Developing Sustainability Metrics for Water Use in Arizona Small Grain Production

Final Report to the
Arizona Grain Research and Promotion Council

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Executive Summary — December 2015

What Is the Issue?

Grain buyers and consumers increasingly evaluate their potential grain purchases in terms of "sustainability metrics" such as carbon or water "footprints." In the future, grain growers' access to markets and the prices they receive for their crops may depend increasingly on how crops are produced in terms of such sustainability metrics.

This study estimated a number of sustainability measures for water use in Arizona small grain production including: water application intensity, water productivity, water economic productivity, and water footprint. The study also evaluated how grain production, particularly as part of grain-vegetable crop rotations, enhances the regional sustainability of local agricultural production in the arid Southwest. Finally, the study evaluated estimates of Arizona durum wheat's water footprint (water consumed per bushel produced) reported in popular water footprint calculators. It identified several methodological and data errors in these calculators that lead to an over-estimate of the water footprint of Arizona's durum wheat production.

What Did the Study Find?

Among all crops grown in Arizona, wheat and barley have relatively low water application rates. According to recent USDA survey data, only 3.1 acre-feet (AF) / acre of water are applied to wheat and barley. This is 26% lower than the state average application rate of 4.2 AF / acre across all crops.

Over the last 30 years, the amount of water that growers apply to produce a bushel of wheat has fallen by 18%, while the amount of water applied to produce a bushel of barley has fallen 17%. Put another way, the amount of Arizona wheat produced per acre-foot of water applied has increased by 22% over the last 30 years. Arizona barley

has seen a similar increase in “crop per drop” (bushels per acre foot of water applied) of 21% over the same time.

Over the last 30 years, water applied annually per acre to wheat and barley fell by 10%. Given 2013 acreage of these crops, growers were applying 37,066 fewer acre-feet of water than if they were applying water at the higher rates of 1984. This reduction in water applications is equivalent to the annual residential water use of 376,029 people in Tucson, Arizona. Put another way, this reduction in applications is equivalent to 40 percent of water deliveries Tucson Water makes to all customers (residential, commercial, and industrial) over its entire service area, which encompasses more than 700,000 people.

In 2013, Arizona growers of all crops (not just grains) spent $53.3 million on new irrigation equipment, facilities, land improvements, and computer technology. This amounted to investments in irrigation improvements of $151 per acre and $42,939 per farm. Of this $53.3 million, $12.2 million were investments primarily to conserve water, while another $1.1 million was devoted to conserving energy.

Recent research on irrigation efficiency in Yuma County, Arizona highlights the important role of wheat planted in rotation with vegetables, both in terms of (a) reducing absolute consumptive use of water and (b) improving economic water productivity. Since 1970, many Yuma County acres have shifted from continuous and long-season crops to vegetable-wheat rotations. Multi-cropped systems use less water because wheat following vegetables matures in late spring, eliminating the need to irrigate in the latter half of the summer, when there is high evaporative demand. The shift to wheat-vegetable rotations has reduced per acre water use (measured in terms of crop evapotranspiration) by 24% - 56% compared to previous cropping patterns. The shift to rotations has also dramatically improved economic water productivity – the dollar value of crop production per acre-foot of water consumed. Compared to older cropping patterns, wheat-vegetable rotations increase economic water productivity 9 to 21 times.

Environmental groups have increasingly called for shifts within agriculture toward relatively *more* wheat production in the Lower Colorado Basin as a means of both conserving water and preserving the sustainability of agriculture in the region.

Some recent reports have suggested that Arizona durum wheat has a substantially larger water footprint (water used per unit of crop output) than wheat production in other areas. Some of the data reported in these studies and reports, however, do not match the original data sources that they cite, with unexplained omissions and changes to data that overstate water footprint of durum production in Arizona, while understating it elsewhere.

This study adjusted water footprint estimates for Arizona durum wheat production by making use of more accurate and relevant data available on regional rainfall patterns, planting season length, and crop consumptive water use. Prior estimates either underestimate Arizona durum wheat yields, overestimate water available for use by crops, or both. Both types of errors mistakenly suggest that Arizona durum production has a larger water footprint than production in most other regions. **However, using better data to develop more accurate estimates, we find that Arizona durum wheat production has a water footprint that is *lower* (in some cases *much lower*) than many other durum production regions.**

Finally, estimates of crop water footprints, in general, often base their calculations on estimated water use on harvested acreage only. This approach ignores three critical facts of crop production:

1. Many crop acres are regularly abandoned (not harvested at some point after planting).
2. Although significant amounts of water and other inputs (such as fertilizers and seed) are applied to these abandoned acres, they yield no output.
3. Irrigation is a key factor in reducing rates of crop abandonment.

Water footprint measures that do not account for water used on abandoned acreage can understate the true water footprint of crop production. This is important when comparing Arizona with other regions because abandonment rates are usually much lower in Arizona than elsewhere. Properly accounting for the effects of abandonment would increase measures of the true water footprint in all regions. This increase, however, would be negligible in Arizona, where abandonment rates are very low. The increase in the true water footprint in high-abandonment areas could be much higher. This study has developed and presents a formula to adjust water footprints for the effects of abandonment.

How Was the Study Conducted?

This report used data from various years of the US Department of Agriculture's (USDA's) Farm and Ranch Irrigation Survey (FRIS). FRIS data are collected roughly every five years as a follow-up survey to the *Census of Agriculture*. The most recent survey was conducted for 2013. FRIS data were used to compare water application intensity and water productivity over time.

To construct measures of economic water productivity, the study combined data on consumptive use of water by cropping pattern from the report *A Case Study in Efficiency – Agriculture and Water Use in the Yuma, Arizona Area* with production and economic data from *Annual Statistical Bulletins* of the USDA National Agricultural Statistics Service (NASS) Arizona Field Office.

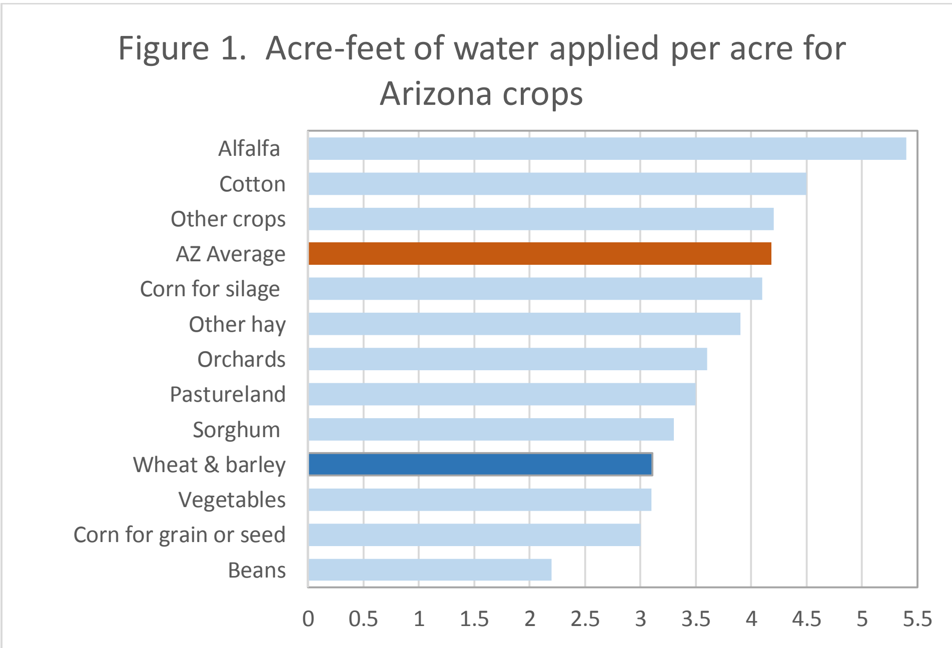
The study next examined water footprints estimated for durum wheat production in Arizona and other regions as reported by the Water Footprint Network (WFN) (http://waterfootprint.org/en/) – a non-governmental organization based in The Hague, Netherlands that develops and reports water footprints for (among other things) specific commodities. WFN provides one of the most widely-used water footprint calculators in the world. Data from this website were compared with water footprint estimates published by other studies and compared with more locally specific data available for durum wheat production in Arizona. Because the water footprint calculators are adapted from more general water use models and are applied at a more general geographic scale, their application does not necessarily fit production conditions in the main durum wheat growing areas of Arizona.

Finally, the study developed a simple formula to estimate biases in water footprint calculations that fail to account for land abandonment. The degree of bias increases with the percentage of acres abandoned and the amount of water consumed before abandonment.

Results and Discussion

Irrigation application intensity

Among all crops grown in Arizona, small grains have relatively low water application rates. Only 3.1 AF / acre of water were applied to wheat and barley in 2013 (the most recent year data are available) (USDA, 2013). This is 26% lower than the Arizona average across all crops of nearly 4.2 AF / acre (Figure 1).



Source: USDA, Farm and Ranch Irrigation Survey, 2013

Water applied to wheat and barley averaged 3.45 AF / acre in 1984, but this rate fell by 10%, to 3.11 AF / acre by 2013.

Because agriculture accounts for a large share of Arizona's water use, even modest improvements in irrigation efficiency can have important implications for water conservation in the state. To illustrate, we calculated how much *less* water was applied to Arizona wheat and barley acres because application rates had fallen from their 1984 levels. To do this, we took data on acreage and irrigation water applied from the years 1984 and 2013 of USDA's Farm and Ranch Irrigation Survey (Table 1). First, in 2013, consider that 65,301 acres of wheat were harvested while 61,072 acres of barley were harvested. Water application rates were 3.4 AF / acre for wheat and 2.8 AF / acre for barley. Second, consider how much more water *would have* been applied in total if application rates were at their higher 1984 levels (3.5 AF / acre for wheat and 3.3 AF / acre for barley). The savings in water applied to wheat is 65,301 acres x (3.5 AF / acre –

3.4 AF / acre) = 6,530 acre-feet. The savings to water applied to barley was 61,072 acres x (3.3 AF / acre – 2.8 AF / acre) = 30,536 acre-feet. By reducing water application rates below their 1984 levels, Arizona small grain growers applied 37,066 fewer AF of water than would have been the case on the same number acres in 1984. Of this 37,066-AF reduction, 82% is attributable to reduced irrigation intensity on barley, while 18% is attributable to reduced intensity on wheat acreage.

Table 1. Estimated reduction in water applications to Arizona wheat and barley because of reduced irrigation application intensity from 1984 to 2013.

	Wheat	**Barley**	**Total**
1. 2013 acres	65,301	61,072	126,373
2. 2013: AF* of water applied / acre	3.4	2.8	3.1
3. 2013: AF applied (row 1 x row 2)	222,023	171,002	393,025
4. 2013 acres (same as row 1)	65,301	61,072	126,373
5. 1984: AF of water applied / acre	3.5	3.3	3.4
6. 2013: AF that ***would have been*** applied ***if*** 2013 acreage were irrigated at 1984 rates (row 4 x row 5)	228,554	201,538	430,091
Reduction in water use from reducing irrigation application rates between 1984 and 2013 (row 6 – row 3)	6,530	30,536	37,066
% of reduction in applied water attributable to each crop	18%	82%	100%

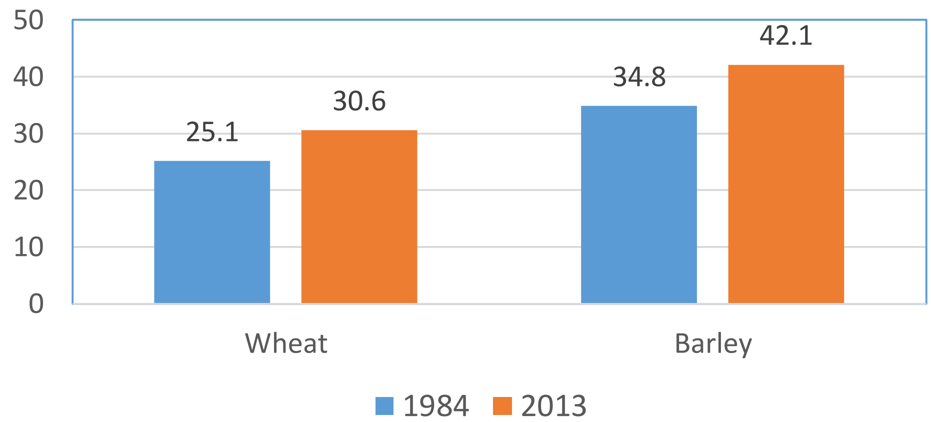
Source: USDA, NASS Farm & Ranch Irrigation Survey and author's calculations.
* AF denotes acre-feet.

How significant is a 37,066 AF reduction in water applications? To place this amount in context, let's compare it with residential water use. Tucson Water is the primary potable water supplier of the Tucson metro area, serving more than 700,000 people. Residential water use by people served by Tucson Water was 88 gallons per capita per day (Tucson Water, 2015). This amounts to 0.0985727 AF per person per year, or slightly less than one acre foot (0.985727 AF, to be exact) for every 10 people. This means that the 37,066 AF reduction in small grain irrigation applications are equivalent to the annual average water use of 376,029 Tucson metro area residents. Tucson Water supplied 92,534 AF of water to all customers (residential, commercial, and industrial) in 2013. So, put another way, the 37,066 AF reduction in small grain irrigation applications is equivalent to 40% of all the potable water provided by Tucson Water annually to the customers in its entire service area. The relatively lower water application intensity for growing wheat in the Southwest has led some conservation groups to call for shifts toward *relatively* more wheat production as means of conserving water and maintaining the sustainability of farming in the Lower Colorado Basin (for example, see Cohen et al., 2013).

Water productivity

Productivity measures the amount of an output produced per unit of input (or inputs) used. Yield (output per unit of land) measures land productivity. Labor productivity measures output per unit of labor input. Productivity measures may also be applied to water.

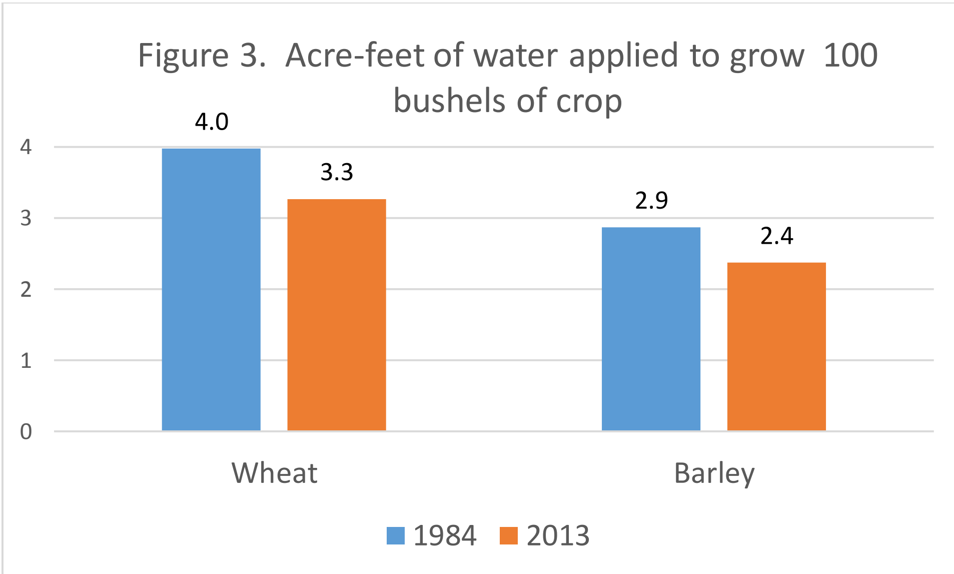
Figure 2. Bushels of wheat and barley produced per acre-foot of water applied



One way to measure water productivity is in terms of crop output per AF of irrigation water applied. Figure 2 illustrates that, over the last 30 years, Arizona growers have greatly increased the amount of grain they can produce per AF of water applied. In 1984, growers produced 25.1 bushels of wheat for every AF of water applied. By 2013, this increased 22% to 30. 6 bushels / AF. Arizona growers produced 34.8 bushels of barley / AF of water applied in 1984. This figure rose 21% to 42.1 bushels / AF applied in 2013.

While productivity is a ratio of output to an input (or inputs), this ratio can be flipped and expressed as input per unit of output. This flipping may be useful if one is interested in the amount of resources that are needed to produce a given amount of output. For example, one can measure the amount of water applied in the production of grains. Figure 3 illustrates this relationship.

In 1984, Arizona growers applied 4 AF of water to produce 100 bushels of wheat. By 2013, the amount of water applied to grow that same 100 bushels had fallen by 18% to just 3.3 AF. Arizona growers reduced the amount of water applied to grow 100 bushels of barley by 17% from 1984 to 2013, with applications falling from 2.9 AF to 2.4 AF.



Source: USDA Farm and Ranch Irrigation Survey, 1984 and 2013

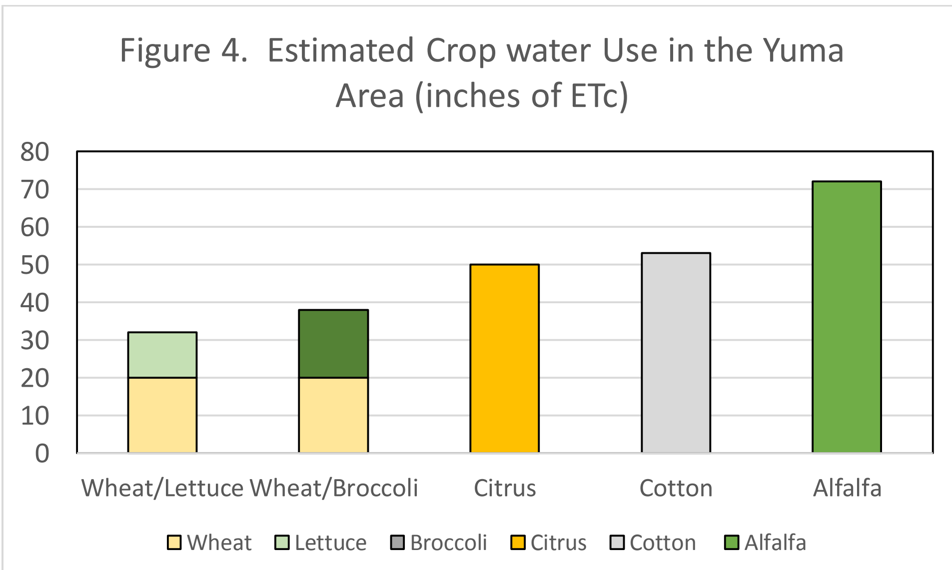
Investments to improve irrigation efficiency

According to USDA survey data, in 2013, Arizona growers (of all crops) spent $53.3 million on new irrigation equipment, facilities, land improvements, and computer technology. This amounted to investments in irrigation improvements of $151 per acre and $42,939 per farm. Of this $53.3 million, $12.2 million were investments primarily to conserve water, while another $1.1 million was devoted to conserving energy.

A recent study of the Yuma, Arizona area highlights how irrigation investments and changes in cropping patterns have combined to reduce water consumption per acre (Noble, 2015). Wheat production has played an important role in this transition. State-level data published by USDA reports water use in terms of AF applied. This, however, does not measure consumptive use of water – water removed from available supplies without return to the hydrological system. Crop consumptive water use is the amount of water transpired during plant growth plus what evaporates from the soil surface and foliage in the crop area. The Yuma study (Noble, 2015) documented patterns of consumptive use, measured by evapotranspiration.

Yuma growers have made many changes to improve irrigation efficiency and conserve water. These included constructing concrete lined irrigation ditches and high flow turnouts, shortened irrigation runs and adopting sprinkler irrigation systems. Yuma growers level their fields each year using precision laser leveling systems and growers utilize press wheels (“bolas”) and other management operations to improve water flow across fields. Most Yuma growers use highly efficient level furrow or level basin surface irrigation systems with average application efficiencies in the 80-85 percent range. Application efficiencies can approach 90 percent in finer textured valley soils. Sprinklers also are now routinely used to establish stands in wheat. This results in further water savings. Since the 1970s the water use efficiency of wheat production – measured as bushels of wheat per inches of crop evapotranspiration (ETc) – has increased 55 percent.

Also since the 1970s in Yuma County, Arizona, durum wheat grown in rotation with winter vegetables has replaced continuous crops (citrus and alfalfa) and long-season cotton on many acres. This shift in cropping patterns has reduced water use (measured in ETc) on these acres 24% - 56%. Multi-cropped systems use less water because the crop (such as wheat) following vegetables matures in late spring, eliminating the need to irrigate in the latter half of the summer, when there is high evaporative demand.



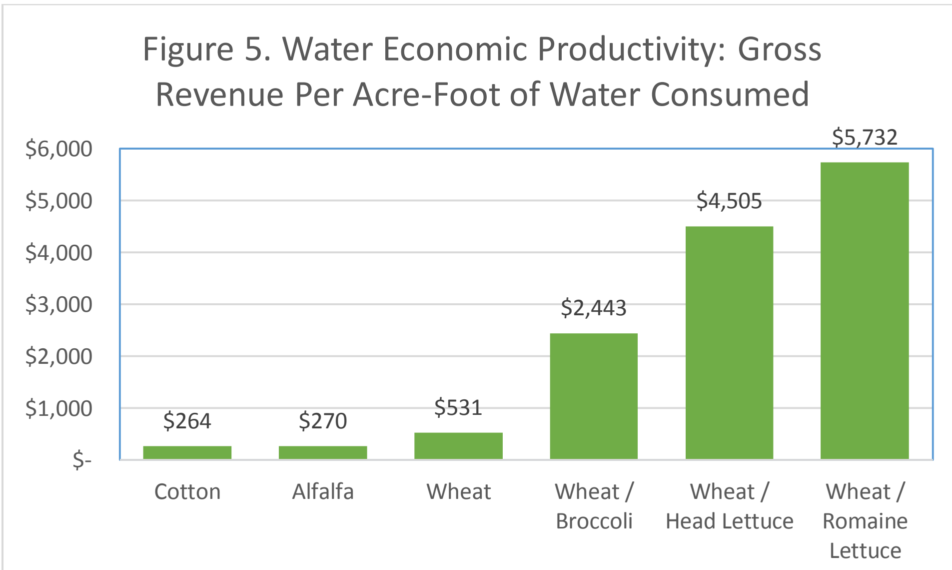
Source: Nobel, 2015

Figure 4 illustrates the reduction on absolute water consumption achievable by shifting to winter vegetable – wheat rotations. Water consumption for a wheat / lettuce rotation is 32 inches per acre, while it is 38 inches per acre for a wheat / broccoli rotation. These rotations have replaced citrus, cotton and alfalfa cropping patterns that consume 50 to 72 inches of water per acre.

Economic water productivity

The UN Food and Agriculture Organization defines economic water productivity as the monetary value generated from each unit of water consumed (UN FAO, 2015). Isolated, crop-specific measures of water use or productivity often ignore the important role of crop rotations and multi-cropping systems agriculture. Crop rotations are particularly important considerations for evaluating *economic* water productivity.

Figure 5 compares the water economic productivity of different cropping patterns in Yuma, where growers have dramatically increased their economic productivity by switching to wheat / vegetable rotations. Gross income per AF of water consumed for wheat alone was $531 / AF, double that of cropping patterns it replaced, cotton and alfalfa. When one accounts for the fact that the acres planted are devoted to a multi-crop system, the economic productivity is several orders of magnitude greater. A wheat / broccoli rotation would generate $2,443 / AF of water, while wheat / lettuce rotations generate $4,505 / AF to $5,732 / AF. So, Yuma growers have been able to increase their water economic productivity by 9 to 21 times by switching to crop rotations. Wheat continues to be a critical rotation crop with vegetables and is the second largest acreage crop in Yuma County.



Sources: Noble (2015); Arizona Agricultural Statistical Bulletin, 2014; author's calculations

Comparative Water Footprint Calculations

Recent studies have attempted to estimate "water footprints" for durum wheat production, calculating the amount of water consumed per unit of output. Water used is divided among three types. First, "green water" refers to consumptive use of rainwater stored in the soil (Falkenmark and Rockström, 2004). Green water use equals the minimum of effective rainfall and crop water requirement (Chapagain et al., 2006; Aldaya et al., 2010). Effective rainfall refers to the percentage of rainfall available to plants and crops, subtracting out losses from runoff, evaporation and deep percolation. One can see from this definition that the amount of green water used by a crop in a given area *will be less than* the total amount of precipitation. Next, "blue water" refers to consumptive use of ground and surface water applied via irrigation. Finally, "grey water" refers to polluted water. Mekonnen and Hoekstra (2011) define grey water as, “the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards (p. 1578).”

The Water Footprint Network (WFN) (http://waterfootprint.org/en/water-footprint/product-water-footprint/) provides estimates of water footprints for a variety of commodities, including durum wheat. The site reports how much water is used (measured in cubic meters, m^3) to produce one metric ton (MT) of durum wheat. Table 2 provides conversion factors between metric system measures and English units of measure used in the United States.

Table 2. Conversion factors for units of measure	
Value	Converts to:
1 acre – foot (AF) of water	1,233.48 cubic meters (m^3)
1 cubic meter (m^3)	0.00081 acre-feet (AF)
1 metric ton (MT)	2,204.62 pounds (lbs)
Barley: 1 bushel (bu)	48 pounds (lbs)
Barley: 1 bushel (bu)	0.021772 metric tons (MT)
Barley: one metric ton (MT)	45.9296 bushels (bu)
Barley: 100 bushels (bu)	4,800 pounds (lbs)
Barley: 100 bushels (bu)	2.177 metric tons (MT)
Barley: 1,000 (m^3) of water / MT	1.76 AF of water / 100 bushels
Wheat: 1 bushel (bu)	60 pounds (lb)
Wheat: 1 bushel (bu)	0.0272155 metric tons (MT)
Wheat: one metric ton (MT)	36.7437 bushels (b)
Wheat: 100 bushels	6,000 pounds (lbs)
Wheat: 100 bushels	2.7216 metric tons (MT)
Wheat: 1,000 (m^3) of water / MT	2.2 AF of water / 100 bushels

Mekonnen and Hoekstra (2011) report on the methods used to develop water footprints reported on the WFN site. Table 3 shows estimates from the WFN site of the water footprint for durum wheat production in Italy and Arizona, as well as WFN’s calculated global average. Table 3 also compares WFN estimates with those from other published studies as well as from this author’s calculations. The study by Aldaya and Hoekstra (2010) reports water footprint estimates that are quite different from the WFN website. This is despite the fact that one of the co-authors also developed the WFN estimates. Aldaya and Hoekstra’s estimates of green water use for durum wheat production for all of Italy are 37% lower than those reported by the WFN site (748 m^3 / MT compared to WFN’s estimate of 1,188 m^3 / MT). Their green water estimates were based on precipitation estimates from local weather stations. This suggests that the WFN is systematically overstating green water use, perhaps because of inaccurate underlying precipitation data. Aldaya and Hoekstra also appear to more accurately account for the extent of irrigation in Italian durum wheat production. Their estimate of Italy’s blue water footprint is 525 m^3 / MT, 33 times larger than the WFN estimate of just 16 m^3 / MT.

Table 3. Comparative water footprint estimates in m^3 / MT				
Region	**Green Water**	**Blue Water**	**Grey Water**	**Total Footprint ***
Global Average	1,277	342	207	1,827
Italy, Water Footprint Network (WFN)	1,188	16	187	1,391
Italy, Aldaya & Hoekstra	748	525	301	1,574
South Italy, Ruini et al.	1,372	not reported	212	1,584
Middle Italy, Ruini et al.	1,157	not reported	193	1,350
North Italy , Ruini et al.	997	not reported	172	1,169
Arizona, Ruini et al. & WFN	399	848	156	1,403
Arizona, author's calculation	97	848	156	1,101
Yuma AZ, author's calculation	71	670	156	897

* Total footprint in Ruini et al. calculations omit blue water.

Thus, the WFN site appears to have critical discrepancies in how precipitation is measured and how local production processes are characterized. Another odd aspect of the WFN site is that it does not report the water footprint for durum production in Sicily, even though Sicily is a major durum production region and has one of the largest water footprints. Aldaya and Hoekstra estimate that Sicily's green water footprint for durum production is 895 m^3 / MT and that its blue water footprint is 870 m^3 / MT. The sum of Sicily's blue and green water footprint alone is 1,765 m^3 / MT, much higher than the national average for Italy, according to Aldaya and Hoekstra. They do not report a separate grey water footprint for Sicily, which would only add to this total. Obviously, the omission of values for Sicily on the WFN site would bias the WFN estimates of national totals for Italy downward.

The study by Ruini et al. (2013) cites data from Mekonnen and Hoekstra (2010) as their sources. They report footprint estimates for Italy, divided across three regions: South, Middle, and North Italy. These estimates appear comparable to regional estimates from the WFN site. Their reported figure for the Southwest United States matches the reported figures for Arizona on the WFN site. In comparing water footprints across countries, Ruini et al. (2013) include blue water estimates in the total for Arizona, but inexplicably exclude them for Italy. As noted above, the Aldaya and Hoekstra analysis suggests that the WFN estimates substantially understate the water footprint of durum production in Southern Italy, first because it ignores the significant amount of irrigation carried out in the region and second because estimates from Sicily a large, water-intensive durum producer are excluded. Because Ruini et al.'s estimates are based on those from the WFN site, they also will understate the water footprint of South Italy. Even so, the water footprint of durum wheat production (taking these figures at face value) is clearly larger in Southern Italy than in Arizona.

But how does Arizona's water footprint compare with those reported for Middle Italy and Northern Italy? The figures reported by Ruini et al. (2013) for Middle and North Italy are relatively close to those reported by Aldaya and Hoekstra (2010), so we will start with Ruini et al.'s (2013) values of 1,350 m^3 / MT for Middle Italy and 1,169 m^3 / MT for Northern Italy. Let us now, however, consider the estimates reported for Arizona by the WFN website (and by Ruini et al. (2013)) more carefully.

The WFN site reports a water footprint of 1,403 m^3 / MT for durum wheat production in Arizona. This is divided into 399 m^3 / MT for green water, 848 m^3 / MT for blue water, and 156 m^3 / MT for grey water. Let us consider the 399 m^3 / MT of durum wheat green water estimate first. Over the past three years, durum wheat yields in Yuma County Arizona averaged 3.072 MT / acre (or 112.87 bushels / acre) according to USDA data (http://www.nass.usda.gov/Quick_Stats/). Recall that green water is the consumptive use of rainwater stored in the soil, equal to the minimum of effective rainfall and crop water requirements. Given Yuma wheat yields of 3.072 MT / acre, a green water footprint of 399 m^3 / MT implies effective rainfall in Yuma (rainwater taken up by wheat) of nearly 12 inches per acre per year.

Anyone familiar with the climate of Arizona in general and Yuma in particular will see an obvious problem with this estimate. First, the long run average precipitation in the area (based on the Tacna weather station) is 4.1 inches per year. Next, much of the region's rainfall comes in the form of summer monsoons, while durum wheat is planted in January and harvested by June. If one deducts monsoon (June to September) rainfall from this total, the amount potentially available for crop uptake is only 2.65 inches per acre. Only counting precipitation from October through May, this implies that an absolute upper bound for a green water footprint for durum wheat production in Yuma would be less than 89 m^3 / MT, not 399 m^3 / MT. This figure, however, assumes that 100% of the rain that falls over these months is taken up and used for the durum wheat crop and that 0% is lost to runoff, evaporation, or deep percolation. If one assumes, however, that at least 20% of rainfall is lost to runoff, evaporation, or deep percolation, then the durum wheat green water footprint would fall further, to 71 m^3 / MT. This suggests that a procedure similar to one carried out by Aldaya and Hoekstra is needed to correct errors in effective precipitation estimates reported on the WFN website.

We took USDA durum wheat yield and acreage data (from the USDA Quickstats database: http://www.nass.usda.gov/Quick_Stats/) over the most recent three available years to construct similar estimates for Pinal, Maricopa, and La Paz Counties. These counties (along with Yuma) accounted for virtually all the durum wheat produced in Arizona. A weighted average was used to estimate an upper bound green water estimate for durum wheat production in Arizona. Long-term average data for rainfall from the Western Regional Climate Center (http://www.wrcc.dri.edu/) was collected for stations (named in parentheses) in La Paz (Parker), Maricopa (Gila Bend), Pinal (Casa Grande), and Yuma (Tacna) Counties, using precipitations totals from October through May. Aggregating up for the entire state, the estimated green water footprint was 121 m^3 / MT. This figure, however, assumes that 100% of the rain that falls over these months is taken up and used for the durum wheat crop and that 0% is lost to runoff, evaporation, or deep percolation. If one assumes, however, that at least 20% of rainfall is lost to runoff, evaporation, or deep percolation, then the durum wheat green water footprint would fall to 97 m^3 / MT.

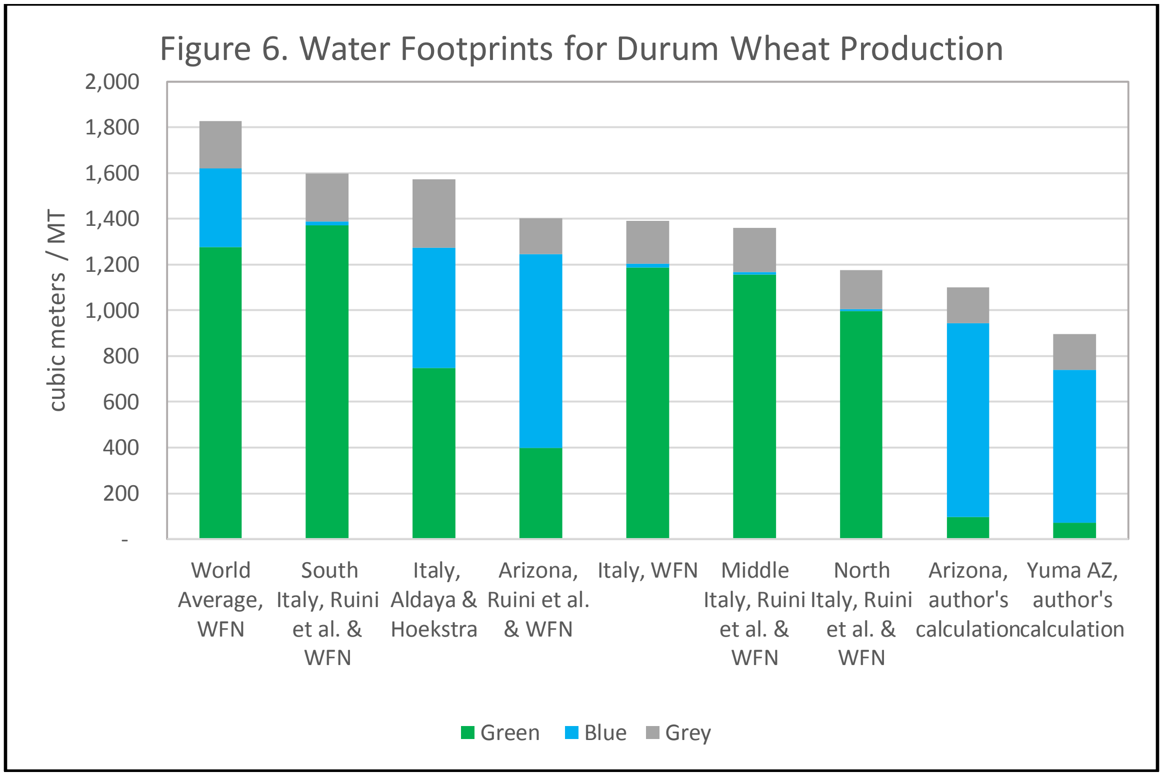
If one takes at face value the WFN's estimate of Arizona's blue and grey water footprints, the simple adjustment based on local data to green water estimates suggests that Arizona's water footprint would be 1,101 m^3 / MT. This is 6 percent lower than the North Italy estimates reported by Ruini et al. (2013) of 1,169 m^3 / MT.

There is evidence, however, that given the high yields of Arizona's durum wheat that this 848 m^3 / MT blue water footprint may also be overstated, at least for some parts of the state. In Yuma, estimated consumptive use of water in durum wheat production is about 20 inches per acre (Noble, 2015). Given recent average yields in Yuma, this amounts to a blue water footprint of about 670 m^3 / MT. Given a green water footprint for Yuma (calculated above) of 71 m^3 / MT, and assuming the same 156 m^3 / MT grey water footprint WFN reports for Arizona as a whole, Yuma County's water footprint of durum wheat production is 897 m^3 / MT.

This study was not able to find independent estimates of grey water use for durum wheat production. However, the WFN website lists values for Arizona of 156 m^3 / MT and an average value for Italy of 187 m^3 / MT. According to the WFN website, the global average grey water footprint for durum wheat production is 207 m^3 / MT. Further, Aldaya and Hoekstra report an average grey water footprint of 301 m^3 / MT for Italy. So, accounting for grey water use would increase the water footprints in other regions *more* than it would in Arizona.

Table 3 summarizes water footprint estimates reported by other studies alongside corrected estimates derived in this current study. When one more-accurately estimates the green water footprint of Arizona durum production and accounts for the fact that Arizona tends to have a lower grey water footprint than other areas, Arizona has a lower water footprint than the global average and a lower footprint than lower-footprint areas of Italy.

Figure 6 reports the comparative numbers in a slightly different way. Ruini et al. did not report any blue water use for the South, Middle, or North Italy, biasing those estimates downward. In figure 6, we took estimates of blue water use from the WFN website and added the lowest value available from each region to Ruini et al.'s estimates. This actually changes results very little given the already low estimates for blue water use on the WFN site. Figure 6 shows what happens if one takes the WFN values for blue and grey water use at face value and simply corrects for errors in green water use based on local precipitation and cropping pattern information. Arizona durum's water footprint with just this one correction is not only much lower than the global average; it is lower than the water footprint in North Italy, the part of Italy with the lowest water footprint there. If one goes a step further and uses local weather and water use data from Yuma County, Arizona, one finds that Yuma's water footprint is lower still.



Effects of crop abandonment on water footprint calculations

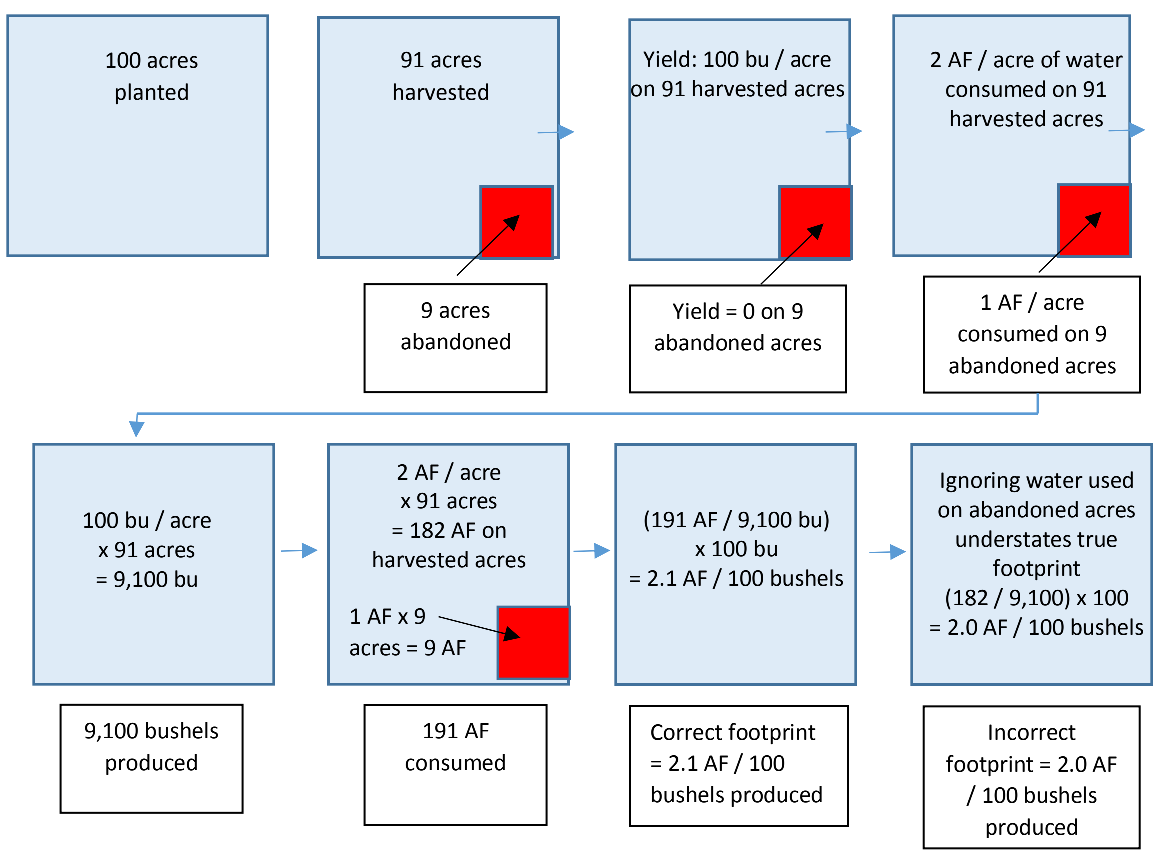
The water footprint estimates provided by the Water Footprint Network are based on water use and output per *harvested* acre of crop. This approach ignores three critical facts of crop production:

1. Many crop acres are regularly abandoned (not harvested at some point after planting).
2. Although significant amounts of water and other inputs (such as fertilizers and seed) are applied to these abandoned acres, they yield no output.
3. Irrigation is a key factor in reducing rates of crop abandonment.

Water footprint measures that do not account for water used on abandoned acreage can greatly understate the true water footprint of crops. This is important when comparing Arizona with other regions because abandonment rates are much lower in Arizona than elsewhere. Over the past 10 years, for example, abandonment rates on Arizona durum wheat acreage have averaged 1%, while abandonment rates on the rest of U.S. durum wheat acreage has averaged 4.5%, with rates commonly exceeding 10% in individual states and years (USDA, NASS Quickstats database). Here, we are measuring abandoned acres as the difference between official NASS estimates of final acres planted minus acres harvested.

Properly accounting for the effects of abandonment would increase measures of the true water footprint of production in other, higher-abandonment areas than it would for Arizona. To illustrate this point, see Figure 7 below. Consider a field where 100 acres of wheat are planted initially, but where 9 of those 100 acres are abandoned. Yield per *harvested* acre is 100 bushels. With 91 acres harvested 9,100 bushels of wheat are produced on this 100-acre field. While 2 AF of water were consumed producing the wheat on the harvested acres, let's assume 1 AF / acre was consumed on the other 9 acres before they were abandoned. These 9 AF of water were nevertheless consumed in

Figure 7. Ignoring water use on abandoned acres leads to an underestimate of the true water footprint of production.



the production of wheat (even though they led to no output). On this 100-acre field, 191 AF of water (182 AF on the 91 harvested acres and 9 AF on the 9 abandoned acres) were used and 9,100 bushels of wheat were produced. The water footprint (water consumed to produce a unit of crop output) on this field then is 2.1 AF / 100 bushels produced [191 AF / 91,000 bushels) x 100 bushels]. Most water footprint estimates only consider water use on harvested acres. Ignoring water use on abandoned acres, however, yields a water footprint that is only 2.0 AF / 100 bushels [182 AF / 91,000 bushels) x 100 bushels].

In this simple example, 191 AF of water were used to produce 9,100 bushels of wheat. Because of acreage abandonment, 9 AF of water were consumed that produced no wheat. Abandoned acres still use water (and other inputs). If the purpose of a water footprint is to measure how much water is actually used in the production process, then the fact that abandonment is part of the production process needs to be considered. In the stylized example from Figure 7, the true water footprint is 4.9% greater than the incorrect one that ignores abandonment. The bias in water footprint estimation is important when comparing water footprints for Arizona durum wheat production with other regions, because other regions have higher abandonment rates.

Because Arizona's abandonment rates are so low (about 1% on average), adjusting water footprints to account for abandonment would not change estimates much. In other, high-abandonment regions, correcting for abandonment effects could increase estimates of their true water footprint more substantially. In addition, because dryland production areas tend to have relatively high abandonment rates, the downward bias in estimates of water footprints for dryland crops (which consume green water) could be substantial. Thus, standard methods of estimating water footprints will tend to underestimate estimates for dryland production relative to irrigated production.

Writings on water footprints imply that production relying on green water (i.e., dryland production) is superior to production relying on blue water (i.e. irrigated production) because blue water can be more easily captured and applied to other valued uses and thus has a higher opportunity cost (e.g. Aldaya et al., 2010; Yang et al., 2006). This line of reasoning, however, ignores the problems of inherent risk and lost resource costs associated with dryland production – or production in general in high abandonment regions. There are costs associated with using up water resources that lead to zero production. Production in high-abandonment regions can have significant amounts of water and other agricultural inputs used to no avail. Water footprints, carbon footprints, and other environmental footprints on abandoned acreage are infinitely large because some quantum of water (or other inputs) produces nothing. Failure to account for this makes irrigated water appear more resource intensive relative to dryland production than it actually is because irrigation substantially reduces abandonment rates.

The following simple mathematical formula can be used to estimate the size of the bias in water footprint measurements caused by ignoring acreage abandonment. The water footprint on the harvested acreage is *x*, but the water footprint on the abandoned acreage is infinitely large. This is because water is being used up (numerator positive) without producing any crop (denominator zero).

Let

a = the proportion of acres abandoned; $0 \leq a \leq 1$.

W_H = water used on harvested acres

b = water used on abandoned acres as a proportion of water used on harvested acres; $0 \leq b \leq 1$.

It is reasonable to assume that the amount of water used on abandoned acreage will be no more and possibly less than on acres that are ultimately harvested. In the case of irrigated crops, farmers may cease irrigation on crops that are abandoned. One can calculate the percentage bias, *B,* of ignoring abandoned acres on water footprint measures, where

B = Percentage bias = $(a / 1 - a) \times b$

What does this formula mean? For example, assume that the crop abandonment rate is 20%. This seems large, but is not unheard of for rain-fed crops. Further assume that water use on abandoned acreage is just 50% of water use on harvested crops. How much will one's estimate of crop's water footprint be biased downward by ignoring crop failure? In this case the bias would be (0.2 /0.8) x 0.5 = 0.125 or 12.5%.

For Arizona, the bias from ignoring abandonment will be small because, abandonment rates are small, only about 1% over the long term. Assuming that water consumed on abandoned durum acreage is only 50% of water consumption on harvested acreage, then the bias would be

B = (0.01 / 0.99) x 0.5 = 0.005 or 0.5%.

In contrast, assume another durum wheat producing area has a 10% abandonment rate with abandoned acreage consuming 50% the water of harvested acreage. Here the bias would be

B = (0.1 / 0.9) x 0.5 = 0.0555 or 5.55%.

Correcting for abandoned acreage would increase Arizona's durum wheat water footprint by 0.5%, but would increase the water footprint of the example area by 5.55%. In this case, making the correction would increase the other region's water footprint by about 5% relative to Arizona's footprint. One could thus use abandonment rate data from other areas to adjust accordingly. Because most other regions are likely to have higher abandonment rates than Arizona's low 1% rate, other regions would have their footprints increased by a greater percentage. Thus, properly accounting for Arizona's relatively low abandonment rates would further reduce Arizona's water footprint *relative* to other regions.

Conclusions of this study

One measure of water use efficiency is irrigation application intensity – the amount of irrigation water applied per acre. Compared to many crops grown in Arizona, less irrigation water is applied per acre to small grains. Only 3.1 acre-feet (AF) of water per acre were applied to small grains, which is 26% less than the state average for all crops of 4.2 AF / acre. The lower water application intensity for wheat in the Southwest has led some conservation groups to call for shifts toward relatively more wheat production as means of conserving water and maintaining the sustainability of farm in the Lower Colorado Basin.

The shift to wheat-vegetable crop rotations in Yuma County, Arizona over the past 30 years has led to significant reductions in the consumptive use of water when compared to previous cropping patterns. Compared to older cropping patterns, wheat-vegetable rotations have reduced absolute water consumption per acre. The shift in cropping patterns has also substantially increased water economic productivity – the dollar value of production per acre-foot of water consumed.

Popular water footprint calculators that are available on water resource group websites yield estimates of Arizona water use in durum production that do not match more accurate hydrological, weather, and consumptive use data that are available for the state. Using better data to develop more accurate estimates, we find that Arizona durum wheat production has a water footprint that is *lower* (in some cases *much lower*) than many other durum production regions.

Water footprint measures that do not account for water used on abandoned acreage can understate the true water footprint of crop production. This is important when comparing Arizona with other regions because abandonment rates are usually much lower in Arizona than elsewhere. Properly accounting for the effects of abandonment would increase measures of the true water footprint in all regions. This increase, however, would be negligible in Arizona, where abandonment rates are very low. The increase in the true water footprint in high-abandonment areas could be much higher. This study has developed and presents a formula to adjust water footprints for the effects of abandonment.

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