Appendix A
Agricultural Efficiency

Numerous studies have shown that the efficiency of water application varies by irrigation method. In general, drip systems are more efficient than sprinklers, and sprinklers are more efficient than gravity or flood irrigation. While the efficiency of each method varies by crop type, this general trend holds true.

Surveys of irrigation methods throughout California have been conducted approximately every ten years since 1972. Most recently, Orang et al. (2005) conducted an irrigation method survey in 2001. These surveys show that for most crop types, gravity and sprinkler system use have declined, while micro/drip and subsurface irrigation use have increased. An important exception to this trend is for vegetable crops, for which both sprinkler and drip use has increased.

The adoption of more efficient irrigation systems, as implied by the historic data, has led to greater water-use efficiency in the agricultural sector, measured in various ways, including increases in crop produced per unit water applied, decreases in water use per acre, increases in farm income per acre-foot, and so on. We project that this trend will continue and will lead to even greater efficiency improvements in the agricultural sector over time. To explore a "High Efficiency" scenario for the agricultural sector, we used a three-step process:

1. Calculate the percentage of irrigated land by crop type and irrigation method in 2030. This number will vary by major crop type (grouped by field, vegetable, orchard, and vineyard). Major crops grown in California are classified into crop types according to Table A-1.
2. Calculate the relative efficiency of each irrigation method. This number will also vary by crop type.
3. Combine the changes in irrigation method and the relative efficiencies of each method to project the applied water for each crop and hydrologic region in 2030.

Table A-1. Classification of major crops grown in California into four crop types.

Crop	Crop Type
Grain	Field
Rice	Field
Cotton	Field
Sugar Beet	Field
Corn	Field
Dry Bean	Field
Safflower	Field
Other Field Crops	Field
Alfalfa	Field
Pasture	Field
Processed Tomato	Vegetable
Fresh Tomato	Vegetable
Cucurbit	Vegetable
Onion/Garlic	Vegetable
Potato	Vegetable
Other Truck Crops	Vegetable
Almond/Pistachio	Orchard
Other Deciduous Trees	Orchard
Subtropical Trees	Orchard
Vineyard	Vineyard

Step 1: Calculate the percentage of irrigated land by crop type and irrigation method

The recent Orang et al. (2005) paper reports the percentages of irrigated land area by crop type and irrigation method in California for 1972-2001. Using a linear trend on this data, we estimate the percentages of irrigated land area by crop type and irrigation method in 2030 (Figure A-1).

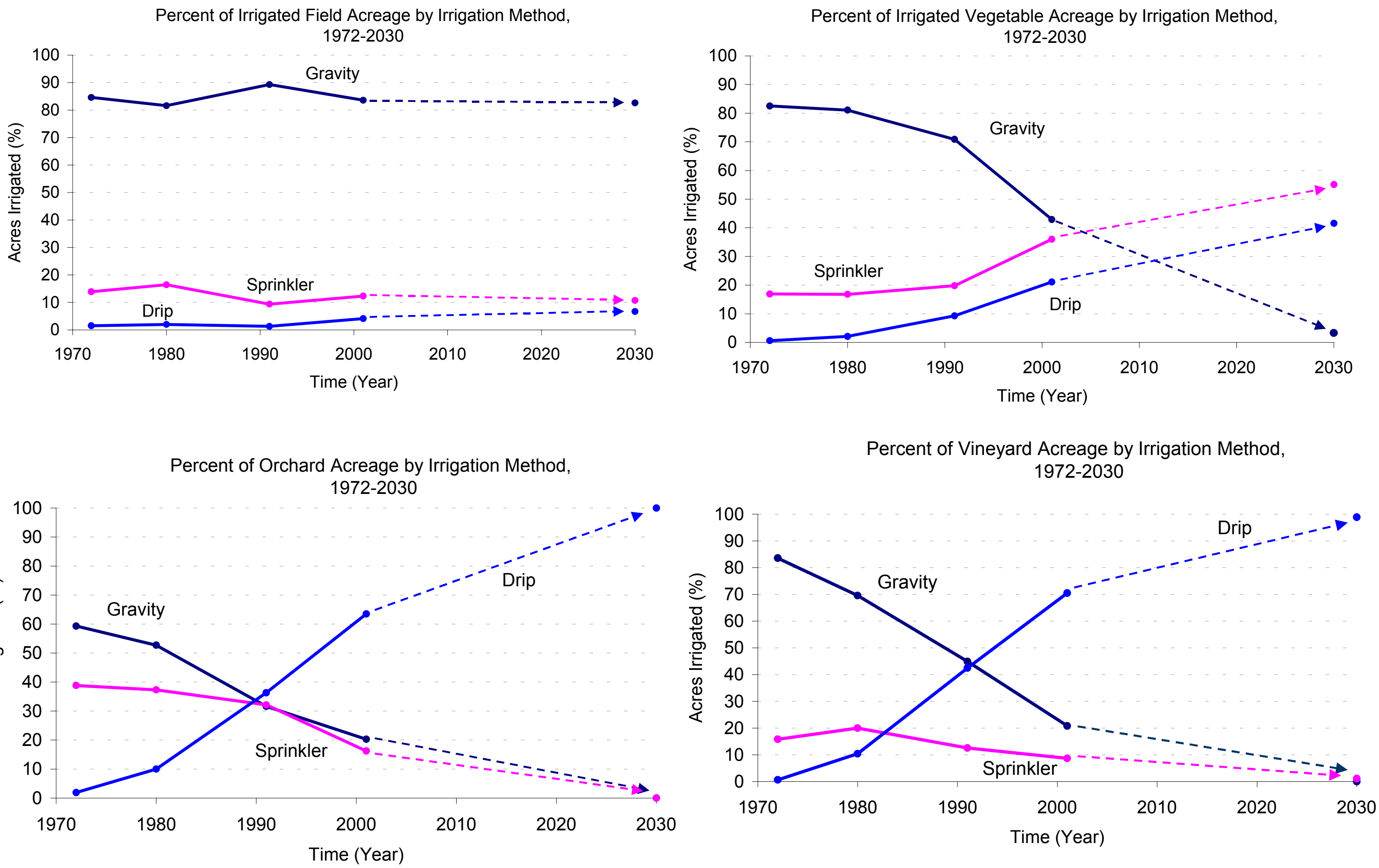

Figure A-1. The percent of irrigated crop acreage by irrigation method for (a) field crops, (b) vegetable crops, (c) orchards, and (d) vineyards. Data from 1972 to 2001 are historical estimates; data from 2001 to 2030 are linear extrapolations of the historical trends.

Step 2: Calculate the relative efficiency of each irrigation method for each crop type

We conducted a survey of the literature to quantify differences in water use among irrigation methods. We focused on studies that compared at least two of the three irrigation methods of interest (gravity, sprinkler, or micro/drip) and reported information on applied water and yield. Applied water includes both precipitation and irrigation water. Because precipitation varies tremendously among the studies, we included precipitation as a means of normalizing the data.

Some studies relied on different methods to determine when to irrigate the fields, e.g. soil moisture for gravity systems and CIMIS data for drip systems, resulting in differing levels of applied water (AW). To address this complication, we compared only those treatments that used similar irrigation levels.

Irrigation studies typically report the water use efficiency, WUE, of a particular crop under each irrigation method, which is defined by the equation

$$WUE_{crop,method} = \frac{Yield_{crop,method}}{AW_{crop,method}} \qquad (1)$$

Because we want to compare water use among the irrigation methods for a given crop while keeping yield constant, we calculate the inverse of equation 1, or 1/WUE, for each crop type and irrigation method, which is defined by the equation

$$\frac{1}{WUE_{crop,method}} = \frac{AW_{crop,method}}{Yield_{crop,method}} \qquad (2)$$

It is important to note that in many cases, more efficient irrigation methods lead to both yield improvements and a reduction in applied water. By keeping yield constant, we are capturing yield improvements by reducing water use. This effectively assumes that a grower has a choice of balancing water use and yield. This may or may not be true in practice: farmers may not be able to take water savings and apply that water to boost overall yields because of limits on land availability or other factors. Nevertheless, it provides a way of estimating an optimal level of water savings while maintaining agricultural yields approximately constant.

Because water use efficiency can vary geographically in response to climate and soil type, we limited cross-study comparisons. Thus, we only compared irrigation methods within a single study. To compare irrigation methods, we calculated a ratio of 1/WUE according to the equation

$$\frac{1/WUE_{crop1,method1}}{1/WUE_{crop1,method2}} = \frac{AW_{crop1,method1}/Yield_{crop1,method1}}{AW_{crop1,method2}/Yield_{crop1,method2}} \qquad (3)$$

We grouped studies by crop type and calculated an average 1/WUE ratio. This ratio is effectively the relative efficiency of each irrigation method for a single crop type. Table A-2 contains the 1/WUE for each irrigation method and the ratio of 1/WUE for each study. It is important to note that a few studies are listed multiple times in Table A-2. These studies compare irrigation levels in addition to irrigation methods. Thus a single study may compare drip and sprinkler systems at four irrigation levels: 0.25 ET_0, 0.5 ET_0, 0.75 ET_0, and ET_0. While drip may be more efficient across all irrigation levels, the difference in efficiency may be highest at higher irrigation levels. In this situation, we chose to include all irrigation levels, which we felt represented the full range at which these methods may be used. We chose not to compare irrigation methods across irrigation levels.

Table A-2: Relative efficiency of each irrigation method by crop type.

		1/WUE			Ratio of 1/WUE		
Study	**Crop Type**	**Gravity m^3/kg**	**Sprinkler m^3/kg**	**Drip m^3/kg**	**Sprin/Grav Ratio**	**Drip/Grav Ratio**	**Drip/Sprin Ratio**
Ayars et al. 1999	Field	1310/0.67x		1174/x		0.600	
Ayars et al. 1999	Field	1310/0.67x		1174/0.83x		0.723	
Ayars et al. 1999	Field	1.31		1.13		0.862	
Ayars et al. 1999	Field	1.31		1.11		0.845	
Colaizzi et al. 2004	Field		1.36	0.76			0.561
Colaizzi et al. 2004	Field		0.79	0.65			0.828
Colaizzi et al. 2004	Field		0.70	0.72			1.022
Colaizzi et al. 2004	Field		0.74	0.81			1.103
Kamilov et al. 2003	Field	1.77		1.00		0.564	
Average	**Field**					**0.719**	**0.879**
Abu-Awwad 1994	Vegetable		0.91	0.35			0.383
Abu-Awwad 1994	Vegetable		0.31	0.28			0.878
Abu-Awwad 1994	Vegetable		0.31	0.22			0.721
Abu-Awwad 1994	Vegetable		0.28	0.25			0.917
Ayars et al. 1999	Vegetable	0.07		0.05		0.701	
Yohanes and Tadesse 1998	Vegetable	0.58		0.33		0.564	
Bogle et al. 1989	Vegetable	0.18		0.06		0.335	
Tarantino et al. 1982	Vegetable	0.07		0.06		0.874	
Tarantino et al. 1982	Vegetable	0.10		0.09		0.915	
Bernstein and Francois 1973	Vegetable	0.12	0.13	0.11	1.045	0.927	0.887
Bernstein and Francois 1973	Vegetable	0.15	0.14	0.12	0.907	0.781	0.861
Ellis et al. 1986	Vegetable	0.24	0.24	0.25	1.027	1.055	1.027
Sammis 1980	Vegetable	0.28	0.25	0.15	0.867	0.524	0.605
Sammis 1980	Vegetable	0.20	0.35	0.20	1.806	1.041	0.576
Trout et al. 1994	Vegetable	0.17	0.13		0.749		
Trout et al. 1994	Vegetable	0.24	0.17		0.711		
Fidell et al.1999	Vegetable		0.15	0.09			0.620
Fidell et al.1999	Vegetable		0.18	0.13			0.705
Average	**Vegetable**				**1.016**	**0.772**	**0.744**
Rumayor-Rodriguez and Bravo-Lozano 1991	Orchard	0.32		0.19		0.589	
Rumayor-Rodriguez and Bravo-Lozano 1991	Orchard	0.44		0.33		0.743	
Rumayor-Rodriguez and Bravo-Lozano 1991	Orchard	0.81		0.51		0.637	
Rumayor-Rodriguez and Bravo-Lozano 1991	Orchard	0.32		0.12		0.365	
Rumayor-Rodriguez and Bravo-Lozano 1991	Orchard	0.44		0.17		0.390	
Rumayor-Rodriguez and Bravo-Lozano 1991	Orchard	0.81		0.35		0.428	
Blaikie et al. 2001	Orchard		0.01	0.00			0.599
Average	**Orchard**					**0.525**	**0.599**
Araujo 1995	Vine	0.15		0.16		1.048	
Peacock et al. 1977	Vine		1.48	1.13			0.766
Srinivas et al. 1999	Vine	0.51		0.28		0.545	
Average	**Vine**					**0.796**	**0.766**

Step 3: Project the applied water for each crop and hydrologic region in 2030

DWR calculated an applied water for each crop and HR ($AW_{crop,HR}$). We treated the 2000 AW value as a weighted average of the applied water for each irrigation method according to the following equation:

$$AW_{crop,HR,2000} = (Drip\%_{crop,2000})(AW_{crop,\ drip,\ HR}) + (Sprinkler\%_{crop,2000})(AW_{crop,sptinkler,HR}) + (Gravity\%_{crop,2000})(AW_{crop,gravity,HR}) \quad (4)$$

where $Drip\%_{crop,2000}$ $Sprinkler\%_{crop,2000}$ and $Gravity\%_{crop,2000}$ are the fraction of each crop type irrigated with drip, sprinkler, and gravity, respectively, in 2000. The AW for each irrigation method is unknown, but we know the ratio of 1/WUE for each irrigation method by crop type. For field crops, for example,

$$\frac{AW_{field,drip}/Yield_{field,drip}}{AW_{field,sprinkler}/Yield_{field,sprinkler}} = 0.879 \quad (5)$$

By holding yield constant, we can calculate the relative applied water for drip versus sprinkler, or Rel $AW_{crop,d/s}$, according to the equation

$$\mathrm{Re}\,lAW_{field,d/s} = \frac{AW_{field,drip}}{AW_{field,sprinkler}} = 0.879$$

$$\text{or } AW_{field,drip} = 0.879(AW_{field,sprinkler}) \quad (6)$$

According to equation six, drip uses 12 percent less water than sprinklers use to produce the same yield. We repeat this process for all crop types and all irrigation methods. We then substitute the relative AW for each crop type into equation four to obtain the following equation

$$AW_{crop,HR,2000} = (Drip\%_{crop,2000})(AW_{crop,drip,HR}) + (Sprinkler\%_{crop,2000})(AW_{crop,drip,HR})\left(\mathrm{Re}\,lAW_{crop,d/s}\right) + (Gravity\%_{crop,2000})(AW_{crop,gravity,HR})\left(\mathrm{Re}\,lAW_{crop,d/g}\right) \quad (7)$$

We solve for $AW_{crop,drip,HR}$ and using the relative applied water relationships, we are able to solve for the AW for sprinkler and gravity.

We now need to calculate the 2030 AW given that the distribution of irrigation methods will change. To accomplish this, we combine the AW for each irrigation method by the percent of each crop type irrigated with that method according to the following equation:

$$AW_{crop,HR,2030} = \left(Drip\%_{crop,2030}\right)\left(AW_{crop,drip,HR}\right) + \left(Sprinkler\%_{crop,2030}\right)\left(AW_{crop,sprinkler,HR}\right) + \left(Gravity\%_{crop,2030}\right)\left(AW_{crop,gravity,HR}\right) \quad (8)$$

where $Drip\%_{crop,2030}$ $Sprinkler\%_{crop,2030}$ and $Gravity\%_{crop,2030}$ are the fraction of each crop type irrigated with drip, sprinkler, and gravity, respectively, in 2030. We can then estimate future irrigation water use in 2030 (IU_{2030}) by the following equation:

$$IU_{2030} = \sum_{HR=1}^{R} \sum_{crop=1}^{C} \left(ICA_{crop,HR,2030}\right) \times \left(AW_{crop,HR,2030}\right) \quad (9)$$

Caveats and Suggested Improvements

The outlined approach provides an approximation of non-price-driven efficiency improvements due to projected changes in irrigation technology. Projections were based on a linear extrapolation of historical data. While a linear extrapolation may be the easiest method for projecting future trends, it may not represent actual trends. External factors, such as prolonged drought, climate change, or improvements in irrigation technology, may alter these trends.

In this study, we calculated changes in water use by normalizing yield. This approach provides a way of estimating an optimal level of water savings while maintaining agricultural yields at approximately constant levels. Irrigation studies examined in this report, however, suggest irrigation efficiency improvements save water ***and*** substantially improve crop yields. Crop yields can rise in response to a number of factors, including reduced fungal infestations, more efficient fertilizer applications, and less water lost through evaporation (and consequently more available for transpiration). A more comprehensive effort might explore BOTH yield improvements and water savings.

Additional studies on relative irrigation efficiencies are needed. These studies should focus on regional differences in the distribution and efficiency of irrigation methods given variations in climate. They should also examine the role of regulated deficit irrigation and other management practices in reducing crop water demand. These studies would improve our understanding of the potential for greater water use efficiency.

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