaches 50% of plant available water for all crops. Crop stress reduces the growing season ET by 17-19% from a change in allowable depletion from 50% to 80% in the same root depth. With the higher allowable depletion threshold, the magnitude of crop stress equals or exceeds the magnitude of the green water resource at all root depths.

There is also crop water stress in the 30-50% allowable depletion scenarios, due to four factors that arise from how the FAO56 dual Kc method was encoded for this particular study, in order to roughly match existing conditions in California (see Methods): (1) winter irrigation in Central Valley alfalfa is not allowed even though the alfalfa is assumed to remain growing throughout the winter, which causes some alfalfa water stress during dry winters; (2) irrigation is not allowed for ± 4 days at alfalfa cutting times across all alfalfa, causing some growing season water stress (3) grape wine irrigation management is for intentional crop water stress for all grapes in the Foothills surrounding the Central Valley and Coastal regions of California (see Methods), such that crop stress is 24% of growing ET in the moderate scenario; and (4) timing the last fall irrigation on a defined date, based on the study datasets’ 14-year (2004-2017) dataset to achieve allowable depletion at the leaf-drop date for a given climate, crop, and soil combination.

The goal of this last practice is to deplete the profile of irrigation water and to make room for capture of fall and winter storms to supply green water in the spring before the first irrigation. This strategy is akin to Fall reservoir management when reservoirs are drawn down to pre-specified levels for flood control capture of winter runoff. This place-based timing strategy leads to some Fall crop water stress when average precipitation is below the 14-year average during autumns (Figure ???). The effect of fall irrigation scheduling in this manner also results in more water stress when the scenario rooting depth is decreased within a given level of allowable depletion (Table 2). For instance, within the 50% allowable depletion scenarios, water stress increases from 2.3 to 2.9 to 5.1 total MAF from a 3.0 to 2.0 to 1.0 m rooting depth. As the rooting depth is made shallower, the soil water buffer shrinks, making these scenarios more susceptible to late season crop water stress during dry falls before leaf-drop. However, in the moderate scenario, it should be kept in mind that 53% of the growing season crop water stress total is due to intentional wine grape water stress and another 25% is due to winter alfalfa water stress when it is assumed that irrigation is not practiced in the Central Valley. Thus, only 22% is due to fall crop water stress resulting from the fall irrigation management strategy for green water in orchards, grapes, and intermountain alfalfa. When the allowable depletion is decreased to 30% for a given root depth, crop water stress decreases slightly, because there is a larger soil water buffer to sustain the irrigation-free fall period with unreliable precipitation.

**Table 3.** Water balance details (mm) by crop for 0.5 m root depth and 30% allowable depletion scenario

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Crop | | AD | Irr Count | First irr. | Last irr | GW | | | Irr | ET | | E | | DP | | P | | | DP | | CS | | ETdormant | | | DPfall | | |
|  | | *mm* | *Days yr-1* | | *--doy--* | | | *----mm growing season----* | | | | | | | | | | *-mm annual-* | | | | | | *--mm season--* | | | |
| Almonds | 20 | | 69 | 52 | 293 | 102 | 1535 | | 1636 | | 447 | | 36 | | 284 | | 108 | | | 5 | | 78 | | | 26 | |
| Alfalfa, intermountain | 25 | | 37 | 93 | 283 | 129 | 939 | | 1068 | | 184 | | 14 | | 376 | | 109 | | | 13 | | 140 | | | 50 | |
| Alfalfa, Imperial | 22 | | 69 | 8 | 359 | 53 | 1929 | | 1982 | | 250 | | 9 | | 64 | | 11 | | | 60 | | 0 | | | 1 | |
| Alfalfa, CV | 21 | | 51 | 45 | 300 | 179 | 1287 | | 1466 | | 191 | | 39 | | 279 | | 104 | | | 52 | | 0 | | | 25 | |
| Walnuts | 23 | | 55 | 94 | 284 | 86 | 1355 | | 1441 | | 340 | | 12 | | 424 | | 189 | | | 9 | | 152 | | | 58 | |
| Pistachios | 20 | | 62 | 113 | 299 | 6 | 1425 | | 1430 | | 380 | | 3 | | 197 | | 45 | | | 20 | | 150 | | | 12 | |
| Grapes, CV | 19 | | 66 | 76 | 286 | 45 | 1440 | | 1485 | | 304 | | 19 | | 264 | | 87 | | | 5 | | 135 | | | 22 | |
| Grapes, wine | 22 | | 28 | 98 | 265 | 117 | 737 | | 854 | | 282 | | 5 | | 599 | | 330 | | | 60 | | 155 | | | 109 | |

**Table 4.** Water balance details (mm) by crop for 1.0 m root depth and 50% allowable depletion scenario

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Crop | AD | | Irr Count | | First irr. | | | | Last irr | GW | | Irr | ET | | E | DP | | P | DP | CS | ETdormant | | DPfall | |
|  | *mm* | | *Days yr-1* | | | | *--doy--* | | | *----mm growing season----* | | | | | | | | *-mm annual-* | | | | *--mm season--* | |
| Almonds | | 65 | | 21 | | 80 | | 275 | | 147 | 1259 | | | 1406 | 219 | 5 | 284 | | 67 | 7 | 77 | | 15 | |
| Alfalfa, intermountain | | 77 | | 13 | | 108 | | 267 | | 165 | 816 | | | 982 | 99 | 4 | 376 | | 74 | 13 | 140 | | 29 | |
| Alfalfa, Imperial | | 70 | | 25 | | 22 | | 347 | | 58 | 1838 | | | 1896 | 136 | 4 | 64 | | 5 | 32 | 0 | | 1 | |
| Alfalfa, CV | | 67 | | 18 | | 65 | | 279 | | 223 | 1167 | | | 1390 | 101 | 12 | 279 | | 64 | 39 | 0 | | 14 | |
| Walnuts | | 73 | | 17 | | 111 | | 268 | | 137 | 1158 | | | 1295 | 196 | 2 | 424 | | 141 | 10 | 153 | | 35 | |
| Pistachios | | 65 | | 19 | | 116 | | 279 | | 25 | 1207 | | | 1232 | 183 | 1 | 197 | | 25 | 17 | 154 | | 6 | |
| Grapes, CV | | 62 | | 21 | | 93 | | 273 | | 82 | 1272 | | | 1354 | 174 | 4 | 264 | | 54 | 6 | 134 | | 12 | |
| Grapes, wine | | 66 | | 15 | | 134 | | 265 | | 147 | 506 | | | 653 | 184 | 1 | 599 | | 298 | 159 | 159 | | 89 | |

**Table 5.** Water balance details (mm) by crop for 2.0 m root depth and 50% allowable depletion scenario

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Crop | AD | | Irr Count | | First irr. | | | | Last irr | GW | Irr | ET | | E | DP | | P | | | DP | | CS | | ETdormant | | | DPfall | | |
|  | *mm* | | *Days yr-1* | | | | *--doy--* | | | *----mm growing season----* | | | | | | | | *-mm annual-* | | | | | | | *--mm season--* | | |
| Almonds | | 126 | | 11 | | 90 | | 260 | | 173 | 1164 | | 1338 | 149 | 4 | 284 | | | 41 | | 4 | | 78 | | | 6 | | |
| Alfalfa, intermountain | | 136 | | 9 | | 114 | | 252 | | 186 | 786 | | 972 | 86 | 3 | 376 | | | 54 | | 9 | | 140 | | | 18 | | |
| Alfalfa, Imperial | | 133 | | 13 | | 35 | | 329 | | 64 | 1799 | | 1863 | 81 | 1 | 64 | | | 2 | | 11 | | 0 | | | 0 | | |
| Alfalfa, CV | | 128 | | 10 | | 75 | | 265 | | 253 | 1125 | | 1378 | 70 | 8 | 279 | | | 37 | | 19 | | 0 | | | 5 | | |
| Walnuts | | 142 | | 9 | | 125 | | 254 | | 186 | 1043 | | 1229 | 127 | 1 | 424 | | | 95 | | 6 | | 154 | | | 16 | | |
| Pistachios | | 126 | | 10 | | 121 | | 264 | | 35 | 1120 | | 1155 | 105 | 0 | 197 | | | 12 | | 10 | | 160 | | | 2 | | |
| Grapes, CV | | 123 | | 11 | | 102 | | 259 | | 106 | 1189 | | 1295 | 114 | 3 | 264 | | | 30 | | 3 | | 136 | | | 4 | | |
| Grapes, wine | | 113 | | 9 | | 155 | | 265 | | 183 | 442 | | 625 | 141 | 0 | 599 | | | 264 | | 143 | | 160 | | | 69 | | |



Figure 7A-E. Average green water availability by crop. Class breaks are at the 20th, 40th, 60th, and 80th percentiles by area.



Figure 8A-E. Average blue water demand by crop. Class breaks are at the 20th, 40th, 60th, and 80th percentiles by area.

**Figure 10.** Mean green water availability vs. mean allowable depletion for each of the 12 soil reservoir scenarios by crop

*Discussion*

Green water availability varied widely by crops with pistachios having extremely low values of 5.8 cm yr-1 in Imperial Valley alfalfa to the highest 22.3 cm yr-1 in Central Valley alfalfa in the moderate scenario. The proportion of growing season ET met by green water was highest in wine grapes, 23-29% in the moderate-to-deep scenario. Crop specific results also demonstrate the simple principle that the more each perennial crop’s growing season overlaps the rainy season, the higher percentage of precipitation will be utilized as green water. An actively growing crop decreases surface soil evaporation of winter precipitation and deep percolation. Finally, the green water resource ranges widely for each crop’s geographic range (Figure 7A-E), generally following orographic and latitudinal gradients in precipitation (Figure 4A). In conclusion, each crop could not be managed as a monolithic block to optimize use of green water, given the wide range in climate and soil combinations. Thus, irrigation management would need to adapt to each new water year for the same location.

Such empirical evidence of irrigation frequency driven increases in blue water consumption may also be evident in the amplification of the almond Kc curve the past several decades (Figure 9). While amplification of the crop coefficient curve is likely at least partially due to canopy management that favors fuller, denser canopies (Sanden, 2007), the trend is speculated to be driven by increases in irrigation frequency in the experiments or monitoring sites (Steduto *et al.*, 2012). Unfortunately, specifications of the irrigation methods used in crop coefficient studies are typically not documented, revealing a lack of research in how irrigation systems and practices also affect observed evapotranspiration rates.

**Figure 9.** Evolution of the almond single crop coefficient (Kc) curve, reflecting increases in canopy coverage and possible irrigation frequency