Water Sustainability Indicators in Arizona's Small Grains Industry

George Frisvold, Claudia Montanía, & Dari Duval

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Executive Summary

What is the issue?

Small grains production (wheat and barley) in Arizona plays a strategic role in high-value specialty crop systems, as well as in providing feed for the state's livestock industries. Furthermore, shifts away from relatively higher water use field crops towards vegetable-small grains rotations have enabled growers to achieve high economic productivity of water use in major agricultural regions of the state. This study analyzes the economics of small grain production in Arizona, including as part of rotational vegetable-small grains production systems in arid regions. The report provides an overview of small grains production in the state, including industry structure, farm characteristics, geographic distribution, and market trends. From there, the study provides an extensive analysis of water use in Arizona small grains production, comparing water use intensity, productivity, efficiency, and economic productivity to other crops and growing regions. This includes the development of updated water footprint measures for Arizona durum wheat production. Finally, the report presents an economic contribution analysis for Arizona's small grains industry, estimating direct sales and resulting economic multiplier effects.

What did the study find?

In 2024, Arizona's small grains industry has a statewide economic contribution of $120 million in sales, $54 million in Gross State Product, and more than 460 jobs (including multiplier effects)

- Arizona's small grains industry had direct sales (output) of $56.7 million in 2024. Of the total, $45.9 million came from durum wheat and $10.7 million came from barley sales.
- Including multiplier effects, the value added (Gross State Product) generated by small grains was nearly $54 million in 2024.
- The production of durum wheat and barley directly and indirectly supported 466 jobs, of which 149 jobs were directly in small grain production, and 316 were in other Arizona industries.

Small grains production in Arizona is achieved with comparatively high levels of water use efficiency and productivity relative to other crops and other regions.

- In 2023, Arizona growers applied 3.4 acre-feet / acre of water to wheat on average and 3.3 acre-feet / acre to barley. This is 17% and 20% below the statewide average of over 4.12 acre-feet/acre across all crops, respectively.
- Over the last 40 years, Arizona growers have greatly increased the amount of grain they can produce per acre-foot (AF) of water applied. In 1984, growers produced 25.7 bushels of wheat for every AF of water applied. By 2023, this increased 18% to 30.3 bushels / AF. Arizona growers produced 30.6 bushels of barley / AF of water applied in 1984. This figure rose 31% to 40 bushels / AF applied in 2023.

- Shifts towards high-value vegetable-small grain rotations in areas of the state have improved economic water productivity. 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.

Water footprints measure how much water is consumed in the production of commodities or provision of services. Blue water footprints measure the use of groundwater and surface water for irrigation. Green water footprints measure the consumption of rainfall. Finally, grey water footprints measure the water needed to assimilate pollutants generated in production, in this case, nitrogen. We estimated blue, green, grey, and total water footprints for Arizona durum wheat production.

- Arizona durum wheat had a lower total water footprint than 80% of global river basins producing wheat. Arizona's footprint was 29-42% below the global average for irrigated wheat.
- Arizona durum wheat has a lower green water footprint than any of 26 major wheat-producing countries or across the 220 river basins analyzed. This is due to the low rainfall levels that characterize regions of the state that produce durum wheat.
- We developed 15 combined green-blue water footprint estimates across Western and Central Arizona. Of these, 14 were below the 20th percentile across all wheat production globally, meaning that 80% of global wheat production used more water per unit of wheat produced. The remaining estimate was below the 25th percentile, meaning that 75% of global wheat production used more water per unit of wheat produced.
- Arizona's grey water footprint (measuring water needed to assimilate nitrogen from fertilizers reaching water bodies), in contrast, was greater than the global average. There are a variety of fertilizer management practices that can allow growers to better match nitrogen fertilizer applications to plant nutrient requirements in durum wheat production. Improving fertilizer management in Arizona durum wheat production has the potential to be a win-win strategy, both improving farm profitability and water quality.

How was the study done?

We estimate efficiency measures for water use in Arizona small grain production, such as water application intensity, water productivity, water economic productivity, and water footprints, drawing from a series of federal data sources and academic publications. To estimate the economic contribution of the small grains industry to Arizona's economy, we rely on federal agricultural statistics, as well as the IMPLAN Pro model for Arizona to estimate economic multiplier effects.

Introduction

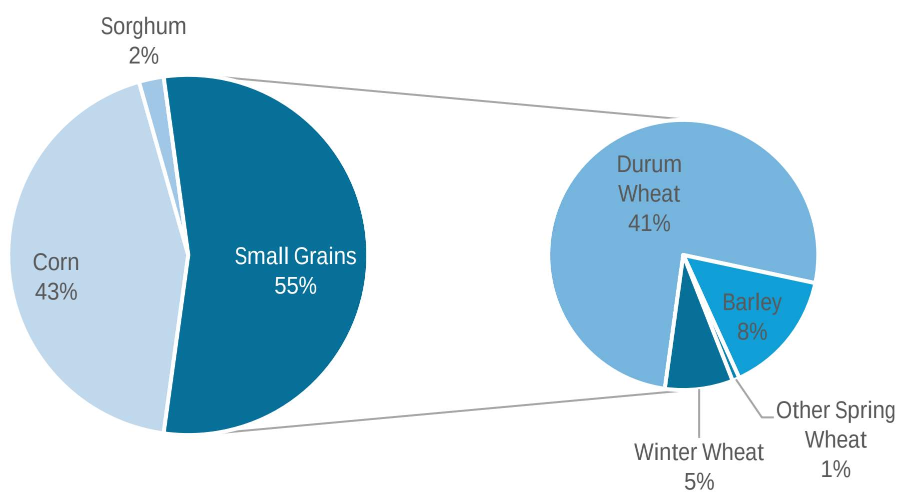
Production of small grains (wheat and barley) in Arizona plays a strategic role in the state's high-value specialty crop systems, as well as in providing feed for the state's livestock industries. Small grains contribute to maintaining soil health in rotational cropping systems. In areas like Yuma County, shifts away from relatively higher water use field crops towards vegetable-small grains rotations have enabled growers to achieve high economic productivity of water use.

This study analyzes the economics of small grain production in Arizona, including as part of rotational vegetable-small grains production systems in arid regions. The report begins by providing an overview of small grains production in the state, including industry structure, farm characteristics, geographic distribution, and market trends. Following that, the study offers an extensive analysis of water use in Arizona small grains production, comparing water use intensity, productivity, efficiency, and economic productivity to other crops and growing regions. This includes the development of updated water footprint measures for Arizona durum wheat production. Finally, the report presents an economic contribution analysis for Arizona's small grains industry, estimating direct sales and resulting economic multiplier effects.

Arizona Small Grains Production

Arizona has a long and rich tradition of small grains production, rooted in a history that goes back to the 17th century, when Spanish missionaries first introduced wheat and barley to the region, likely from Andalusia, Spain. Among the varieties introduced, White Sonora wheat proved especially well suited to the arid environment. White Sonora wheat continues to be produced in Arizona to this day, fulfilling demand for locally grown heritage grains. Meanwhile, small grains have come to serve important roles in Arizona's agricultural production systems, particularly high-value specialty crops. Generally, small grains accounted for over half the volume of grains produced in Arizona. Wheat and barley made up the entirety of reported small grains production (Figure 1).

Figure 1. Grain Production by Commodity (Percentage of Bushels), 2022

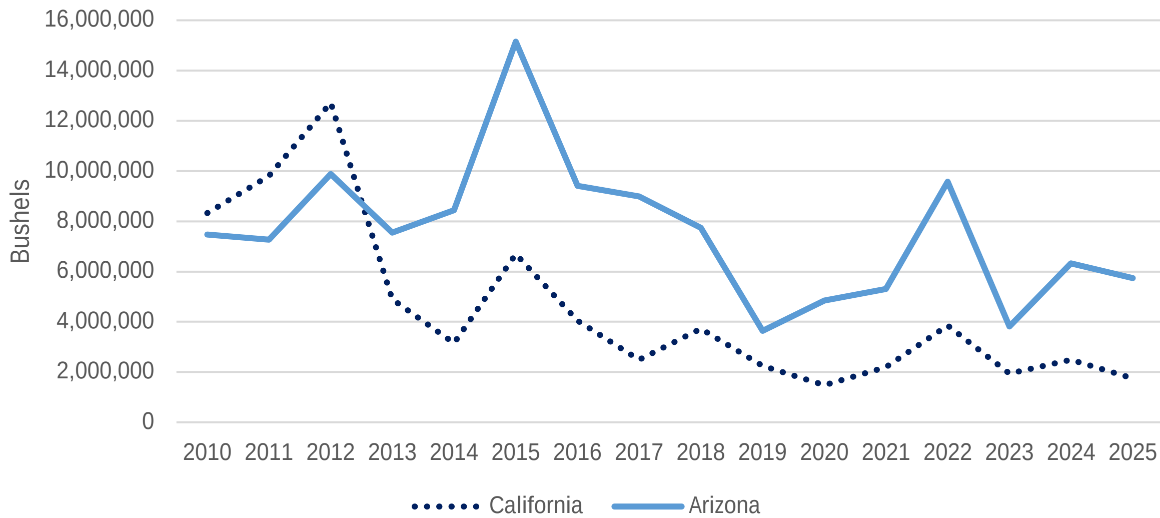


* Percentages calculated based on bushels of production
** Excludes production of commodities for silage or green chop
Source: USDA, 2022 Census of Agriculture

Wheat production can be further divided into durum wheat and common wheat. Common wheat includes winter wheat and spring wheat varieties. Most of Arizona's small grains production is wheat, of which durum wheat is the predominant variety. Arizona and California produced roughly 11% of the national durum wheat crop in 2024. Top states for durum wheat production were North Dakota (64%), Montana (25%), Arizona (8%), and California (3%). Figure 2 presents recent trends in spring durum wheat production in Arizona and California, the two states that produce Desert Durum®. Desert Durum® is durum wheat grown in the low deserts of Arizona and California with desirable properties for use in pasta-making.

In addition to durum wheat, Arizona also produces common wheat, officially classified as "winter wheat" and "other spring wheat" in USDA production statistics. In 2022, 961,000 bushels of winter wheat and 101,355 bushels of spring wheat were produced in Arizona, accounting for just over 10% of total wheat production.

Figure 2. Durum Spring Wheat Production in California and Arizona (Bushels), 2010–2025



Source: USDA NASS QuickStats Database

In 2024, cash receipts for wheat and barley totaled nearly $60 million in Arizona, with wheat constituting roughly five-sixths of cash receipts. Among Arizona agricultural products sold in 2024, wheat ranked 13th for cash receipts with roughly $48 million in sales. Barley ranked 23rd with roughly $11 million in sales (Table 1).

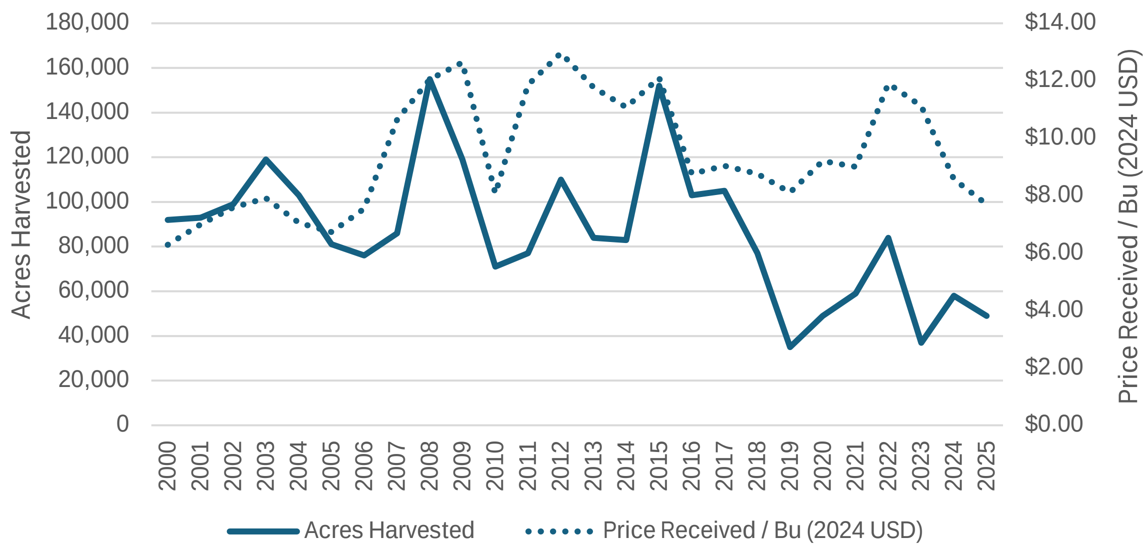
Table 1. Ranking of Cash Receipts for Arizona Agricultural Products Sold, 2024

Rank	Commodity	*State Receipts ($1,000)*	*Percent*
1	Cattle and calves	$1,502,702	28.3%
2	Dairy products, Milk	$1,057,906	19.9%
3	Lettuce	$934,102	17.6%
4	Miscellaneous crops	$562,827	10.6%
5	Hay	$215,327	4.1%
6	Cauliflower	$152,681	2.9%
7	Cantaloups	$114,089	2.2%
8	Broccoli	$107,381	2.0%
9	Pecans	$85,652	1.6%
...	...	...	...
13	**Wheat**	**$45,912**	**0.9%**
...	...	...	...
23	**Barley**	**$10,750**	**0.2%**

Source: ERS, USDA, 2026. Cash receipts by state, commodity ranking, and share of U.S. total, 2024.

Wheat acres harvested have tracked with price received in Arizona since 2000, suggesting that growers respond to prevailing market prices, though the relationship appears to have weakened since 2018 (Figure 3).

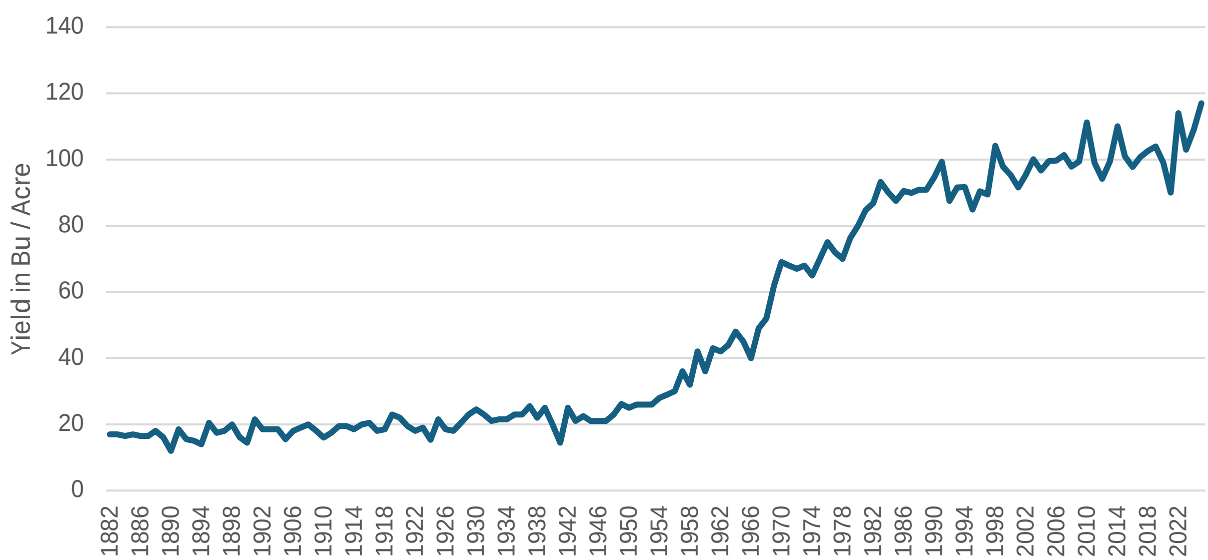
Figure 3. Arizona Wheat Acres Harvested versus Price Received



Source: USDA NASS, 2026

Wheat yield in Arizona has increased by a factor of 6 since statistics first became available for the state in the late 1800s (Figure 4). Those gains in yield were especially large between 1950 and 2000, though increases continue to this day.

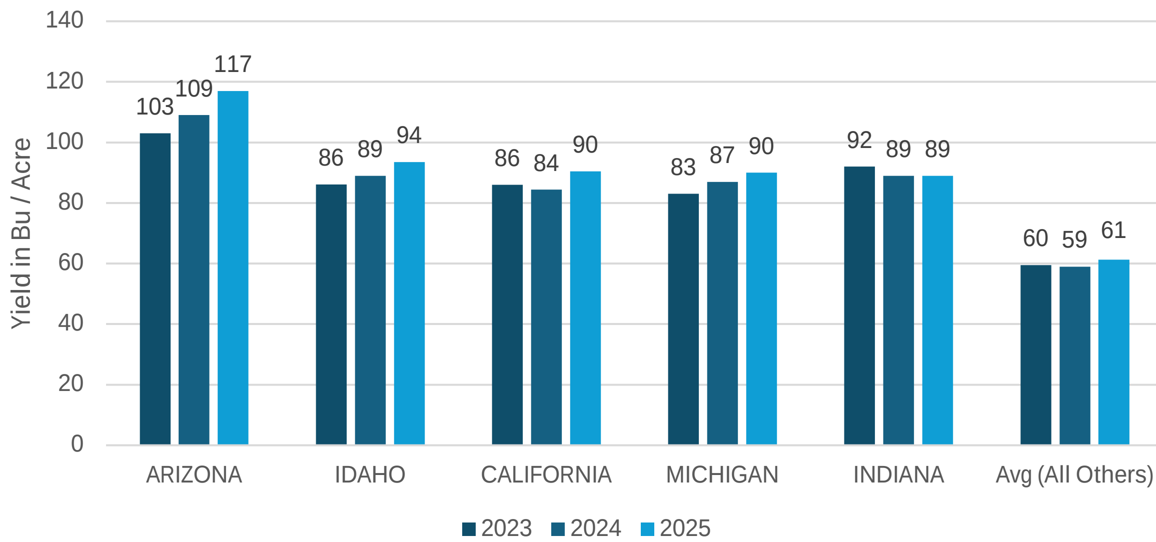
Figure 4. Arizona Wheat Yield in Bushels per Acre, All Types, 1882-2025



Source: USDA NASS, 2026

Arizona has the highest wheat yields in the country, averaged over all varieties. This likely reflects the state's year-round growing season in many areas and near-exclusive use of irrigation for crop production (Figure 5).

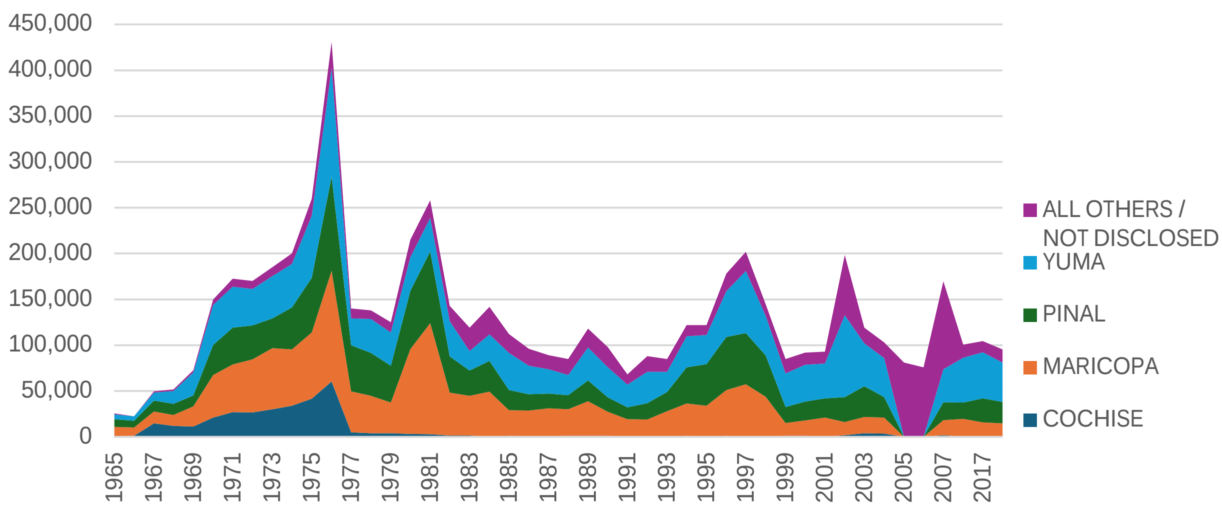
Figure 5. Wheat Yield for Top 5 States & All Others, 2023-2025



Source: USDA NASS, 2026

Statewide wheat acreage has seen major rapid changes over time, though total statewide acreage has fluctuated around 100,000 acres since the 1980s (Figure 6). While a large share of production occurred in Maricopa County in the 1970s and 1980s, that share has since declined as agricultural land in Maricopa County has gradually transitioned out of agriculture and into residential and commercial uses.

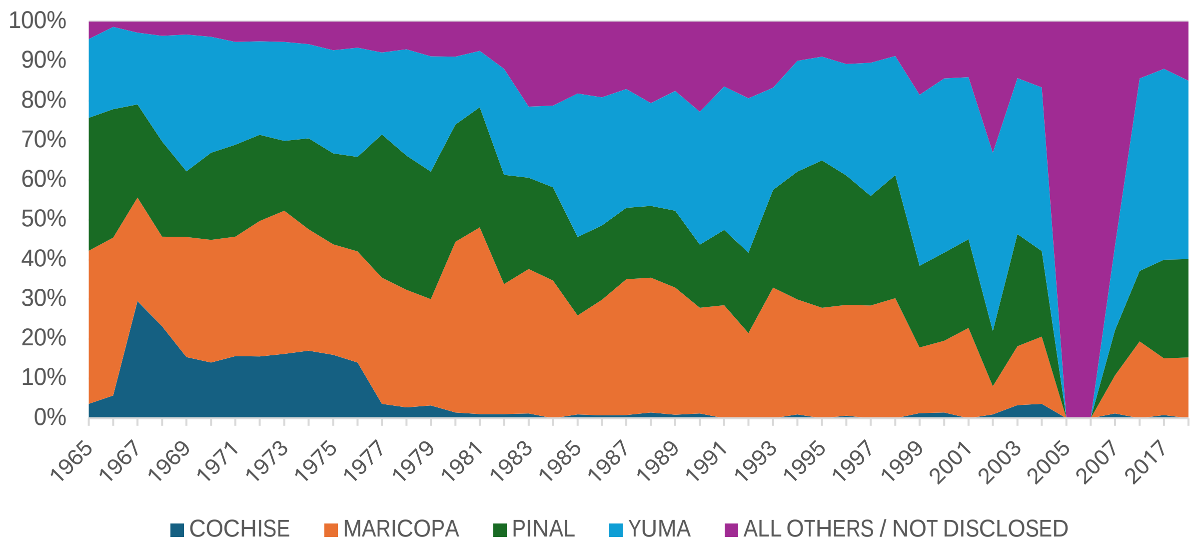
Figure 6. Arizona County Wheat Acreage, 1965-2022



Source: USDA NASS, 2026

This same trend can be seen when viewing total acreage in terms of the share of total by county. The share of production by Cochise and Maricopa Counties has decreased over time, while the relative importance of production in Yuma County has increased (Figure 7).

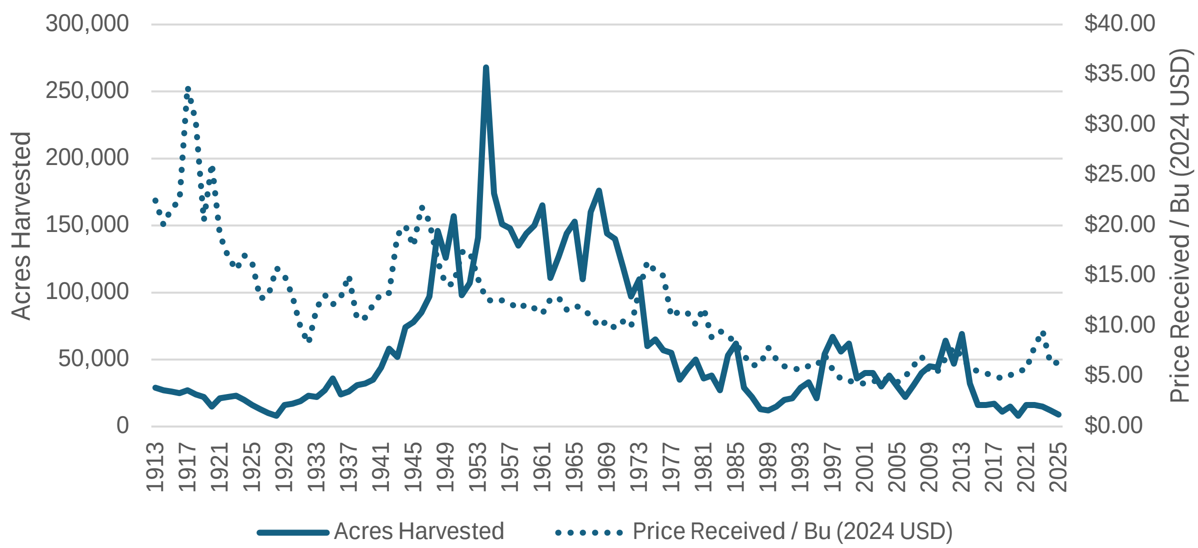
Figure 7. County Wheat Acreage as Percent of Total Statewide Wheat Acreage, 1965-2022



Source: USDA NASS, 2026

Much like wheat production in Arizona, barley production peaked after an initial buildup, and has since declined, though more so than wheat production (Figure 8). Barley production has not tracked as closely with the price received in Arizona in recent years. Nationally, barley acreage has been decreasing over time (USDA ERS, 2025), consistent with trends in Arizona.

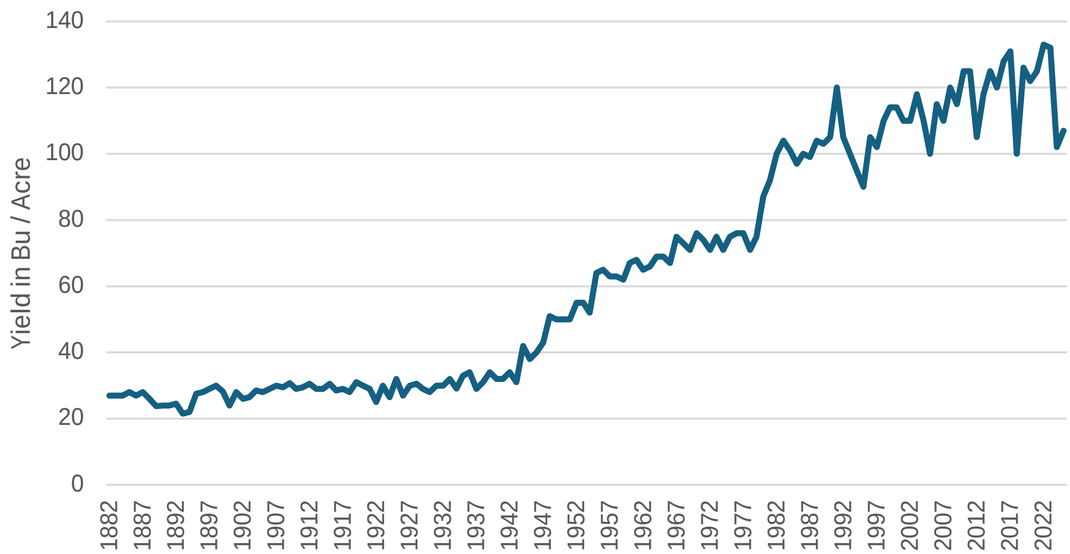
Figure 8. Barley Acres Harvested vs Price Received, Arizona



Source: USDA NASS, 2026

State-level barley yields in Arizona have also seen impressive increases over time, with continuing improvements to this day (Figure 9).

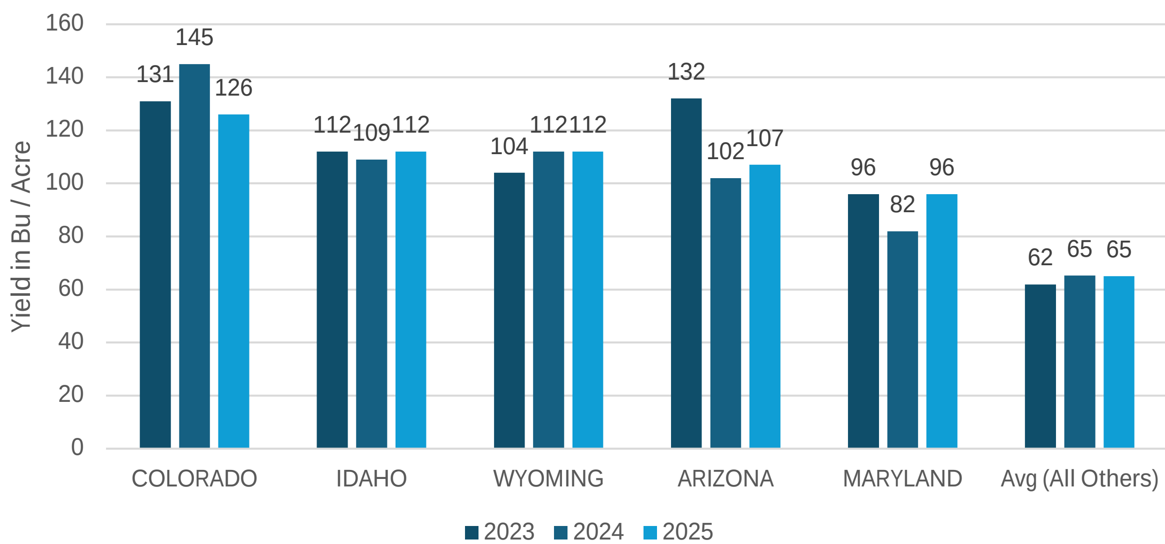
Figure 9. Arizona Barley Yield in Bu / Acre



Source: USDA NASS, 2026

Arizona also has one of the highest barley yields per acre in the country. Again, this reflects the reliability of yields under irrigated production, as well as year-round growing seasons in much of the state (Figure 10).

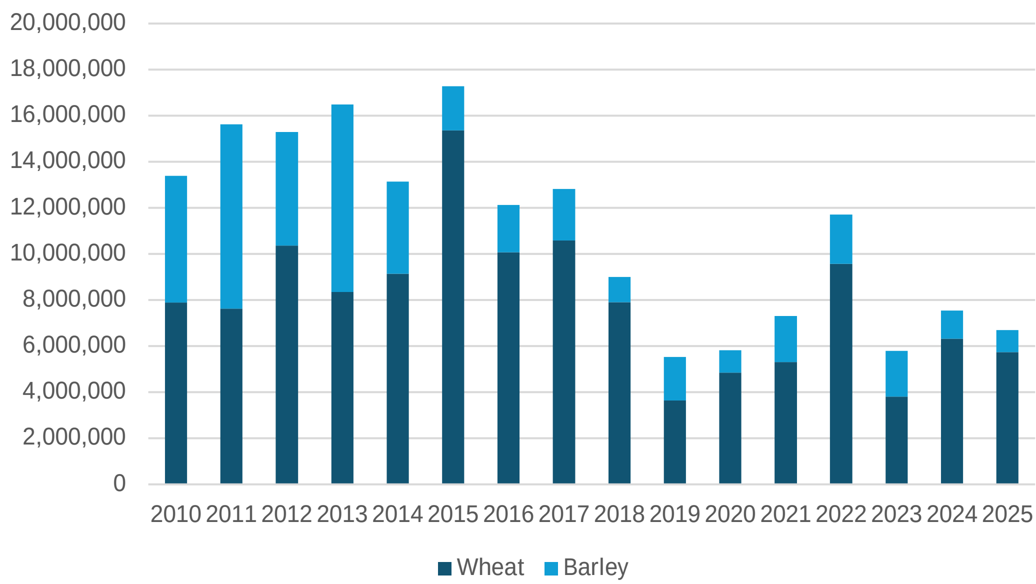
Figure 10. Barley Yield for Top 5 States & All Others, 2023-2025



Source: USDA NASS, 2026

Figure 11 illustrates the volume of small grains production in Arizona. From 2010 to 2017, combined production never fell below 12 million bushels. After 2017, combined production has remained below 12 million bushels.

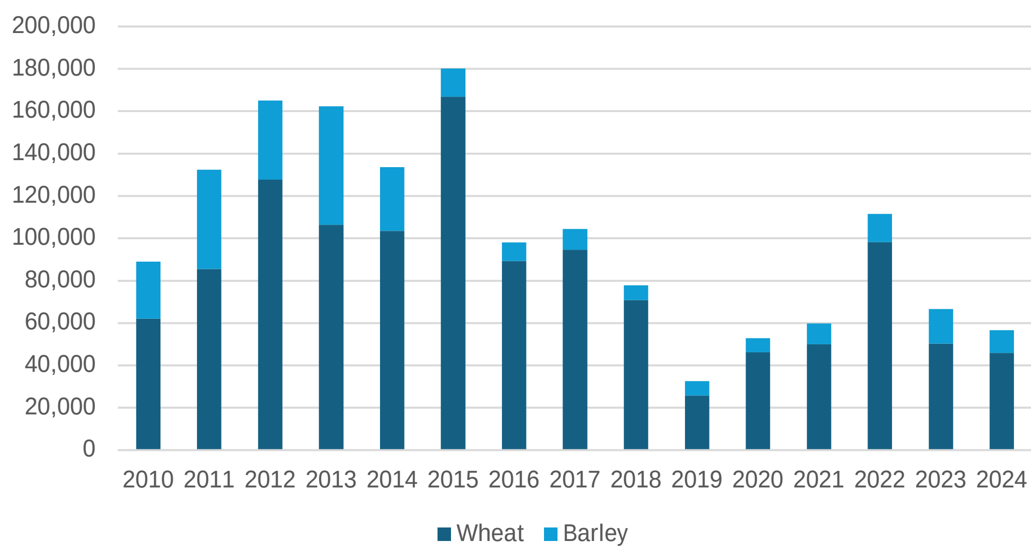
Figure 11. Arizona Small Grains Production (Bushels), 2010-2025



Source: USDA NASS, 2026

Similar to volume of production, combined cash receipts from small grains production experienced a decline during the period between 2015 and 2019. Cash receipts recovered in 2022, before declining again after 2022 (Figure 12).

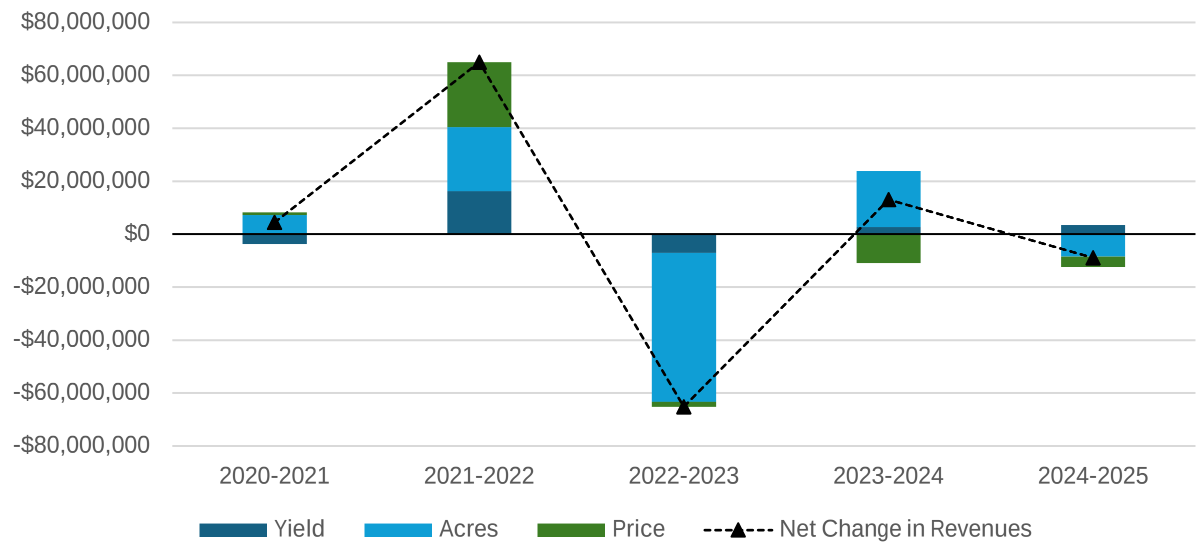
Figure 12. Arizona Small Grains Cash Receipts, 2010–2024 (Thousands of 2024 Dollars)



Source: USDA, ERS, Farm Income and Wealth Statistics. BLS, 2026.

As the top source of cash receipts in Arizona's small grains industry, wheat is the primary driver of changes in cash receipts. To investigate the source of these changes in wheat sales, we decompose the changes in the estimated value of production based on acreage, yield, and price received in 2024 dollars from 2020 to 2025. During this period, changes in acreage harvested are the largest driver of changes in value of production, followed by changes in prices. Changes in yield account for a small share of the changes in value of production (Figure 13).

Figure 13. Factors Contributing to Changes in Value of Wheat Production in Arizona, 2020-2025, in 2024 Dollars



Structure of the Arizona Small Grains Industry

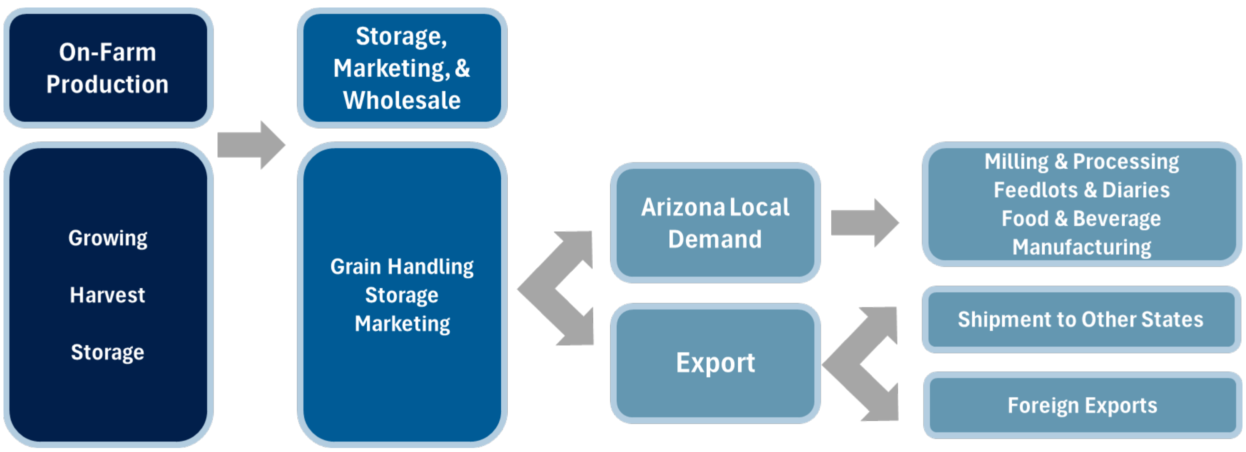
Arizona Small Grains Industry Value Chain

Arizona's small grains industry consists of on-farm production, including growing, harvesting, and storage, both on and off farm. In addition to primary production, other downstream industries are involved in getting raw products from producers to customers (Figure 14). Grain handlers are involved in storage, marketing, and wholesale of small grains. Most Arizona-grown barley is used as feed for the state's animal products industries. Major sources of demand are feedlot and dairy operations, but small grains feed also supplies hog and poultry production. There is also a growing interest by Arizona-based manufacturers of food and beverage products and restaurants in developing small-grain products to supply small but growing "local food" market niches.

To validate the value chain shown in Figure 14, we conducted several semi-structured interviews with stakeholders from the small grain institutions and businesses in Arizona. Interviewees confirmed that small grains (primarily durum wheat) are grown largely as rotational crops alongside higher-value vegetables, providing agronomic benefits such as soil health management and salinity control rather than serving as a primary source of profit. Harvested grain moves directly to local elevators, where grain handlers serve as intermediaries providing temporal flexibility, hedging through futures markets, and quality verification services.

From the elevator, grain flows into two distinct end markets. The export channel, which accounts for the majority of Arizona durum wheat, moves by rail to Houston or Long Beach for shipment primarily to Italy, where it is processed into pasta and marketed under the Desert Durum® trademark. The domestic channel feeds a shorter supply chain concentrated in the Phoenix metro area, where local milling processes durum into semolina, which is then converted into pasta for distribution across the western United States. Feed barley and small grains from the Parker area follow a separate path to dairies, feedlots, and livestock operations in Maricopa and Pinal counties in Arizona, and Riverside County in California.

Figure 14. Arizona Small Grains Industry Value Chain



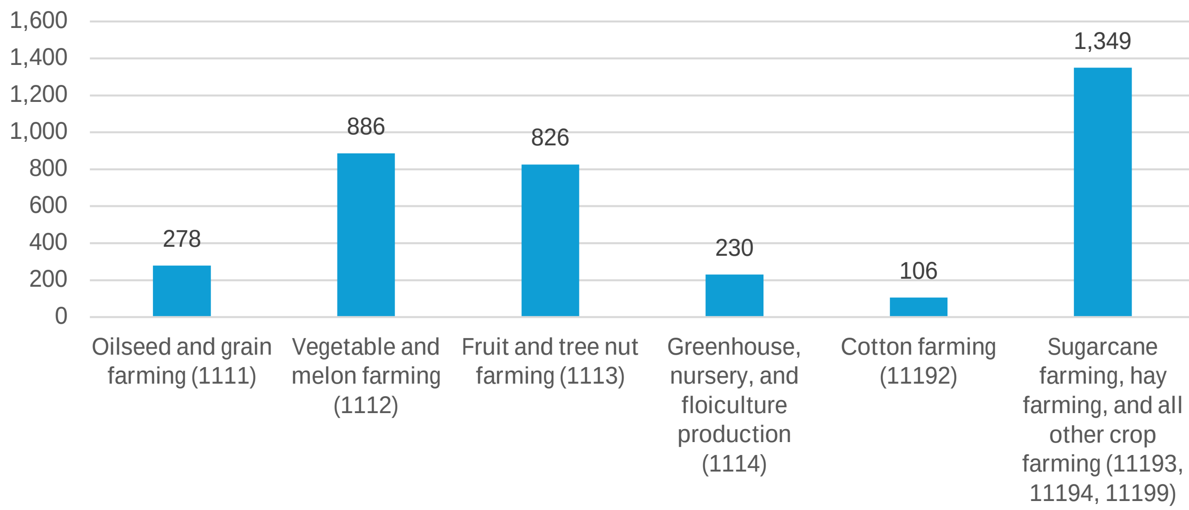
Growers

Number of Operations

According to the 2022 Census of Agriculture, there were a total of 1,391 farms with sales of grains, oilseeds, dry beans, and dry peas in Arizona. Of these farms, ***259 operations reported sales of wheat, and 55 reported barley sales.***

In Arizona, small grains are produced by a wide variety of farms, including farms specializing in grains and oilseed production, farms specializing in vegetable and melon production that use grains as a rotational crop, and other farms that specialize in the production of cotton, hay, and other field crops. Specialization is defined as having sales of 50% or greater of a particular commodity. According to the 2022 Census of Agriculture, there were 278 farms in Arizona specialized in the cultivation of oilseed and grain farming, of which small grains would be a subset (Figure 15).

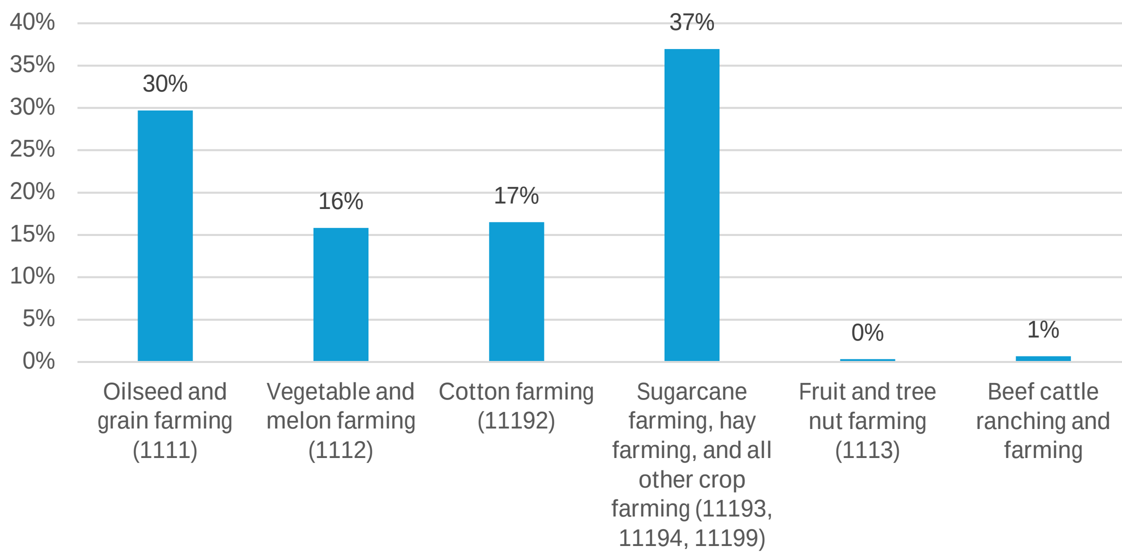
Figure 15. Number of Arizona Agricultural Operations by Specialization as defined by the North American Industry Classification System (NAICS), 2022



Source: USDA, 2022 Census of Agriculture (Numbers in parentheses are NAICS Codes).

Production of small grains is not limited to farms specializing in grain production, however. Of the 314 farms reporting sales of small grains in 2022, roughly 30% specialized in oilseed and grain production (Figure 16). Farms specializing in "hay farming and all other crop farming" had more small grains sales, representing roughly 37% of the total. Farms categorized under "Vegetable and melon" and "cotton farming" represent most of the remaining sales. The diversity in wheat and barley production by farm specialization reflects the common practice of using small grains in crop rotations, as well as the use of small grains in animal feed production.

Figure 16. Number of Arizona Farms with Sales of Small Grains (Wheat and Barley) by Farm Specialization, 2022



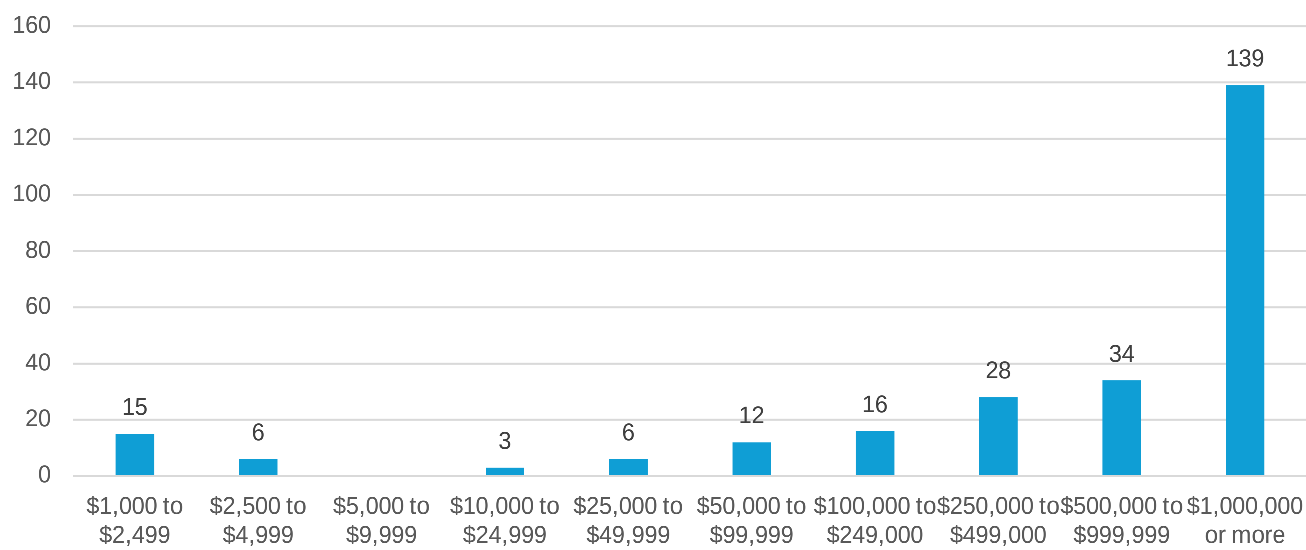
Source: USDA, 2022 Census of Agriculture (Numbers in parentheses are NAICS Codes).

Sizes and Types of Operations

Sales

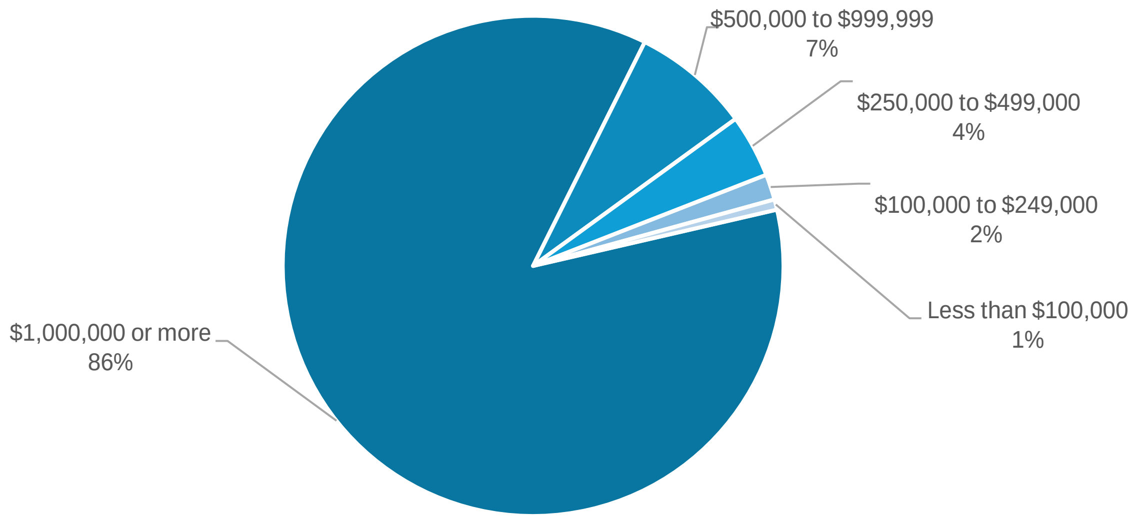
Large farms with annual sales of over $1,000,000 (for all commodities) represent the majority of small grains producers in Arizona (Figure 17). Farms with total annual sales of over $1,000,000 accounted for 50% of wheat-producing farms by number and 86% of sales in 2022 (Figure 17).

Figure 17. Number of Arizona Farms with Sales of Wheat by Market Value of All Agricultural Sales, 2022



Source: USDA, 2022 Census of Agriculture

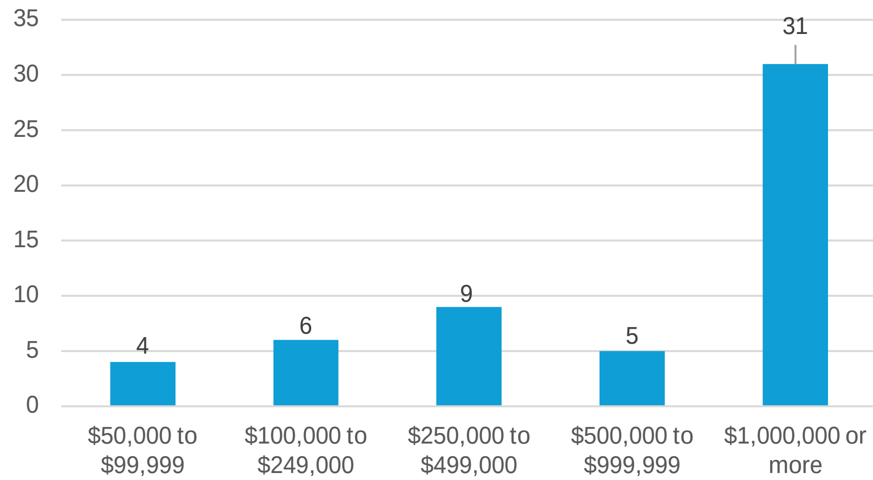
Figure 18. Percentage of Total Arizona Wheat Sales by Market Value of Wheat Sales, 2022



Source: USDA, 2022 Census of Agriculture

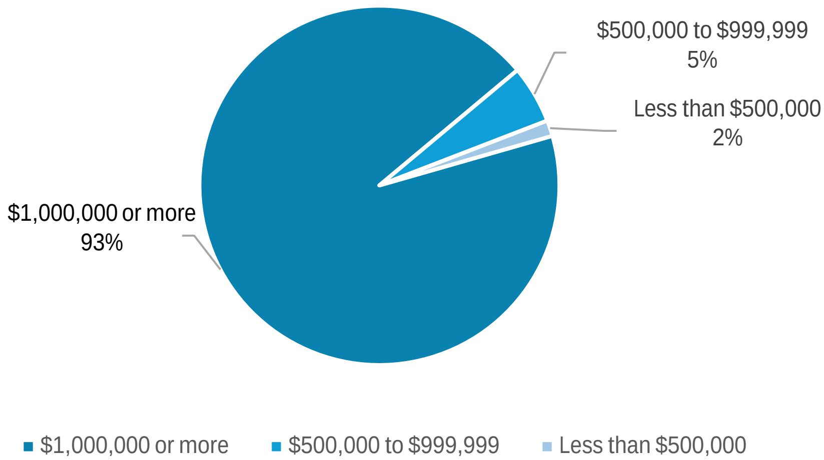
Barley-producing farms with total annual sales of over $1,000,000 (from all commodities) accounted for 56% of barley-producing farms by number and 93% of sales in 2022 (Figure 19 and Figure 20). The concentration of wheat and barley production reflects the use of small grains as rotational crops on large commercial vegetable, melon, and cotton farms in Arizona.

Figure 19. Number of Arizona Farms with Sales of Barley by Market Value of Barley Sales, 2022



Source: USDA, 2022 Census of Agriculture

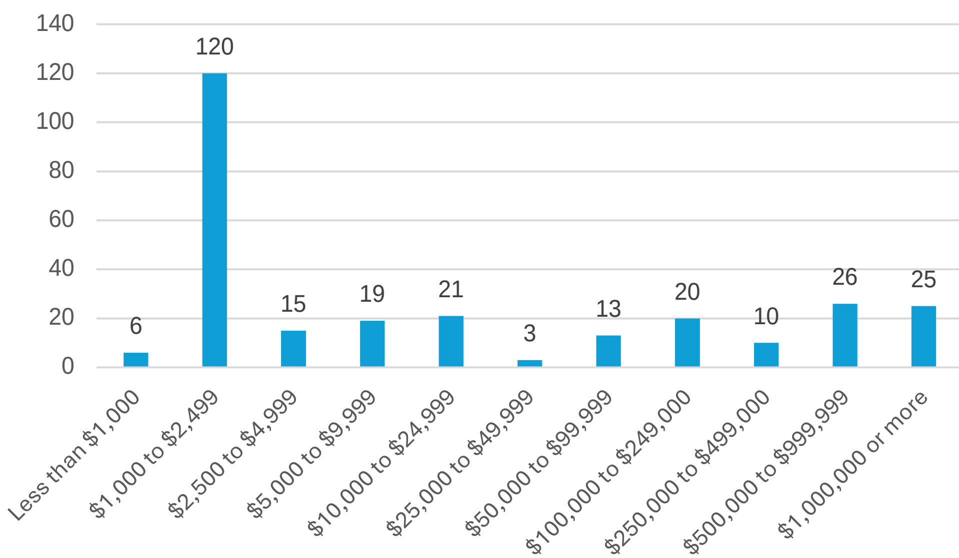
Figure 20. Percentage of Total Arizona Barley Sales by Market Value of Barley Sales, 2022



Source: USDA, 2022 Census of Agriculture

While overall sales and production of small grains are concentrated among large farms, this does not represent farms specializing in grains production. Among the 278 farms specialized in the production of oilseed and grain farming, just over 50% have less than $5,000 in total annual sales (Figure 21). Many of these farms are family-run operations not in commercial production.

Figure 21. Farms Specializing in Grain Production by Economic Class, 2022

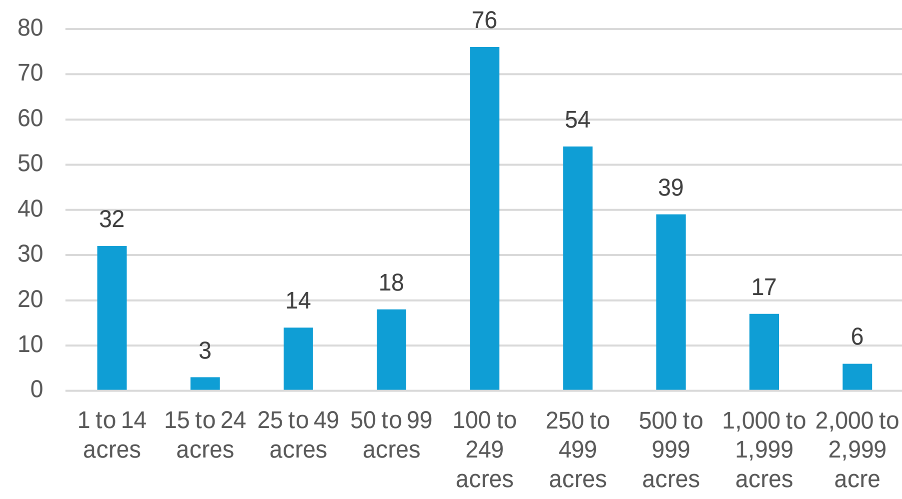


Source: USDA, 2022 Census of Agriculture

Acreage

In terms of acreage, 74% of Arizona wheat-producing farms harvest more than 100 acres of wheat, though only 9% harvest more than 1,000 acres. Half of the farms producing wheat (50%) harvest between 100 and 500 acres (Figure 22).

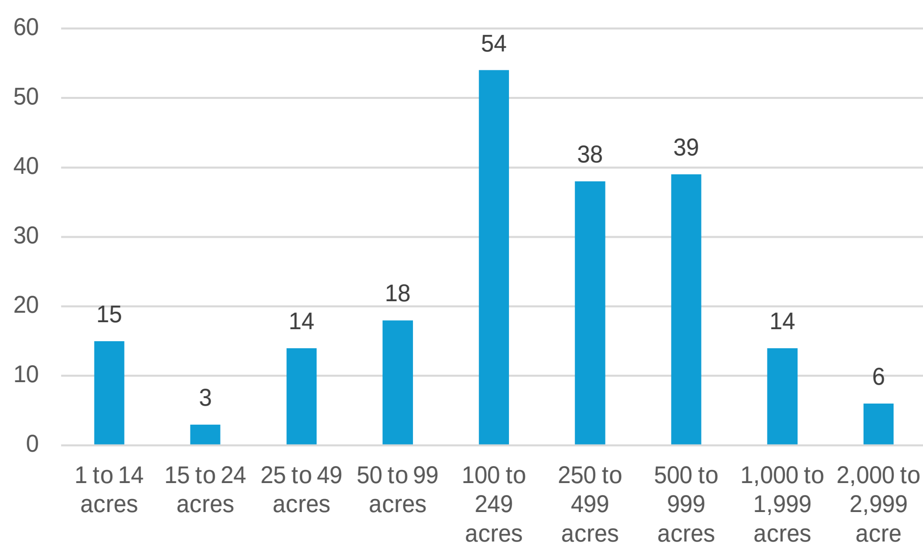
Figure 22. Number of Arizona Farms with Sales of All Wheat-by-Wheat Acreage Harvested, 2022



Source: USDA, 2022 Census of Agriculture

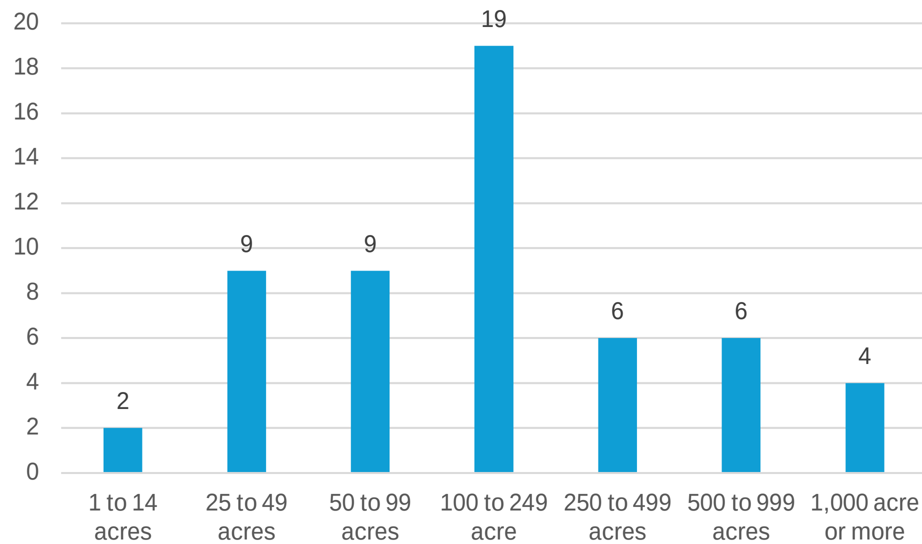
For durum wheat, a large subset of all wheat produced in Arizona, the same pattern holds, with 46% of farms having harvested between 100 and 500 acres of durum wheat (Figure 23). Nearly 62% of all barley-producing farms harvest between 50 and 499 acres of barley, with 35% harvesting between 100 and 249 acres (Figure 24).

Figure 23. Number of Arizona Farms with Sales of Durum Wheat by Durum Wheat Acreage Harvested, 2022



Source: USDA, 2022 Census of Agriculture

Figure 24. Number of Arizona Farms with Sales of Barley-by-Barley Acreage Harvested, 2022

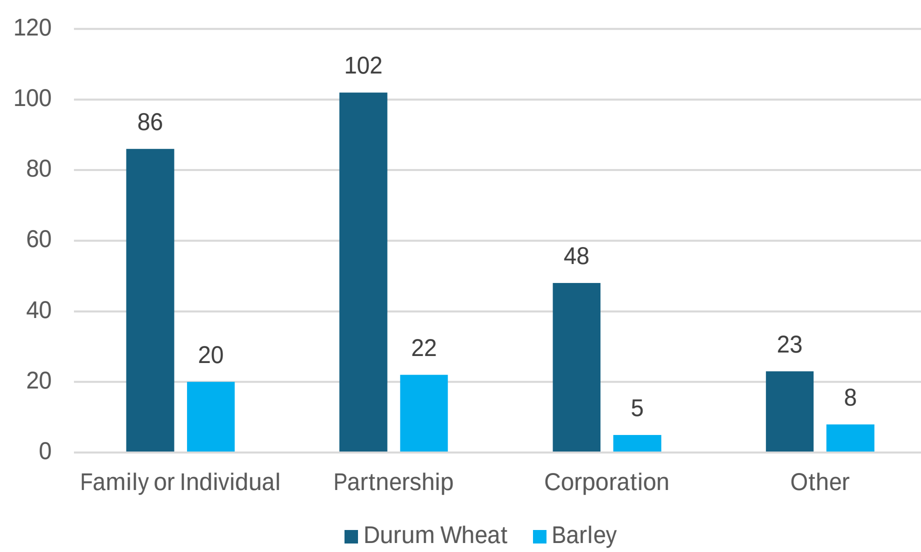


Source: USDA, 2022 Census of Agriculture

Farm Business Type

The most common business type for Arizona farms with sales of wheat is a partnership (39%), followed by family or individual business (33%), and then corporations (19%). Similarly, Arizona farms that produce barley are dominated by partnerships (40%), followed by family or individual businesses (36%) (Figure 25).

Figure 25. Number of Arizona Wheat and Barley Producing Farms by Legal Status for Tax Purposes, 2022

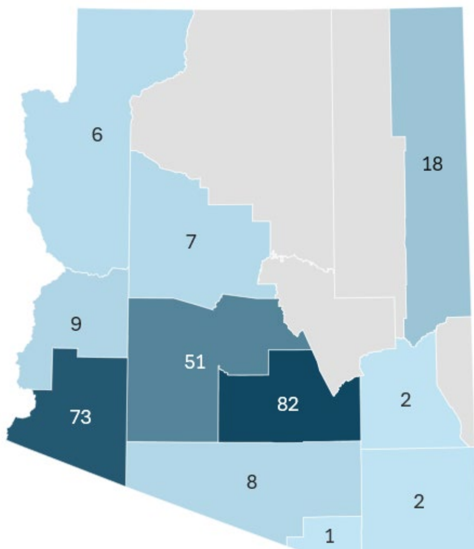


Source: USDA, 2022 Census of Agriculture

Geography

Operations with harvested wheat acreage are concentrated in central and southwest Arizona (Figure 26). Pinal County has the largest number of operations with harvested wheat acreage (82 in 2022), followed by Yuma County (73), and Maricopa County (51).

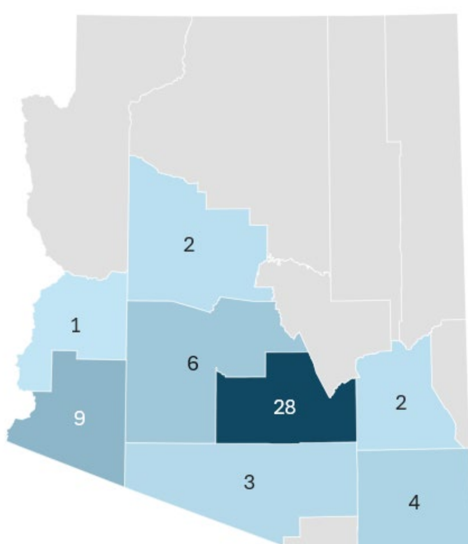
Figure 26. Operations with Wheat Acreage Harvested by Arizona County, 2022



Source: USDA, 2022 Census of Agriculture

Operations with harvested barley acreage are even more concentrated in central Arizona, with 28 operations in Pinal County (Figure 27).

Figure 27. Operations with Barley Acreage Harvested by Arizona County, 2022



Source: USDA, 2022 Census of Agriculture

Measures of Intensity and Productivity of Water Use in Arizona Small Grains Production

There are multiple ways to measure the intensity and productivity of irrigation water use. Water use metrics include:

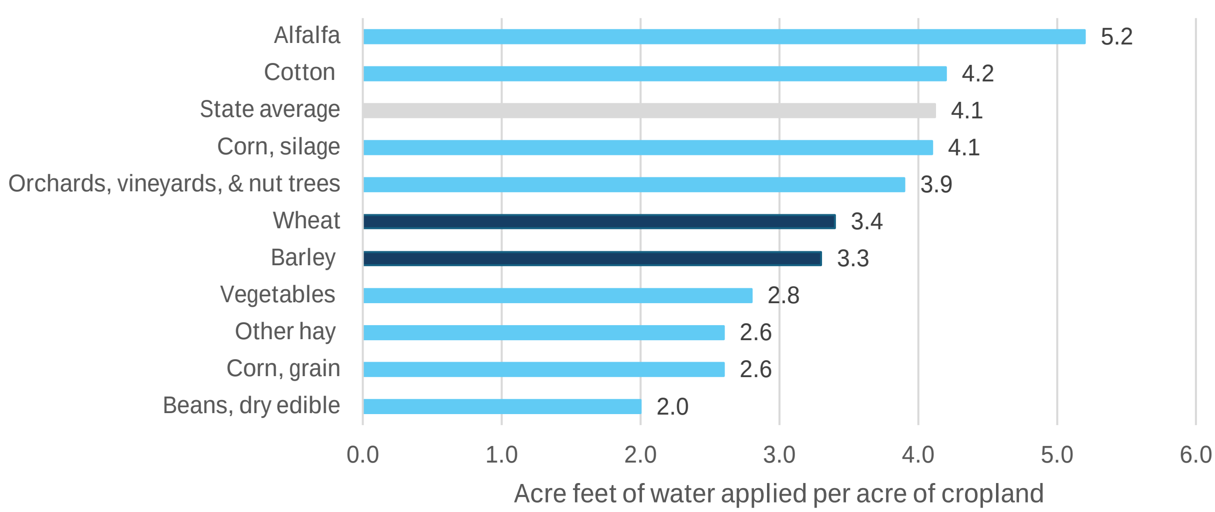
- *Irrigation application intensity* – the quantity of water applied per acre of land
- *Water productivity* – the physical quantity of crop produced (for example, in bushels or tons) per unit of water applied
- *Economic water productivity* – the dollar value of crop revenues generated per unit of water applied or consumed
- *Irrigation efficiency* – the percentage of applied irrigation water that is taken up and used by crops for growth
- *Consumptive use of water* (or *water consumed*) – the physical quantity of water that is taken up by crops, evaporates, or otherwise is lost to the local hydrologic system
- *Water footprint* – the physical quantity of water used to produce a given physical quantity or dollar value of a crop.

This chapter considers all these metrics for Arizona wheat and barley, except for water footprints. Because of complexities with measurement, we deal with water footprint estimation by itself, in the next chapter.

Irrigation Application Intensity

Irrigation application intensity is the quantity of water applied per unit area of cropland grown. Here, land is measured as acres, and water is measured as acre feet (AF). An acre foot of water is the amount of water that would cover an acre of land one foot deep. It is equivalent to 325,851.4 gallons of water or 1,233.48 cubic meters of water.

Figure 28. Acre Feet of Irrigation Water Applied per Acre of Cropland for Major Arizona Crops, 2023



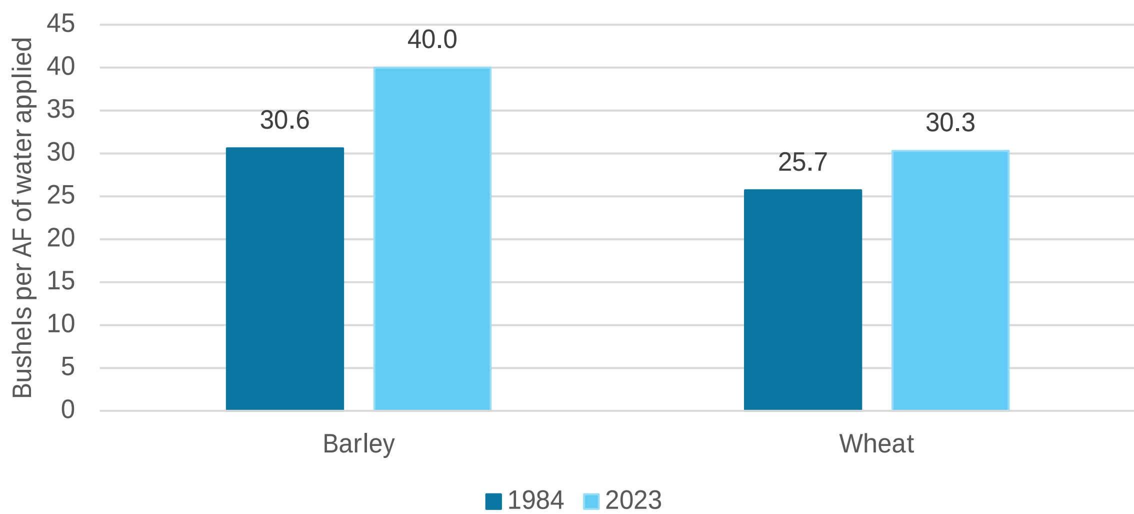
Source: USDA *Irrigation and Water Management Survey*, 2023

Among major crops grown in Arizona, wheat and barley application rates are roughly in the middle, based on data from the USDA Irrigation and Water Management Survey of 2023 (formerly the Farm and Ranch Irrigation Survey). While 3.4 AF / acre of water were applied to wheat on average, 3.3 were applied to barley in 2023 (the most recent year survey data are available) (USDA, 2023). This is 17% and 20% lower, respectively, than the Arizona average across all crops of more than 4.12 AF / acre (Figure 28).

Water Productivity

Productivity measures the amount of 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 (such as per worker). Productivity measures may also be applied to water. One way to measure water productivity is in terms of crop output per AF of irrigation water applied. This is often colloquially referred to as "crop per drop." Figure 29 illustrates that, over the last 40 years, Arizona growers have greatly increased the amount of grain they can produce per AF of water applied. In 1984, growers produced 25.7 bushels of wheat for every AF of water applied. By 2023, this increased 18% to 30.3 bushels / AF. Arizona growers produced 30.6 bushels of barley / AF of water applied in 1984. This figure rose 31% to 40 bushels / AF applied in 2023.

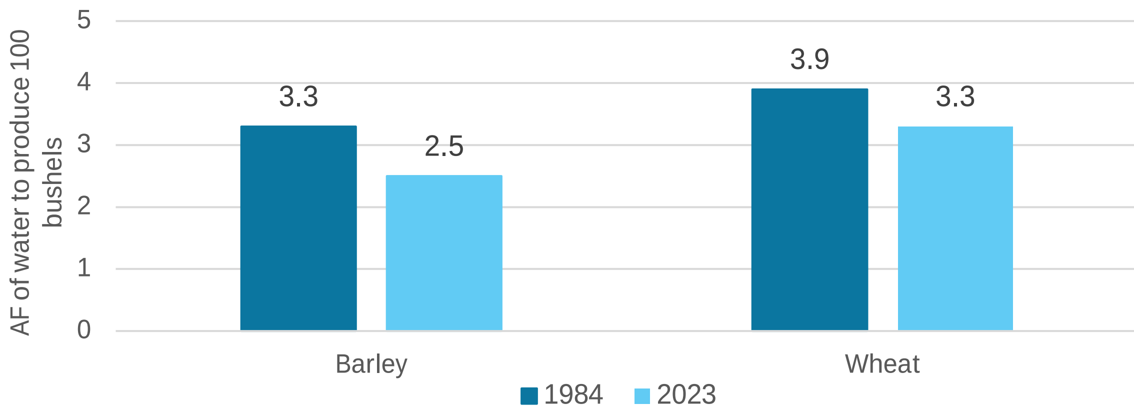
Figure 29. Bushels of Grain Produced per Acre-foot (AF) of Water Applied for Arizona Wheat and Barley, 1984 and 2023



Source: USDA *Irrigation and Water Management Survey*, 2023;
USDA Farm and Ranch Irrigation Survey, 1984; USDA NASS Quick Stats database

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 30 illustrates this relationship. In 1984, Arizona growers applied 3.9 AF of water to produce 100 bushels of wheat. By 2023, 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 32% from 1984 to 2023, with applications falling from 3.3 AF to 2.5 AF.

Figure 30. Acre-feet of Water Applied to Produce 100 Bushels of Arizona Wheat and Barley, 1984 and 2023



Source: USDA *Irrigation and Water Management Survey*, 2023;
USDA Farm and Ranch Irrigation Survey, 1984; USDA NASS Quick Stats database.

Investments to Improve Irrigation Efficiency

USDA's Irrigation and Water Management Survey (IWMS) collects data on irrigation practices every five years, with 2023 the most recent survey year. From the IWMS, in 2023, Arizona irrigators spent $53.6 million on irrigation infrastructure. This amounted to expenditures of $133 per acre and $47,125 per farm. Of the $53.3 million, $46.8 million was invested with the primary purpose of conserving water. Another $3.6 million was devoted to conserving energy.

Adoption of Irrigation Methods

Table 2 compares adoption of irrigation methods at two points in time, 1984 and 2023, for Arizona wheat- and barley-growing farms. The methods are divided broadly into gravity systems and pressure systems. In a gravity system (also called "flood irrigation"), water is delivered to the highest elevation end of a sloped field or to the edge of a level field and released (Frisvold et al., 2018). The force of gravity distributes the water down or across the field. As the name suggests, pressure systems use pressure to move water. These include different types of sprinkler systems, which spray water in the air above the crop canopy or below the crop canopy to mimic precipitation. Another type of pressure irrigation system are low-flow technologies, which include drip irrigation and micro-sprinklers (Frisvold et al., 2018). These supply water through emitters or nozzles attached to porous tubing or a supply pipe.

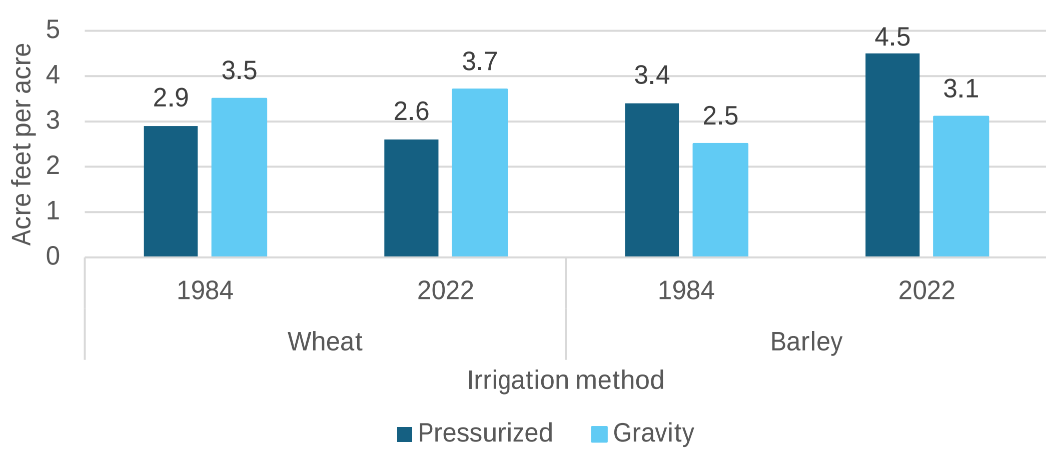
Table 2. Adoption of Pressure System and Gravity Irrigation on Arizona Wheat and Barley Farms, 1984 and 2023

	Wheat		Barley	
All Arizona	**2023**	**1984**	**2023**	**1984**
# of Farms	142	471	112	40
# of Acres	58,843	119,662	29,852	4,597
Primary irrigation method, pressure system				
# of Farms	24	7	23	11
# of Acres	14,950	1,100	3,594	870
% of Farms	17%	1%	21%	28%
% of Acres	25%	1%	12%	19%
Primary irrigation method, gravity				
# of Farms	118	457	89	29
# of Acres	43,893	115,442	26,258	3,727
% of Farms	83%	97%	79%	73%
% of Acres	75%	96%	88%	81%

Source: USDA Irrigation & Water Management Survey 2022 and Farm and Ranch Irrigation Survey 1984
Percentages may not sum to 100% because of rounding or because some farms have no single primary irrigation method.

From 1984 to 2023, the number of farms growing wheat fell significantly, while farms growing barley and barley acreage grew significantly. While wheat acres fell 51%, barley acres grew more than sixfold. Along with a shift toward relatively more barley production, there were shifts in irrigation methods. In 1984, only 1% of Arizona wheat farms and wheat acres were irrigated with pressure systems. By 2023, pressure systems were the primary irrigation method on 17% of farms and 25% of acres. That the acreage percentage is greater than the farm percentage indicates that pressurized systems were adopted more on operations with relatively more wheat acres per farm. On barley farms, the percentage of farms and acreage relying on pressure systems declined, while the share of farms and acres relying on gravity irrigation increased. That the acreage percentage is less than the farm percentage indicates that pressure systems were adopted more on operations with relatively less barley acres per farm.

Figure 31. Acre Feet of Irrigation Water Applied per Acre to Arizona Wheat and Barley Acreage by Irrigation Method



Source: USDA Irrigation & Water Management Survey 2022 and Farm and Ranch Irrigation Survey 1984

Figure 31 compares irrigation application rates by irrigation method between 1984 and 2022. For wheat, application rates for pressurized irrigation fell from 2.9 acre-feet (AF) / acre to 2.6 AF / acre. For gravity irrigation, rates rose from 3.5 AF / acre to 3.7 AF / acre. In both periods, application rates were lower for farms irrigating with pressurized systems. This pattern was reversed for farms with barley acreage. Here, application rates were higher on farms using pressurized systems. For farms using pressurized systems, application rates increased from 3.4 AF / acre in 1984 to 4.5 AF / acre in 2022. For farms using gravity systems, application rates increased from 2.5 AF / acre in 1984 to 3.1 AF / acre in 2022.

Irrigation Efficiency, Water Consumptive Use, and Water Conservation

Pressure irrigation systems (sprinkler and drip) tend to have higher irrigation efficiencies than gravity-flow or surface systems, where efficiency is measured as the percentage of applied irrigation water that is taken up by a crop. Martin (2011) provides estimates for different irrigation systems used in Arizona agriculture (Table 3).

Table 3. Estimated Seasonal Irrigation Efficiencies

Type of Irrigation System		Efficiency (Seasonal Average)
Surface	Furrow (without reuse)	55% – 77%
	Border (without reuse)	63% – 84%
	Basin	70% – 80%
	Precision-leveled basin	77% – 84%
Sprinkler	Moved lateral	70% – 80%
	Traveler or boom	67% – 75%
	Solid set	80% – 87%
	Center pivot	84% – 90%
	Lateral move	84% – 90%
Drip	Point source	74% – 93%
	Drip tape	85% – 95%

Source: Martin (2011)

There has been a *popular and policy consensus* that improving irrigation efficiency is a key element in conserving water in the West. Yet, the scientific consensus is that, as a rule, improving irrigation efficiency alone does not conserve water and, in most cases, *increases* water consumption. There is a large body of scientific evidence spanning many years and locations finding that improving efficiency, in most cases, actually increases water consumption (Huffaker and Whittlesey, 2003; Golden and Peterson, 2006; Jensen, 2007; Upendram and Peterson, 2007; Ward and Pulido-Velazquez, 2008; Lecina et al., 2010; Contor and Taylor, 2013; Gómez and Pérez-Blanco, 2014; Pfeiffer and Lin, 2014; Scheierling and Treguer, 2016; Grafton et al., 2018; Sears et al., 2018; Persons and Morris, 2019; Pérez-Blanco, et al., 2020; 2021). Summarizing the findings of 230 studies, Pérez-Blanco et al. (2021, p. 1) state, "A zombie idea is one that has been repeatedly refuted by analysis and evidence, and should have died, but clings to life… The perception that investments in modern irrigation systems automatically save water constitutes a zombie idea."

For many, this result is highly counter-intuitive. Why does this occur? Water is not like other inputs. It isn't used up entirely by farmers the way fuel or fertilizer are. Withdrawn water, not taken up by the crop, can flow back to rivers or aquifers. This unused water can become available to others.

Irrigation efficiency measures the share of applied water consumed by the crop. Improving efficiency, by definition, reduces the share of unused water that can go back to aquifers or rivers.

Figure 32 illustrates how changing irrigation efficiency can change water applications, water consumption, and groundwater recharge and depletion. The base case is shown in panel (a). A farm pumps 1,000 AF of groundwater and delivers it to a farm field. The irrigation system has 60% efficiency. This means that 60% of the delivered water – 600 AF – is taken up by the crop. This produces, in our example, 300 units of crop output, which the grower can sell. The remaining 400 AF of water percolates down, recharging the aquifer. The net effect is to take 600 AF of water from the aquifer: 1,000 are pumped out and 400 returns to the aquifer.

Now suppose the farm adopts a more efficient irrigation system, which has 80% efficiency (panel (b)). For the farmer to produce 300 units of crop requires that 600 AF of water be consumed by the crop. Now, because of the higher efficiency, the farmer only needs to pump 750 AF from the aquifer for the crop to consume 600 AF and produce 300 units of output. So, the farmer *could* produce the same amount of crop while pumping and applying 750 AF of groundwater instead of 1,000 as before. So, water applied to the crop has declined. But what has happened to water use, groundwater recharge, and groundwater depletion? Here, 750 AF is delivered to the crop, 600 AF (80%) is taken up by the crop, and 150 AF of water percolates down, recharging the aquifer. So, 750 AF is pumped from the aquifer, 150 AF returns, and 600 AF is removed from the aquifer. This is exactly the same amount of groundwater depletion as in panel (a). The increase in irrigation efficiency reduces the amount of water applied to the crop, but it has not reduced the amount of water depleted from the aquifer.

Panel (c) considers a case of "water spreading." The case in panel (b) showed that the farmer could produce the same amount of crop but pump and apply less groundwater. But why would irrigators necessarily want to produce the same amount of the crop? More water gets to the crop per AF pumped, so average pumping costs effectively drop (Caswell and Zilberman, 1986). Why would output remain fixed with a reduction in the input cost? Irrigators have incentives for "water spreading" (Scheierling and Treguer, 2016). The farmer can increase crop production, pumping the same amount of water, but applying water to more acres, increasing yields, or a combination of both. Panel (c) illustrates the case. Here, the farmer pumps 1,000 AF of groundwater and delivers it to the cropped acres. More water is consumed, 800 AF, and this generates more output, 400 units compared to 300 units. So, the farmer will have higher sales revenues. While 1,000 AF were originally pumped from the aquifer, 200 returns via percolation and recharge. With improved irrigation efficiency, groundwater depletion has increased (compared to panel (a)) from 600 AF to 800 AF.

Figure 33 repeats this exercise with withdrawals of surface water from a river. In panel (a), a farm diverts 1,000 AF of surface water from a river and delivers it to a farm field. The irrigation system has 60% efficiency, so 600 AF of water is taken up by the crop, producing 300 units of crop output, which the grower can sell. The remaining 400 AF of water leaves the farm field and goes back to the river as return flow. This 400 AF could be available to other water users downriver. The net effect is that 600 AF of water in net is removed from the river and consumed.

Figure 32. Water Applications, Consumptive Use, and Groundwater Recharge with Different Irrigation Efficiencies

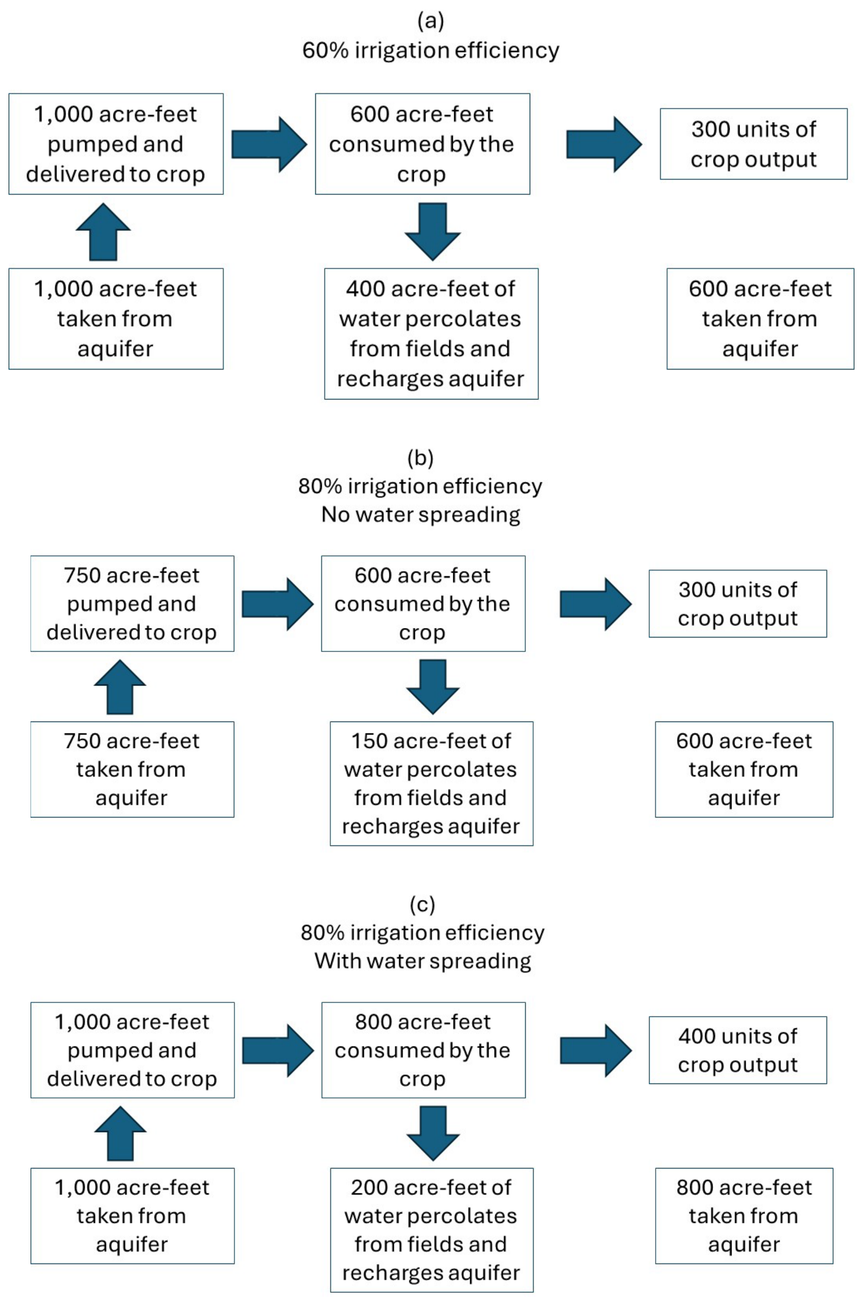
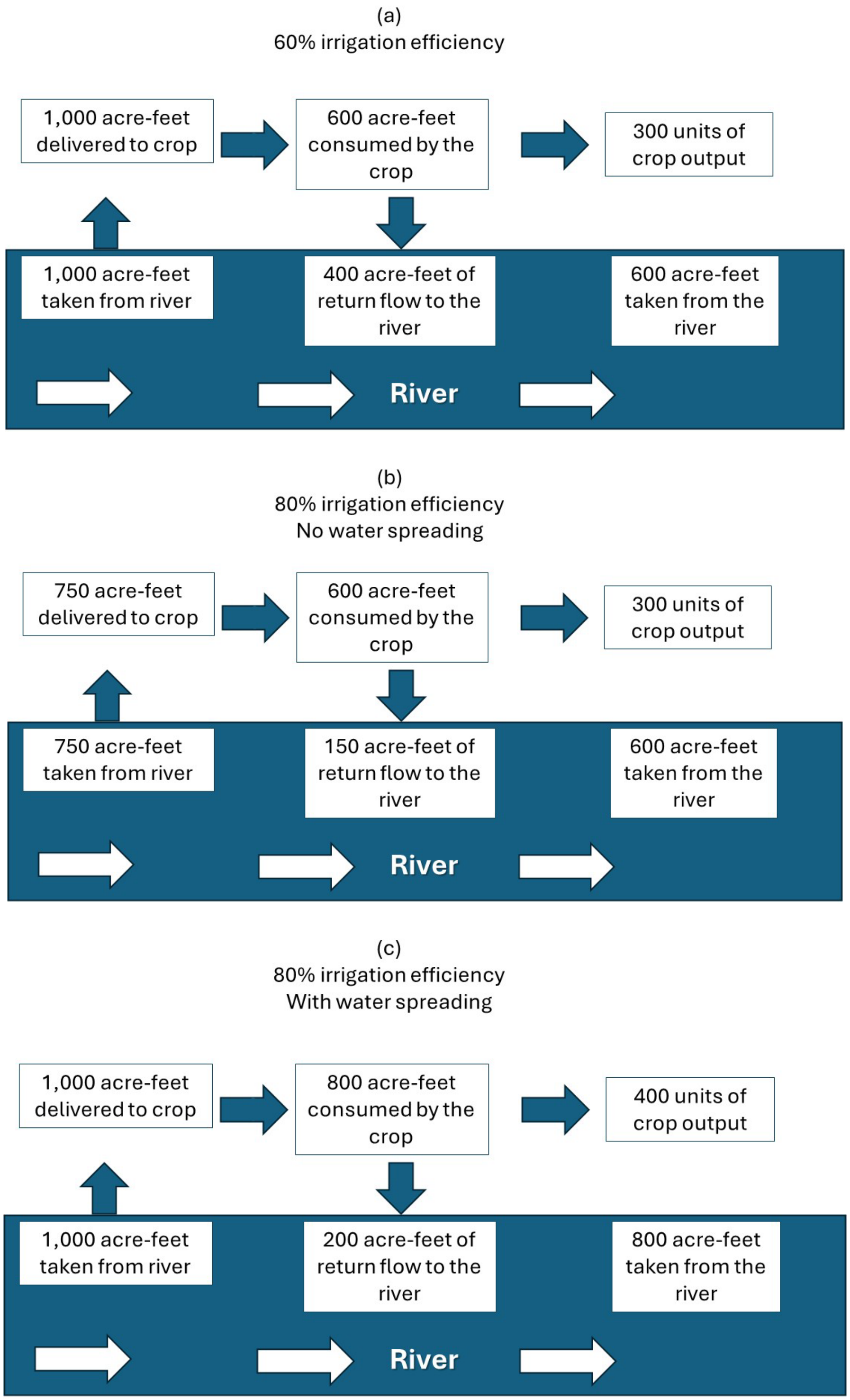


Figure 33. Water Applications, Consumptive Use, and Surface Water Return Flows



Now, the farm adopts a more efficient irrigation system with 80% efficiency (panel (b)). To produce the same 300 units of crop as before, the farmer only needs to divert 750 AF from the river. With 80% irrigation efficiency, the crop takes up 600 AF of water (0.80 x 750 = 600), while 150 AF goes back to the river as return flows. The farmer diverts less water, only 750 AF instead of 1,000. That means there is 250 AF more water, not diverted, that is available to downstream users. But the farmer consumes the same amount of water, 600 AF, as before. While 750 AF is diverted from the river, 150 AF returns. More water stays in the river because it is not diverted (250 AF), but less water returns to the river as return flow (150 AF). The amount available to other users is 400 AF (250 + 150 = 400). With increased irrigation efficiency from 60% to 80%, the exact same amount of water is consumed (600 AF) and available for other users (400 AF) as when irrigation efficiency was 60%. Less water is *diverted* from the river, but the same amount is *consumed*. Improving efficiency does not conserve water.

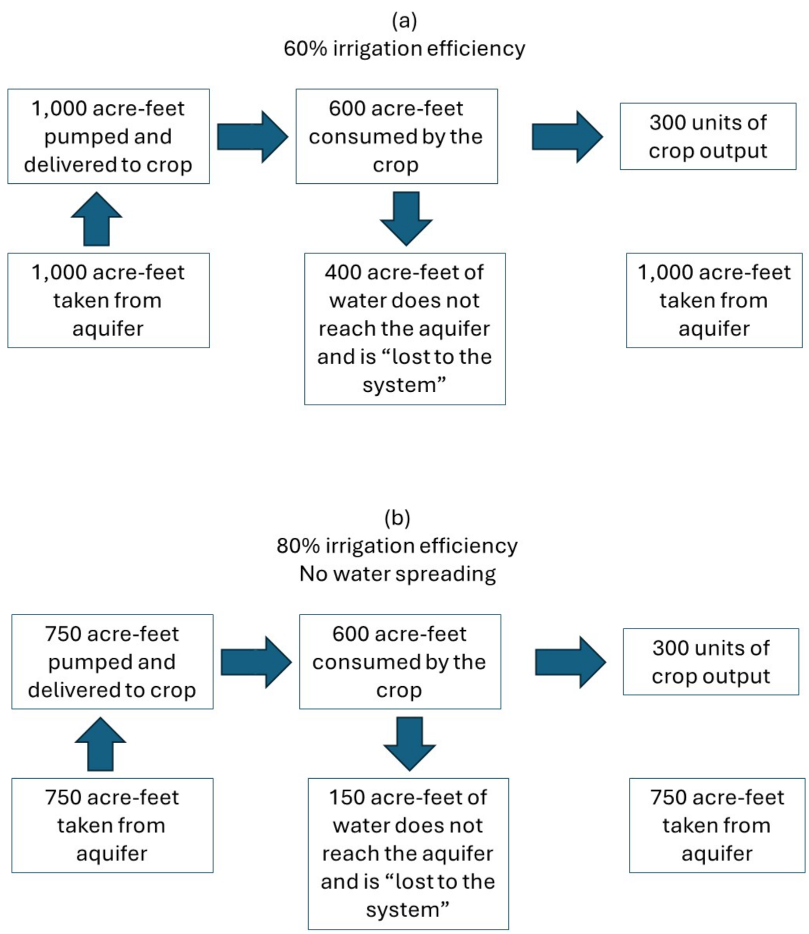
Now assume the farm has a right to divert 1,000 AF of water but installs a new irrigation system that improves efficiency from 60% to 80% (panel (c)). The farmer diverts 1,000 AF, as before, but the more efficient system allows the farmer to apply the water over more acreage and/or increase water consumed by the crop to increase yield. The new system allows the farmer to increase production from 300 to 400 units, increasing farm revenues. Now, however, the more efficient system only returns 200 AF to the river. In this case, diversions are the same as case (a) (1,000 AF) but return flows are lower (200 AF) and water consumed is greater (800 AF). When efficiency was 60%, after the farmer diverted and applied irrigation water, 400 AF was unused and available for other users. With 80% efficiency, after diversion and application, only 200 AF is available for other users. The improved efficiency, in this case, increases water use.

Other studies provide similar illustrations as Figures 32 and 33 showing how improved efficiency does not necessarily conserve water (Huffaker and Whittlesey, 2003; Jensen, 2007; Scheierling and Treguer, 2016). Reviewing 230 studies, Pérez-Blanco et al. (2020) found that improved efficiency *increased* water consumption in 70% of cases, while consumption was unchanged or results were ambiguous in 19% of cases. They found reduced water consumption following improved efficiency in 11% of studies. But in each case, improved efficiency was accompanied by institutional constraints (such as charges or quotas) on water use.

Aren't there cases where improved efficiency leads to actual water conservation? The answer is "yes" but this depends on whether water leaving fields is recoverable or "lost to the system" (Jensen, 2007). For example, if water tables are low enough, then water percolating down from fields may not reach the water table and be usable by others. Here, improved efficiency can reduce groundwater depletion (Peterson and Ding, 2005). Figure 34 illustrates such a case. In panel (a), the farmer pumps 1,000 AF of groundwater and applies it to crops with a system with 60% efficiency. While 600 AF is consumed by the crop, 400 AF percolates down below the root zone. In this case, however, the water table is so deep that the water is unable to return to the aquifer in usable form. Here, the amount consumed – lost to the hydrologic system and unavailable for use by others – is the full 1,000 AF. Panel (b) shows the case with irrigation efficiency improved to 80%. The farmer pumps 750 AF of groundwater to produce the same amount of crop, while the crop consumes 600 AF to produce the same amount of crop, 300 units. The 150 AF of water that percolates below the root zone does not reach the aquifer and is unusable. In this case, 750 AF was pumped from the aquifer, while no water returns and 750 AF is the total amount of water consumed and lost to the system. In this case, water is actually conserved, with consumption falling from 1,000 AF to 750 AF. Do cases, such as those shown in Figure 34, exist in Arizona? Possibly, yes. Clemmens et al. (2000, p. 96) wrote that in the Maricopa-Stanfield Irrigation and Drainage District, "It is unclear whether... water actually reaches the groundwater (transit times are on the order of decades) ... All water delivered is assumed lost to the system." Arizona Department of Water Resources (ADWR) planning models assume that, because of slow seepage and water tables that are deep, it can take 10–20 years in some sub-basins for percolating water to be usable (ADWR, 2009, 2020). So, flows are "lost to the system" in the short- to medium-term, but not the long run. The conditions shown in Figure 34 do not hold along the Colorado River mainstem, where the water table is extremely shallow.

To summarize, it is possible in very special cases for improvement in irrigation efficiency to conserve water. Yet, the dominant finding from studies from the United States and worldwide is that this is usually *not* the case. One cannot expect that adoption of more efficient irrigation systems alone will conserve water or contribute to more sustainable water use. Whether it is possible at all depends on specific hydrological features of watersheds and groundwater basins.

Figure 34. Groundwater Pumping and Consumptive Use with Different Irrigation Efficiencies When Groundwater Recharge is Not Possible

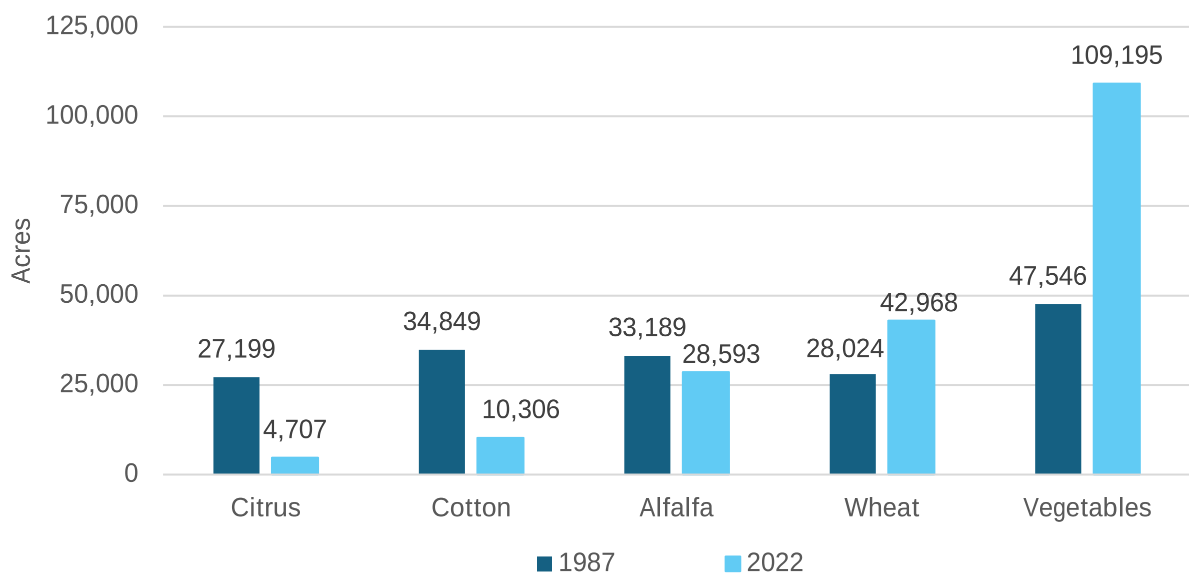


Economic Water Productivity

The UN Food and Agriculture Organization defines economic water productivity as the monetary value generated from each unit of water consumed (UN FAO, 2022). Isolated, crop-specific measures of water use or productivity often ignore the important role of crop rotations and multi-cropping systems in agriculture. Crop rotations are particularly important considerations for evaluating economic water productivity.

The Yuma *Case Study in Efficiency* report (Noble, 2015) highlights how changes in county cropping patterns have increased the county's economic water productivity. Wheat production has played an important role in this transition. First, 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 (Noble, 2015). Water consumed per bushel of wheat produced has also declined. 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.

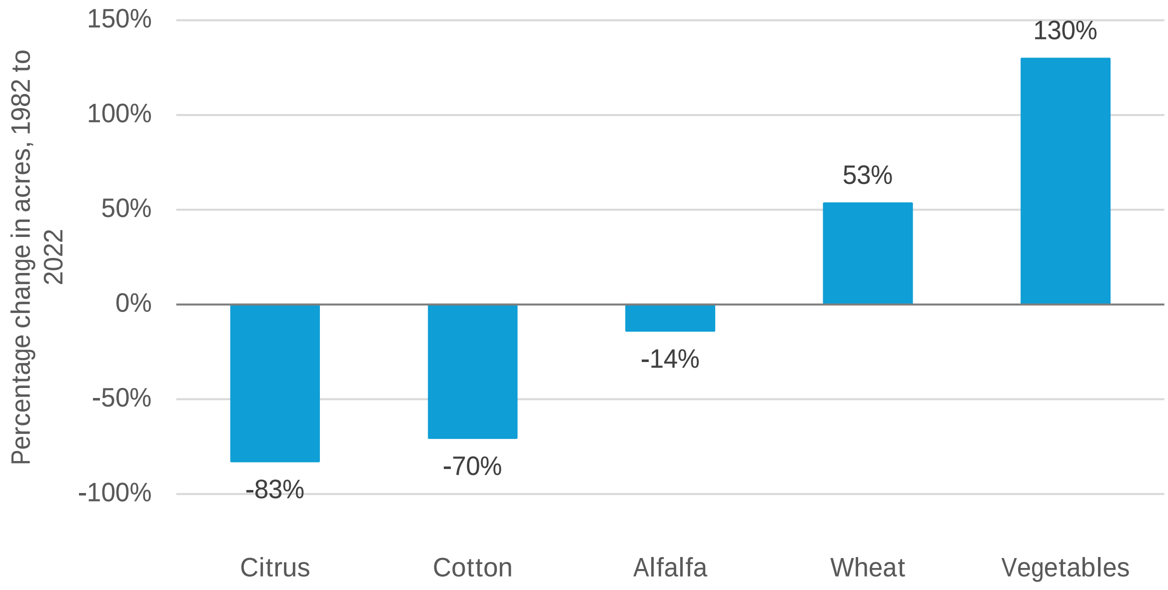
Figure 35. Changes in Acreage of Major Crops in Yuma County, 1987 to 2022



Source: USDA, NASS

Figure 35 shows changes in Yuma County crop acreage between the 1987 and 2022 Census of Agriculture years. Yuma cotton acreage fell from 34,849 acres to 10,306 acres. Citrus acreage fell from 27,199 acres to 4,707 acres, and alfalfa acreage fell from 33,189 acres to 28,593 acres. In contrast, total vegetable acreage increased from 47,546 acres to 109,195 acres and wheat acreage grew from 28,024 to 42,968. Over this period, acreage in continuous crops declined, including alfalfa (-14%), citrus (-83%), and cotton (-70%) (Figure 36). Vegetable acreage, in contrast, grew 130%, and wheat acreage grew 53% (Figure 36).

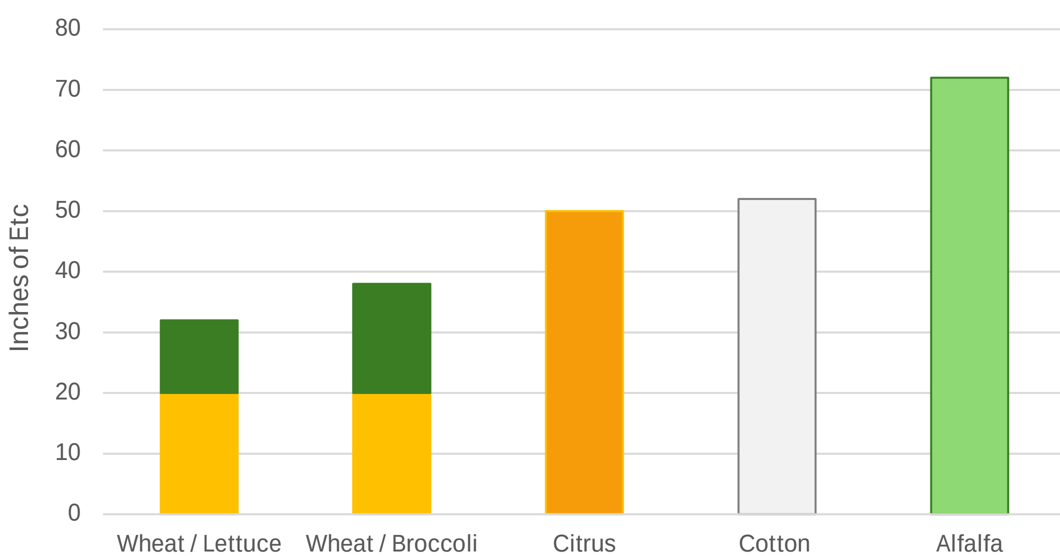
Figure 36. Percentage Changes in Acreage of Major Crops in Yuma, 1987 to 2022



Source: USDA, NASS

Figure 37 illustrates the reduction in 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.

Figure 37. Water Consumption (ETc) per Acre for Selected Yuma Cropping Patterns



Source: Noble (2015)

The Water Footprint of Arizona Durum Wheat

This chapter introduces the concept of water footprints and explains different types of water footprint measures. It then examines previous estimates of the water footprint of wheat production in the US Southwest. These earlier estimates systematically overestimate the water footprint of Southwest wheat production. The chapter develops and presents improved water footprint measures for Arizona durum wheat production, based on more appropriate local data and information on desert production systems. Once proper accounting approaches are used, it is found that Arizona durum wheat production has among the lowest water footprints compared to most other wheat-producing regions.

Introduction to Water Footprints

Water footprints measure how much water is consumed in the production of commodities or provision of services. They can be calculated for different stages of value chains. For example, they may measure water consumed to produce durum wheat or water consumed across the entire value chain producing pasta. Globally, agriculture accounts for the bulk of water consumption. This is because water is such a key element in plant growth (Falkenmark and Rockström, 2006). Other parts of the agricultural value chains, such as processing or distribution, account for relatively small shares of water consumption (e.g., Ruini et al., 2013). Water footprints have been used to inform consumer choices about purchasing goods and services and to inform water management and agricultural policies.

There are three types of water footprints: green water, blue water, and grey water. Green water refers to consumptive use of rainwater stored in the soil (Falkenmark and Rockström, 2004). It is water from precipitation that is stored in the root zone of the soil and evaporated, transpired, or incorporated by plants. Green water use equals the minimum of effective rainfall and crop water requirement (Hoekstra et al., 2009). Effective rainfall is the percentage of rainfall available to plants and crops, subtracting out losses from runoff, evaporation, and deep percolation. From this definition, one can see that the amount of green water used by a crop in a region will be less than the total amount of precipitation. Blue water refers to consumptive use of ground and surface water applied via irrigation (Hoekstra et al., 2009). Grey water refers to water needed to dilute and assimilate pollutants. 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)." Grey water footprints usually measure the water needed to assimilate nitrogen fertilizer applications affecting water bodies. In theory, they could be calculated for other pollutants, but studies have generally focused on the effects of nitrogen fertilizers (Mekonnen and Hoekstra, 2010a, 2010b, 2010c; 2011; Mu et al., 2017).

Water footprints are a ratio of measures of water consumption (green, blue, grey) to a level of output. In other words, it measures how much water is used to produce something. This could be physical quantities of a crop (in kg, pounds, or metric tons (MT)) (Hoekstra et al., 2009). It could be in terms of kilocalories, protein, or other nutrients (Mekonnen and Hoekstra, 2011; Vanham et al., 2013; Damerau et al., 2019). It could also be in dollar value of products sold per unit of water used (Frisvold and Duval, 2023).

Water footprints are increasingly used to inform consumer decisions, corporate sustainability efforts, and water management policies. They have been used in water management planning documents and studies supported by federal agencies (California State Water Resources Control Board, 2013; Richter et al., 2020; Southern Nevada Water Authority, 2024; U.S. Department of Interior, 2011). They have been used for advocacy for or against consumption of particular commodities (Harkinson, 2009; Laubenstein, 2014; Olson-Sawyer, 2022; Richardson, 2018) and to guide or justify corporate value chain decisions (Antonelli and Ruini, 2015; de Souza et al., 2020; Ruini et al, 2013).

Given the growing use of water footprints to inform consumer, corporate sustainability, and public water management choices, it is concerning that reported water footprint estimates for wheat production in the Colorado River Basin and Arizona are inaccurate. Earlier studies significantly overstated the water footprint of Southwest wheat production. If consumer, business, and government decisions are guided by incorrect measurements, choices intended to conserve water could actually lead to greater water use.

Aims and Scope of Chapter

The rest of this chapter is organized as follows. First, we examine earlier studies that provided water footprint estimates for wheat production in the Colorado River Basin and Arizona, more specifically. These include estimates from the IHE Delft Institute for Water Education (formerly the UNESCO-IHE Institute for Water Education) (Mekonnen and Hoekstra, 2010b). Based in Delft, the Netherlands, it is the largest international graduate water education facility in the world. The chapter also examines water footprint estimates for Arizona for durum wheat production (Ruini et al., 2013; Antonelli and Ruini, 2015). These latter estimates were used to inform wheat sourcing decisions by the pasta-producing company, Barilla.

We demonstrate that the reported green and blue water footprints from Mekonnen and Hoekstra (2010b) are highly inaccurate and are inconsistent with observed regional climate and precipitation patterns, inconsistent with the dominant wheat production system in the Basin, and inconsistent with the biological requirements of wheat production. These inaccuracies lead to a large overestimation of the water footprint of wheat production in the region. Subsequent studies have appeared to have addressed these issues, at least partially (e.g., Marston et al., 2018). However, the incorrect estimates are still in the public domain without corrections reported for the Colorado River Basin, while the Mekonnen and Hoekstra (2010b) study continues to be cited.

Ruini et al. (2013) and Antonelli and Ruini (2015) reported green water footprint estimates for Arizona durum wheat production that greatly overestimate the implied precipitation in the region. This causes their estimate of the overall water footprint of Arizona durum wheat production to also be substantially overestimated.

Next, we develop and present green and blue water footprints for Arizona durum wheat production that are based on more accurate, local data for precipitation, crop water consumptive use, and crop yields. Our results are highly consistent across different local data sources. Our "ground-truthed" green and blue water footprints are compared to those of Mekonnen and Hoekstra (2010b), Ruini et al. (2013), and Antonelli and Ruini (2015). The combined green-blue water footprint of Mekonnen and Hoekstra (2010b) is three to four times larger than ground-truthed estimates based on more accurate, local data. The estimates reported by Ruini et al. (2013) and Antonelli and Ruini (2015) overstate the combined green-blue water footprint of Arizona durum wheat by 30-70%. Antonelli and Ruini (2015) touted that shifting durum wheat away from Arizona wheat reduced the blue water footprint of Barilla pasta production. Our findings suggest that Barilla's shift in sourcing likely increased its corporate water footprint of pasta production.

We then compare Arizona's combined green-blue water footprint with those of other countries, river basins, and percentiles of producers. Arizona wheat's green-blue footprint is found to be lower than in most countries and river basins. Compared to producers globally, Arizona wheat production has among the lowest water footprints.

Next, we develop grey water footprint estimates, which measure water needed to assimilate nitrogen from fertilizers that reach water bodies. In contrast to green and blue water footprints, Arizona's grey water footprint of wheat production is higher than global averages. The grey water footprint does not depend solely on nitrogen applications *per se,* but on excess nitrogen leaching from the soil. Improving rates and timing of nitrogen fertilizer applications could better match fertilizer applications to crop nutrient needs. Excess nitrogen adds to grower costs without necessarily improving wheat quality or yields (Wang et al., 2013). Extension programs to improve nitrogen management have the potential for "win-win" outcomes – reducing the grey water footprint of wheat production *and* cutting grower costs.

The chapter concludes with an overall comparison of the total water footprint of Arizona wheat production with global averages and footprints across different counties and river basins. Even with a relatively higher grey water footprint, Arizona has a much lower overall water footprint than most other regions of the globe.

Problems With Water Footprints for Southwest Wheat Production

The USDA Census of Agriculture (conducted roughly every five years) has a follow-on Farm and Ranch Irrigation Survey (FRIS), which includes statistics by river basin. Table 4 reports FRIS estimates of crop acres and yields for the Lower and Upper Colorado River basins over a time period comparable to that of Mekonnen and Hoekstra (2010b). The Lower Basin is primarily Arizona, with portions of Southern California and Southern Nevada that drain into the Colorado River. The Upper Basin includes areas in Eastern Utah, Western Colorado, Southeastern Wyoming, and very small portions of Northeastern Arizona and Northwestern New Mexico.

Table 4. Wheat Acreage, Yields, and Production in the Lower and Upper Colorado River Basis

	1994	1998	2003	2008
Lower Basin				
Irrigated acres	88,899	149,580	122,144	142,692
Irrigated yield (bu / ac)	98	99	103	109
Irrigated production (bu)	8,712,102	14,808,420	12,580,832	15,553,428
Non-Irrigated acres	0	17,500	0	0
Non-Irrigated yield (bu / ac)	0	42	0	0
Non- Irrigated production (bu)	0	735,000	0	0
Upper Basin				
Irrigated acres	6,953	11,014	14,343	14,539
Irrigated yield (bu / ac)	83	121	84	84
Irrigated production (bu)	577,099	1,332,694	1,204,812	1,221,276
Non-Irrigated acres	3,020	320	127,962	27,731
Non-Irrigated yield (bu / ac)	38	13	8	14
Non- Irrigated production (bu)	114,760	4,160	1,023,696	388,234
Total Basin				
Total acres	98,872	178,414	264,449	184,962
Total production (bu)	9,403,961	16,880,274	14,809,340	17,162,938
Average yield (bu /ac)	95.1	94.6	56.0	92.8
Percent acres irrigated	97%	90%	52%	85%
Percent irrigated production	99%	96%	93%	98%
Percent Lower Basin irrigated production	93%	88%	85%	91%

Source: USDA Farm and Ranch Irrigation Survey and authors' calculations

Several things stand out in Table 4. First, in the Colorado River Basin, the dominant mode of wheat production is irrigated production. Irrigated wheat production accounts for 93-99% of total basin wheat production across years. Irrigated production in the Lower Basin alone, a particularly arid environment, accounts for 85-93% of total production. Second, acreage from dryland wheat farming is quite erratic. In the Lower Basin, acreage ranges from 0 to 17,500 acres, while in the Upper Basin, it fluctuates between 320 and 127,962 acres. Dryland wheat yields were also low and erratic. This means that dryland wheat production in the Colorado River Basin is inherently unstable, and not an especially reliable source of supply. Third, by comparison, irrigated wheat yields were relatively stable.

There are basic climatic reasons why the region's wheat production is primarily irrigated and essentially completely irrigated in the Lower Basin. Basin-wide, rainfall averages less than 20 inches annually (Anderson, 2002; Lukas and Payton, 2020). In the driest year on record, precipitation was 11.4 inches, while it was 24.4 inches in the wettest year on record (Lukas and Payton, 2020). The 11- year moving average of precipitation was below 17 inches (USBOR, 2012). In Arizona, the long-run statewide average has been just over 12 inches annually (Frankson et al., 2022). In the Southwest desert areas (the major durum wheat area of the state), annual precipitation can average below 4 inches per year (USBOR, 2012). These precipitation figures, along with wheat yields, are important to keep in mind as we evaluate reported green water footprints for the

Colorado Basin and Arizona. Given wheat yields, a green water footprint has an implied precipitation level.

Water footprint studies overwhelmingly report results in metric units, with footprints for crops measured as cubic meters of water used (m^3) per metric ton (MT) of crop produced. Table 5 provides conversion factors between metric system measures and English units of measure used in the United States.

Table 5. Conversion Factors for Units of Measure

Value	**Converts to**
1 inch of rainfall	25.4 millimeters (mm)
1 mm of rainfall	0.03937 inches
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 (lb.)
1 acre of land	0.4047 hectares (ha)
1 hectare (ha) of land	2.471 acres of land
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)

Mekonnen and Hoekstra (2010b) report a green water footprint for wheat production across the Colorado River Basin of 2,636 m^3/ MT (cubic meters per metric ton) for a study period running from 1996 to 2007. Wheat yields in the Colorado River Basin averaged across 1994, 1998, 2003, and 2008 FRIS surveys were 80.2 bushels per acre (Table 4). Recall that green water is the lesser of effective precipitation and crop water requirement (Hoekstra et al., 2009). Effective precipitation is the percentage of rainfall available to plants and crops, subtracting out losses from runoff, evaporation, and deep percolation. From this definition, one can see that the amount of green water used by a crop in a region will be less than the total amount of precipitation. The green water footprint estimates of Mekonnen and Hoekstra (2010b), given Basin wheat yields, imply that average annual rainfall across the entire Colorado Basin is 56 inches, more than three times greater than the actual, measured Basin average of roughly 17 inches annually. This overestimate is even greater for Arizona, where precipitation averages about 12 inches and less than 4 inches in low desert areas in the Southwestern portion of the state. So, Mekonnen and Hoekstra's (2010b) green water footprint estimates are completely at odds with the region's actual rainfall patterns. Mekonnen and Hoekstra also report a Basin blue water footprint of 366 m^3/ MT. This implies that Basin wheat production is dominated by dryland production, which is inaccurate (see Table 4). It also implies that water consumed in Basin wheat production is more than 5 acre-feet per acre. This is not the implied application quantity but the implied crop evapotranspiration (ET_c) for wheat, the amount of water actually taken up by the crop. This rate is not agronomically possible for wheat production. In sum, the water footprint estimates for wheat production in the Colorado River Basin are inconsistent with the Basin climate, the structure of production in the region, and wheat's biological limits of water use.

The study by Ruini et al. (2013) cites data from Mekonnen and Hoekstra (2010b) as its source. Their reported figure for the "Southwest United States" matched the reported figures for Arizona on the Water Footprint Network website at the time of their study. Ruini et al. (2013) and Antonelli and Ruini (2015) report a green water footprint of Arizona durum wheat production of 399 m^3 / MT. The 10-year average of durum wheat yields in Arizona from 2006 to 2015 was 102.5 bushels per acre. Combining green footprint and yield numbers implies that effective precipitation for Arizona wheat production is 10.8 inches during the growing season.

Again, the implied precipitation from this green water footprint estimate does not match actual Arizona weather patterns. Table 6 shows long-term (30-year) precipitation averages from Arizona weather stations near major durum wheat growing areas. Data come from cooperating weather stations in the Western Regional Climate Center (WRRC) network.[1] WRCC is one of six National Oceanic and Atmospheric Administration (NOAA) Regional Climate Centers in the US. Table 6 reports monthly values from December to May to match the growing season of Arizona wheat. While long-run precipitation averages about 12 inches across the entire state annually, much of this comes during summer monsoon season, which begins well after durum wheat harvests are completed and well before winter planting season. Average growing season precipitation is 3.6 inches, much lower than the 10.8 inches implied by Ruini et al. (2013) and Antonelli and Ruini (2015). Green water, however, is based on effective precipitation – precipitation that is not lost to evaporation or percolation and is available in the soil and usable to the crop. Effective precipitation for wheat in Arizona is lower still than growing season precipitation. To measure effective precipitation in the Lower Colorado River Basin, the US Bureau of Reclamation uses methods developed by Jensen (1993, 1998), which estimate the proportion of monthly rainfall that is effective precipitation. These *effective precipitation coefficients* are as follows: 0.4 from October to February, 0.2 for March, and 0.0 for April to September (Mirzaei and Garcia, 2026). When effective precipitation coefficients are applied to growing season precipitation, effective precipitation averages only 1.1 inches (Table 6). Thus, Ruini et al. (2013) and Antonelli and Ruini (2015) overestimate Arizona's effective precipitation, and so Arizona wheat's green water footprint is tenfold, while Mekonnen and Hoekstra's (2010b) estimates for the Colorado River Basin are more than 50 times higher.

[1] http://www.wrcc.dri.edu/

Table 6. Durum Wheat Growing Season Precipitation and Effective Precipitation

Weather station (precipitation in inches)	Dec	Jan	Feb	Mar	Apr	May	Growing Season
Tacna 3 NE	0.47	0.43	0.52	0.41	0.14	0.07	2.0
Yuma Valley	0.42	0.35	0.27	0.26	0.12	0.01	1.4
Parker	0.61	0.72	0.58	0.49	0.19	0.08	2.7
Maricopa	0.93	0.85	0.92	0.88	0.31	0.15	4.0
Yuma Valley	0.57	0.34	0.28	0.36	0.15	0.01	1.7
Eloy	1.30	1.16	1.23	0.97	0.41	0.21	5.3
Casa Grande	1.06	0.81	0.90	0.81	0.31	0.19	4.1
Casa Grande NM	1.06	1.00	1.06	0.96	0.37	0.19	4.6
Florence	1.24	1.00	0.95	1.03	0.41	0.19	4.8
Buckeye	1.00	0.86	0.82	0.89	0.31	0.12	4.0
Chandler Heights	1.18	1.05	1.26	1.05	0.44	0.13	5.1
Gila Bend	0.78	0.75	0.88	0.66	0.22	0.16	3.5
Monthly average precipitation (in)	0.89	0.78	0.81	0.73	0.28	0.13	3.6
Effective precipitation coefficient	0.40	0.40	0.40	0.20	0.00	0.00	--
Monthly (and season) effective precipitation (in)	0.35	0.31	0.32	0.15	0.00	0.00	1.1

Source: Western Regional Climate Center and authors' calculations

Green and Blue Water Footprints for Arizona Durum Wheat

This section describes data and develops green and blue water footprints for Arizona durum wheat production. It makes use of local data sources that more accurately represent Arizona precipitation and production patterns. It includes a combination of data sources from federal and state agencies as well as peer-reviewed studies.

LCRAS Data

The Lower Colorado River Accounting System (LCRAS) of the US Bureau of Reclamation (BOR) published estimates of consumptive use of water along the Lower Colorado River in annual reports – *Lower Colorado River Annual Summary of Evapotranspiration and Evaporation* – up until 2014. These *Evapotranspiration Reports* included "estimates of annual agricultural, riparian vegetation, and open water acreages and water uses along the lower Colorado River from Hoover Dam to the Southerly International Boundary with Mexico" along with explanation of the estimation methods used. This included data on acreage and evapotranspiration (ETc) of different crops by irrigation districts, Indian Reservations, private farms, and other agricultural water users. In 2015 and 2016, BOR did not publish full reports but did publish data on crop acreage and ET. BOR ceased publishing these data after 2016.

Data from these LCRAS *Evapotranspiration Reports* can be combined with crop yield data from USDA's National Agricultural Statistical Service to develop green and blue water footprints for durum wheat production in Western Arizona (Mohave, La Paz, and Yuma counties). Below we do so for the years 2013-2016 as follows:

$$Annual\ ET_c = \sum_{t=0}^{n} \frac{[(ET_0 \times K_c) - EFF\ PRECIP]\ AC}{12\ inches/foot}$$

where

ET_c = Annual ET by crop group (acre-feet)

n = Time-step (monthly)

ET_0 = Daily reference ET (inches)

K_c = Daily ET coefficient for a specific crop

AC = Acres of crop

Effective PPT = Effective precipitation (in inches)

In this formulation, crop ET_c deducts out effective precipitation, which LCRAS defines as "that portion of precipitation which infiltrates and remains in the soil so as to be available for crop consumptive use." Effective precipitation is deducted from ET_0 x K_c "so the ET calculated reflects only the consumptive use of Colorado River water." Effective precipitation then represents green water, while crop ET_c represents blue water.

LCRAS estimates monthly effective precipitation as the product of recorded precipitation and monthly precipitation coefficients:

$$Monthly\ effective\ precipitation = Daily\ precipitation \times Monthly\ effective\ precipitation\ coefficien$$

LCRAS relies on rain gauge data from CIMIS (California Irrigation Management Information System, AZMET (Arizona Meteorological Network), and NWS (National Weather Service) stations along the Colorado River. LCRAS develops separate precipitation measures for sub-regions along the Lower Colorado River region. This includes the Mohave Valley, the Parker/Palo Verde Valleys, the Wellton-Mohawk Area, the Imperial and Coachella Valleys, and the Yuma area. Area precipitation is obtained by averaging precipitation measured the AZMET, CIMIS, and NWS stations in each area. Jensen (1993, 1998) reports the documentation for the effective monthly precipitation coefficients used by LCRAS. These are as follows: 0.4 from October to February, 0.2 for March, and 0.0 for April to September (Mirzaei and Garcia, 2026). This reflects that only a portion of rainfall is actually available in the ground for crops to use.

Table 7 reports effective precipitation for the four Lower Colorado areas in Arizona. The growing season for durum wheat generally begins in January and ends in May. Most of the region's precipitation comes during post-harvest monsoon rains. The monsoon season, when most of the rain falls in the region, ends at the end of September, well before planting season. Growing season precipitation was 0.6 inches or less for the four regions in the four most recent years of LCRAS data publication. Base growing season precipitation data were taken from LCRAS *Evapotranspiration Reports* for 2013 and 2014 and from regional AZMET weather stations for 2015 and 2016. The 2013

LCRAS Evapotranspiration Report did not report Mohave Valley monthly precipitation data, so AZMET data were used in this case

Table 7. Effective Precipitation and the Green Water Footprint of Durum Wheat Production in Western Arizona Regions

	2013	2014	2015	2016
Effective Precipitation (in)				
Mohave Valley	0.29	0.11	0.60	0.27
Parker	0.28	0.05	0.51	0.24
Wellton-Mohawk	0.18	0.01	0.36	0.03
Yuma	0.36	0.05	0.21	0.22
Effective Precipitation (m^3 / acre)				
Mohave Valley	29.6	10.9	62.1	28.1
Parker	28.4	5.6	52.1	25.1
Wellton-Mohawk	18.5	1.2	37.0	3.3
Yuma	37.4	5.6	21.6	22.9
Durum yield (bushels / acre)	102	111	101	98
Durum yield (MT / acre)	2.78	3.02	2.75	2.67
Green WF (m^3 / MT)				
Mohave Valley	11	4	23	11
Parker	10	2	19	9
Wellton-Mohawk	7	0	13	1
Yuma	13	2	8	9
Region weighted average (annual)	11	1	11	6
Region weighted average (all years)	8			

Sources: Precipitation and effective precipitation: LCRAS Evapotranspiration Reports, AZMET, authors' calculations. Durum wheat yields: USDA NASS Arizona average durum wheat yields 2013-2016. Green water footprint: authors' calculations.

The convention in water footprint measurement is to measure and report footprints in terms of cubic meters of water (m^3) divided by metric tons (MT) of crop output. We follow this convention to make the results for Arizona more easily comparable to estimates from other regions and studies. The green water footprints across the regions are quite low, ranging from essentially 0 to only 23 m^3 / MT. Across Western Arizona, the output-weighted-average green water footprint ranged from a low of 1 m^3 / MT in 2014 to 11 m^3 / MT in 2013 and 2015. The weighted average across all years was 8 m^3 / MT. Among 26 major wheat producing countries, Mekonnen and Hoekstra (2010b) reported a global average green water footprint of 1,279 m^3 / MT. Country estimates ranged from lows of 216 and 413 m^3 / MT for Egypt and the UK and highs of 3,291 m^3 / MT for Morocco and 3,604 m^3 / MT for Kazakhstan.

LCRAS *Evapotranspiration Report* and data files were used to estimate the blue water footprint of durum wheat production in Western Arizona (Table 8). LCRAS data files provide data on crop evapotranspiration net of effective precipitation and acreage for “small grains, spring”. In Yuma, La Paz, and Mohave counties, “small grains, spring” includes primarily durum wheat with roughly 2% of acres planted to barley. For the following analysis, we assume that the crop consumptive use per acre for durum wheat is the same as that derived from LCRAS data for “small grains, spring”. This could introduce small biases in blue water footprint estimates if water use values for barley are substantially different from wheat. However, University of Arizona Cooperative Extension reports make no distinction between wheat and barley, suggesting their water requirements are the same (Loper and Ottman, 2011; Husman and Ottman, 2015). This, coupled with barley's small acreage share, suggests any biases would be minuscule.

Table 8. The Blue Water Footprint of Durum Wheat Production in Western Arizona Regions

Year	Crop consumptive water use per acre (acre feet acre)	Durum yield (bushels / acre)	Acre feet of water / bushels of durum	Blue water footprint (m3 / MT)
2013	1.79	102	0.0176	796
2014	1.82	111	0.0164	743
2015	1.72	101	0.0170	772
2016	1.77	98	0.0181	820
2013-16 weighted avg.				784

Estimates of crop consumptive use net of precipitation per acre of crop come from the LCRAS database. Consumptive use ranges from 1.72-1.82 acre-feet of water per acre. For footprint calculations, we use Arizona state average durum wheat yields. Ideally, one would want county-specific data for yields, but county-level reporting by NASS has many missing values. Data for Mohave and La Paz counties are especially spotty, but there are also missing values for Yuma County. The last column of Table 8 shows the blue water footprint estimates for Western Arizona. These range from 743 m^3 / MT to 820 m^3 / MT, with an output-weighted average of 784 m^3 / MT over the four years of analysis. This is 15% lower than the global average of blue water footprint in irrigated wheat production of 926 m^3 / MT reported by Mekonnen and Hoekstra (2010b) and despite the very low reliance on precipitation. Long-run durum wheat yields are higher than the state average figures used here. As a result, these estimates are likely to overstate the blue water footprint of Yuma durum wheat production.

Vegetation Index Model (VIM) Results

French et al. (2023) developed a satellite-based vegetation index model (VIM) that tracks daily crop evapotranspiration (ETc), validated over the Yuma and Wellton-Mohawk area irrigation districts. The VIM uses remotely-sensed normalized difference vegetation index (NDVI) images, crop type maps, and local weather data. The VIM provides more accurate estimates of crop ETc than the BOR LCRAS *Evapotranspiration Report* method estimates. French et al. (2023) estimated that the BOR reports overestimate wheat ET_c by 25%.

We combine precipitation and ETc data from their study with USDA-NASS crop yield data to develop green and blue water footprint estimates. For their tests, French et al. (2023) had a growing season that began in the latter half of December and ran to mid-May. French et al. (2023) reported monthly precipitation for 2016–2021 obtained from the Yuma Valley AZMET station. Table 9 combines these with Jensen's effective precipitation coefficients to estimate average effective precipitation over this period. Seasonal effective precipitation is just 0.77 inches (5.8 mm).

Table 9. Measured and Effective Precipitation in the Yuma and Wellton-Mohawk Areas, 2016-2021

Month	Precipitation (in)	Precipitation (mm)	Effective Precipitation Coefficient	Effective Precipitation (mm)
December	0.21	5.3	0.4	2.1
January	0.33	8.4	0.4	3.4
February	0.02	0.5	0.4	0.2
March	0.02	0.5	0.2	0.1
April	0.01	0.3	0.0	0.0
May	0.00	0.0	0.0	0.0
Season	0.77	15.0		5.8

Table 10. Effective Precipitation and the Green Water Footprint of Wheat in the Yuma and Wellton-Mohawk Areas, 2016-2021

Measure	Estimate
Effective precipitation (mm)	5.80
Cubic meters / acre	23.41
Durum wheat yield (bushels / acre)	96.67
Durum wheat yield (MT / acre)	2.71
Green water footprint (cubic meters / MT)	8.64
Green water footprint (rounded)	9.00

Table 10 combines effective precipitation with average durum yields to calculate the average green water footprint for the Yuma and Wellton-Mohawk areas over 2016-2021. The multi-year average of 8.64 m^3 / MT is quite close to the multi-year average of 8 m^3 / MT from the LCRAS data above. As water footprint studies usually do not report fractions, we round the green water footprint for the area up to 9 m^3 / MT.

The VIM results suggested the LCRAS *Evapotranspiration Report* methods overestimated the season length for wheat by six weeks, leading to 25% overestimate of crop ET_c. The French et al. (2023) data for wheat ET_c can be combined with USDA-NASS yield data to estimate a combined green-blue water footprint for Yuma durum wheat. The 9 m^3 / MT green water can be deducted to estimate a separate blue water footprint (Table 11). The average blue water footprint estimate based on the VIM results – 731 m^3 / MT – is lower on average than those reported above from the LCRAS data (Table 8). There is a wider range in the VIM estimates 609 to 827 m^3 / MT compared to the LCRAS numbers (Table 11).

Table 11. Green and Blue Water Footprints for the Yuma and Wellton-Mohawk Areas, 2018-2020

Measure	2018	2019	2020	Average
Wheat ET_c (mm)	440	541	556	512
Water consumed (m^3 / acre)	1,782	2,191	2,252	2,074
Durum wheat yield (MT / acre)	2.88	2.83	2.69	2.80
Green-Blue water footprint (m^3 / MT)	618	775	836	740
Green water footprint (m^3 / MT)	9	9	9	9
Blue water footprint (m^3 / MT)	609	766	827	731

Yuma and Maricopa, Arizona data

French et al. (2020) conducted a three-year study to assess how well satellite-based vegetation index images could estimate evapotranspiration of wheat. The study examined measures of wheat ET_c at six sites in Yuma County and one site at the University of Arizona's Maricopa Agricultural Center in Pinal County in Central Arizona. The study reported observed ET_c at these sites, along with the satellite-based estimates. The observed ET_c estimates were used in the present study to calculate the combined green-blue water footprint of wheat production at the seven sites. To estimate the green water footprint, we made use of precipitation data provided by French et al. (2020) in Table 3 of their study. They, in turn, relied on data from the North Gila Yuma AZMET station and the Maricopa Agricultural Center AZMET station.

Table 12. Measured and Effective Precipitation, Yuma and Maricopa Sites

	Year	Dec	Jan	Feb	Mar	Apr	May	Season
Location / Site		Precipitation (mm)						
Yuma S8	2016−17	19.3	6.6	34.0	3.0	0.0	3.0	65.9
Yuma J118	2017	0.0	6.6	34.0	3.0	0.0	3.0	46.6
Yuma S1	2018	0.0	4.0	0.0	0.0	0.0	0.0	4.0
Yuma S2	2018	0.0	4.0	0.0	0.0	0.0	0.0	4.0
Yuma S5	2017−18	0.0	4.0	0.0	0.0	0.0	0.0	4.0
Yuma S6	2018	0.0	4.0	0.0	0.0	0.0	0.0	4.0
Maricopa H8	2018−19	14.0	13.0	63.0	7.0	0.0	0.0	97.0
		Effective precipitation (mm)						
Location / Site	Year	Dec	Jan	Feb	Mar	Apr	May	Season
Yuma S8	2016−17	7.7	2.6	13.6	0.6	0.0	0.0	24.6
Yuma S8	2016−17	7.7	2.6	13.6	0.6	0.0	0.0	24.6
Yuma J118	2017	0.0	2.6	13.6	0.6	0.0	0.0	16.8
Yuma S1	2018	0.0	1.6	0.0	0.0	0.0	0.0	1.6
Yuma S2	2018	0.0	1.6	0.0	0.0	0.0	0.0	1.6
Yuma S5	2017−18	0.0	1.6	0.0	0.0	0.0	0.0	1.6
Yuma S6	2018	0.0	1.6	0.0	0.0	0.0	0.0	1.6
Maricopa H8	2018−19	5.6	5.2	25.2	1.4	0.0	0.0	37.4

Table 12 reports precipitation and effective precipitation for the seven sites. Baseline precipitation is quite low. But baseline and effective precipitation are both proportionally higher in Maricopa than at the Yuma sites.

French et al. (2020) collected actual durum wheat yield estimates from the study sites. These were reported in MT of wheat per hectare of land (Table 13). There were wide differences in yields across sites, with yields at the Yuma S5 site more than double those at the Yuma J118 site. The green water footprint of durum wheat production ranged from lows of 2 m^3 / MT at some Yuma sites to 55 m^3 / MT at the Maricopa site (Table 13).

Table 13. Effective Precipitation and Green Water Footprint of Wheat Production, Yuma and Maricopa Sites

Location / Site	Effective Precipitation	Water consumption (m^3 / ha)	Durum wheat yield (MT / ha)	Green water footprint (m^3 / MT)
Yuma S8	24.6	245.6	7.0	35
Yuma J118	16.8	168.4	5.0	34
Yuma S1	1.6	16.0	8.1	2
Yuma S2	1.6	16.0	8.3	2
Yuma S5	1.6	16.0	10.2	2
Yuma S6	1.6	16.0	7.1	2
Maricopa H8	37.4	374.0	6.8	55

Measured ET_c at the seven sites were combined with durum wheat yield data and green water footprint estimates to develop blue water footprints for the sites (Table 14).

Table 14. Green and Blue Water Footprints of Wheat Production, Yuma and Maricopa Sites

Location / Site	Site area (ha)	Measured ETc (mm)	Water consumed m^3 / ha	Durum wheat yield (MT / ha)	Green-blue water footprint (m^3 / MT)	Green water footprint (m^3 / MT)	Blue water footprint (m^3 / MT)
Yuma S8	129.13	499	4990	6.95	718	35	683
Yuma J118	46.94	540	5400	5.02	1076	34	1042
Yuma S1	129.67	684	6840	8.07	848	2	846
Yuma S2	131.02	588	5880	8.29	709	2	707
Yuma S5	119.74	652	6520	10.18	640	2	639
Yuma S6	130.68	578	5780	7.08	816	2	814
Yuma weighted average					756	9	747
Maricopa H8	247.40	635	6350	6.81	932	55	878

There is wide variation in blue water footprints across the Yuma sites. These range from a low of 639 m^3 / MT (site S5) to a high of 1,042 m^3 / MT (J118). The relatively large water footprint for J118 is driven by very low yields. Actual water used at J118 is the second lowest among Yuma sites, but yields are quite low, driving water use per unit of wheat produced upward. The weighted average blue water footprint for the Yuma sites (747 m^3 / MT) is in line with the aggregate LCRAS estimates (784 m^3 / MT) and VIM estimates (731 m^3 / MT) above. The Maricopa site had both the highest green water footprint and blue water footprint of the sites. The higher green water footprint is explained in part by the relatively high effective precipitation compared to the Yuma sites, as well as the relatively lower wheat yields compared to most Yuma sites. The lower yields also contributed to the relatively large blue water footprint.

Central Arizona Irrigation District Data

French et al. (2018) examined data from the Central Arizona Irrigation and Drainage District (CAIDD) to evaluate remote sensing methods for estimating crop ET_c. Following similar procedures as before (combining precipitation, crop water use, and yield data), we use data from this study to estimate the green and blue water footprints of durum wheat production in Central Arizona (Table 15). ET data for 2008 were estimated based on 137 wheat plots. French et al. did not report the total acreage of wheat in the study but did report that the minimum plot size in the study was 1.4 hectares (ha) (about 3.5 acres) while the maximum was 313.4 ha (about 744.5 acres). CAIDD lies in South Central AZ.

Table 15. Measured and Effective Precipitation and the Green Water Footprint of Durum Wheat Production in Central Arizona

	Season	Jan	Feb	Mar	Apr	May
Precipitation	2.45	0.75	0.75	0	0	0.95
Effective precipitation coefficient		0.4	0.4	0.2	0	0
Effective precipitation	0.6	0.3	0.3	0	0	0
Green water (m3 / acre)	61.67					
Wheat yield (bushels / acre)	98					
Wheat yield (MT / acre)	2.67					
Green water footprint (m^3 / MT)	23					

To estimate the green water footprint, we begin with precipitation data from the Coolidge AZMET station. We again apply Jensen's effective precipitation coefficients to estimate green water use per acre. This is combined with the USDA NASS average durum yield of 98 bushels / acre for 2008. The green water footprint was 23 m^3 / MT (Table 15).

Along with more experimental approaches, French et al. (2018) report ET_c for wheat using the FAO method. The FAO-56 method, named from the FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998) is among the most widely used standardized approaches for estimating crop ET_c. It has been used extensively in water footprint analysis (Hoekstra and Chapagain, 2007; Mekonnen and Hoekstra, 2010a, 2011). We therefore use the FAO-56 ETc estimates reported by French et al. (2018) for our green-blue water footprint estimates (Table 16).

The CAIDD data combined with precipitation and yield data suggest a green water footprint of 23 m^3 / MT, a blue water footprint of 837 m^3 / MT, and a combined green-blue water footprint of 860 m^3 /

MT. As with the Maricopa Agricultural Center site, both the green and blue water footprints are slightly higher than most values from Yuma.

Table 16. Green and Blue-Green Water Footprint of Durum Wheat Production in Central Arizona

Measure	Estimate
Durum wheat ETc (mm)	567
Water consumption (m^3 / acre)	2,294
Durum wheat yield (MT /acre)	2.67
Green-blue water footprint (m^3 / MT)	860
Green water footprint (m^3 / MT)	23
Blue water footprint (m^3 / MT)	837

Comparing Arizona Durum Wheat Water Footprints to Other Studies and Regions

Table 17 reports different estimates of the combined green-blue water footprint (the sum of rain- and irrigation-water consumption) based on data from LCRAS and French et al. (2018; 2020; 2023).

Table 17. Green-blue Water Footprint Estimates for Durum Wheat in Arizona

Location / Study	Green-blue water footprint (m^3 / MT)
Western Arizona	
Wellton-Yuma 2018	618
Yuma S5	640
Yuma S2	709
Yuma S8	718
LCRAS 2014	744
Wellton-Yuma 2019	775
LCRAS 2015	783
LCRAS 2013	807
Yuma S6	816
LCRAS 2016	826
Wellton-Yuma 2020	836
Yuma S1	848
Yuma J11B	1,076
Western Arizona weighted average	766
Central Arizona	
CAIDD FAO-56 (Central AZ Low)	860
Maricopa H6 (Central AZ High)	932

Values range from 618 m^3 / MT to 1,076 m^3 / MT. Area coverage of these estimates ranges from experimental fields to county-wide coverage, to multi-county coverage along the Lower Colorado River mainstem. Data on area covered and crop yields were used to create output-weighted average green, blue, and green-blue water footprints for Western Arizona (including Yuma, La Paz, and

Mohave counties). There was insufficient data to construct an average for Central Arizona. We therefore just present Central Arizona Low and Central Arizona High cases to bound our estimates.

How do these estimates compare to those of other studies and wheat growing regions? Mekonnen and Hoekstra (2014), based on a global analysis, report percentiles of green-water footprints for production of different crops. For wheat, they report a global average green-blue water footprint of 1,292 m^3 / MT. The 20th percentile footprint was 992 m^3 / MT, meaning that 80% of global wheat production had a higher footprint. The 25th percentile footprint was 1,069 m^3 / MT, meaning that 75% of global wheat production had a higher footprint. The 10th percentile footprint was 592 m^3 / MT, meaning that 90% of global wheat production had a higher footprint. Figure 38 compares the Arizona estimates to these percentiles. The lowest Arizona is just above the 10th percentile, while the highest value is just above the 25th percentile. All the estimates but this highest value were between the 10th and 20th percentiles. The Western Arizona weighted average is closer to the 10th percentile value than the 20th percentile value. Both Central Arizona values are below the 20th percentile.

Figure 38. Green-blue Water Footprint Estimates for Wheat Production Compared to Global Percentiles

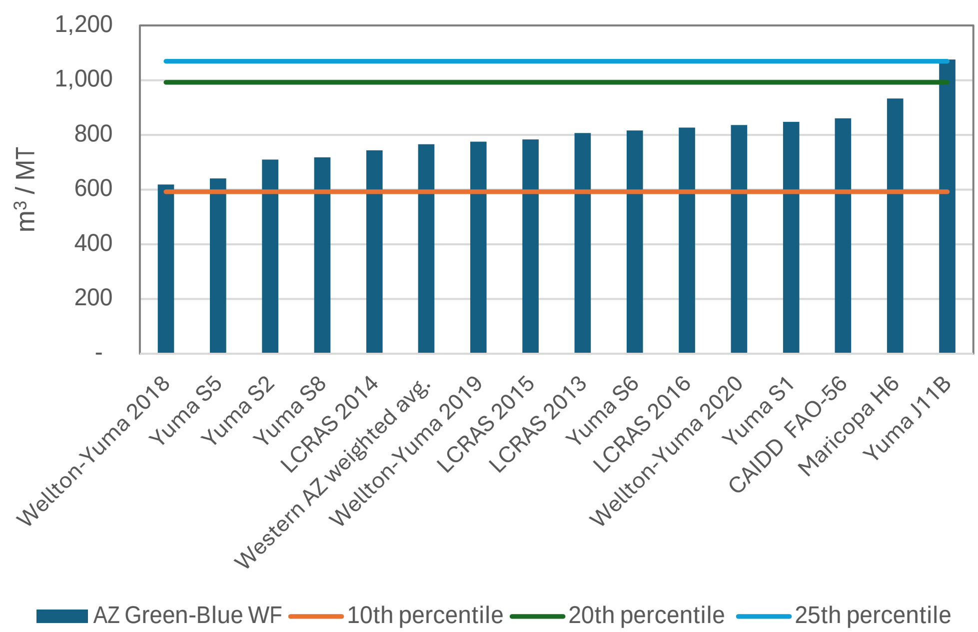
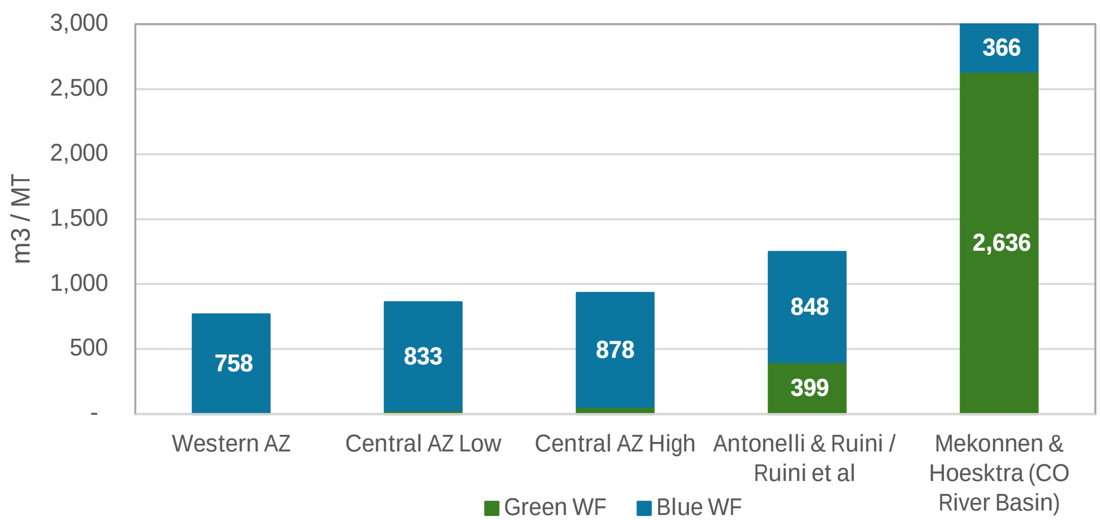


Figure 39 compares estimates of the green and blue water footprints of wheat production with other studies of the US Southwest. As discussed earlier, the green water footprint estimates in Antonelli and Ruini (2015), Ruini et al. (2013) (for Arizona), and Mekonnen and Hoekstra (2010b) are based on implausible assumptions about precipitation and green water use. The Arizona green water footprints for this study – based on local weather station data – are quite small, averaging just 8 m^3 / MT for Western Arizona and ranging from 27-55 m^3 / MT for Central Arizona. While the blue water footprint estimates of Antonelli and Ruini (2015) and Ruini et al. (2013) are in line with our Central Arizona estimates, their green water footprint estimate is 7 to 49 times higher than our estimate based on local rainfall and crop yield data. Consequently, their combined green-blue water footprint estimate is 34-63% greater than our present study. Mekonnen and Hoekstra's green-blue water footprint estimate is 3.2-3.9 times higher than our estimates, which are based on more accurate, local data.

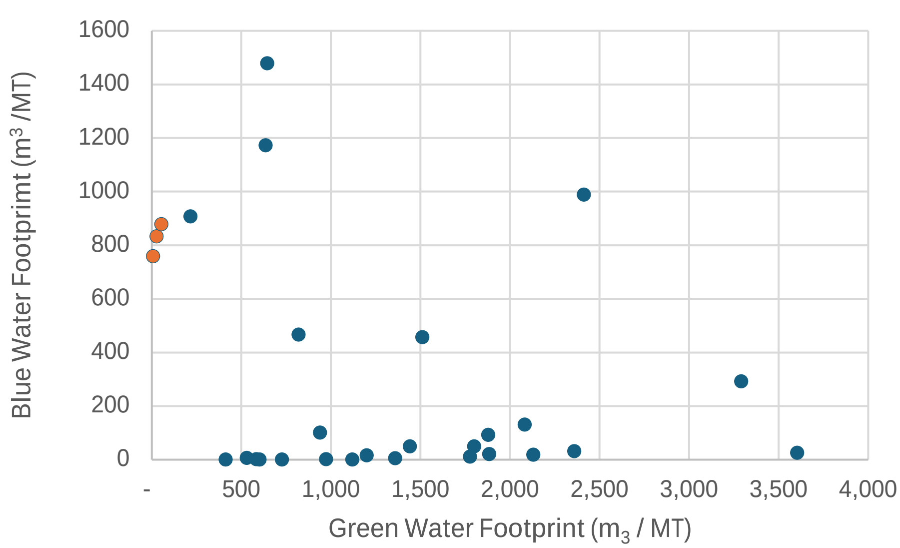
Figure 39. Arizona Green and Blue Footprint Estimates for Wheat Production Compared to Earlier Studies



Comparisons with Wheat Producing Countries

We now compare our Arizona, Western AZ, Central AZ Low, and Central AZ High green and blue water footprint estimates for wheat production with those of other countries. Figure 40 plots the blue water footprint on the green water footprint for our Arizona values and 26 major wheat producing countries. Country data come from Mekonnen and Hoekstra (2010b, c). Arizona values (shown in orange) illustrate the extremely arid production environment of the desert Southwest. All

Figure 40. Green and Blue Water Footprints for Wheat Production for Arizona and 26 Major Wheat Producing Countries

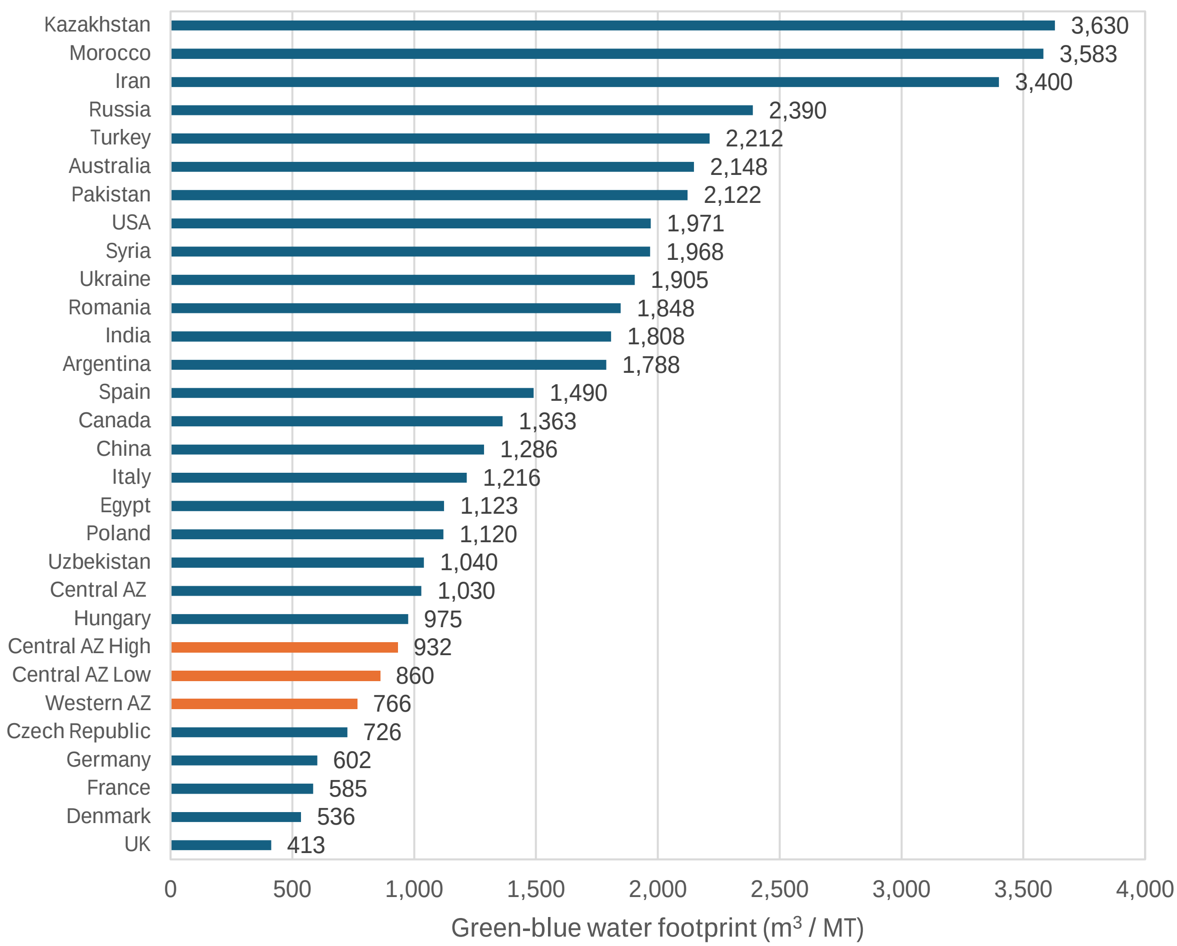


Source: Mekonnen and Hoekstra (2010) and authors' calculations.
Arizona values are in orange

but two countries have green water footprints greater than 500 m^3 / MT. Compared to wheat producing countries, Arizona has an extremely low green water footprint, but a relatively high blue water footprint (reflecting how necessary irrigation is in the state). Only Pakistan, India, Iran, and Egypt have higher blue water footprints.

Arizona's combined green-blue water footprint is lower than that of other countries (Figure 41). The Arizona footprint values are greater than five countries but lower than 21 countries. These results present us with a quandary. Figure 41 shows that countries with very large water footprints are also extremely arid. Mekonnen and Hoekstra (2010b) report quite high green water footprints for these countries. It could be that the same methodological problems that we uncovered for arid production in Arizona are present for these countries.

Figure 41. Green-Blue Water Footprint for Wheat Production for Arizona and 26 Major Wheat Producing Countries

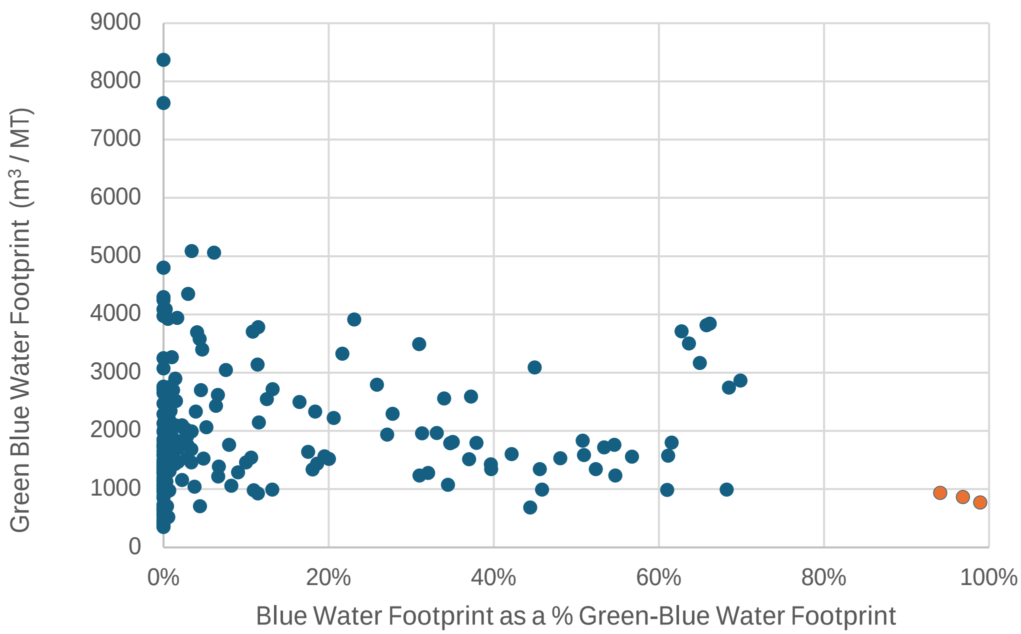


Source: Mekonnen and Hoekstra (2010b) and authors' calculations.
Arizona values are in orange

Comparisons with Wheat Producing River Basins

We now compare Arizona estimates with those of 220 wheat-producing river basins globally. River basin estimates come from Mekonnen and Hoekstra (2010b). Values for the Colorado River Basin were excluded because of the problems discussed above. Figure 42 plots the green-blue water footprint of wheat production against the percentage of green-blue water that is just blue water. This percentage measures the degree to which the production system depends on irrigation relative to rainfall. The Arizona values are much higher than the river basins, with a near 100% reliance on irrigation. Despite Arizona's arid environment and heavy reliance on irrigation, it has a relatively low green-blue water footprint compared to the river basins.

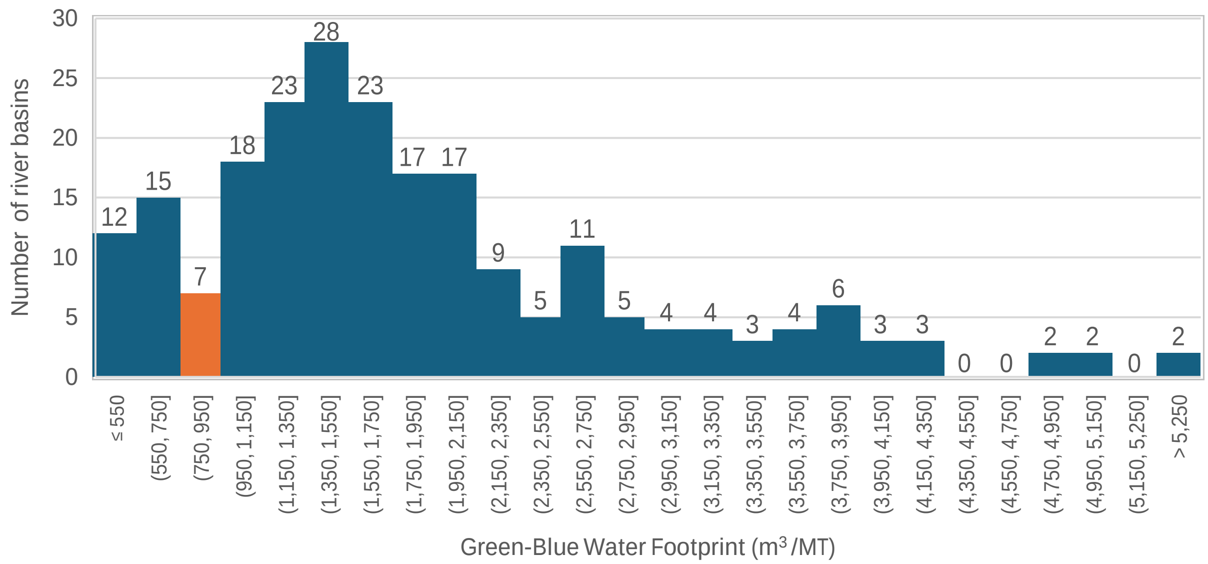
Figure 42. Green-Blue Water Footprint for Wheat Production for Arizona and 220 Wheat Producing River Basins



Source: Mekonnen and Hoekstra (2010b) and authors' calculations.
Arizona values are in orange

Figure 43 shows where Arizona ranks compared to global river basins in the green-blue water footprint of wheat production. The figure shows how many river basins are within a range of water footprint values. The three Arizona values are shown in the orange bar as they have footprint values between 750 and 950 m^3 / MT. The Arizona basins are three of seven observations in this range. While 27 river basins are in a lower range, 189 are in a higher range of green-blue water footprint values.

Figure 43. Ranking of Green-Blue Water Footprint for Wheat Production for Arizona and 220 Wheat Producing River Basins



Source: Mekonnen and Hoekstra (2010b) and authors' calculations.
Arizona values are in orange

Grey Water Footprint of Arizona Durum Wheat Production

Hoekstra et al. (2011) and Franke et al. (2013) identify a three-tier approach for estimating diffuse pollution loads to water bodies. Tier 1 requires the least amount of data. Moving to Tiers 2 then 3 increases measurement accuracy but requires more localized data on soils, climate, and hydrology. To calculate global estimates of the grey water footprint for wheat, Mekonnen and Hoekstra (2010a,b, c, 2011, 2014) consider only nitrogen as a pollutant entering water bodies. We follow this approach here using Tier 1 methods to estimate the grey water footprint for Arizona durum wheat. This method calculates the amount of water needed to assimilate the pollutant (nitrogen) as a simple function of fertilizer application rates, a leaching runoff fraction, water quality standards, naturally occurring nitrogen, and crop yields. The formula is:

$$GWF = \frac{\delta\ AR}{(c_{max} - c_{nat})}\frac{1}{Y}$$

where:

GWF = grey water footprint (in m^3 / MT)

AR = the nitrogen fertilizer (N) application rate (in kg / ha)

δ = the leaching runoff fraction (measured as a %)

c_{max} = the maximum acceptable (or allowable) concentration of nitrogen 10 mg/L = 0.01 kg / m^3

c_{nat} = the natural concentration of nitrogen in the receiving water body

Y = yield per acre of the crop, in this case, durum wheat (in MT / ha)

Mekonnen and Hoekstra (2011) note studies reporting values of nitrogen leaching (δ) of 2% to 13%. Chapagain et al. (2006), Mekonnen and Hoekstra (2010b), and Hoekstra et al. (2011) assume a constant leaching-runoff fraction of 10% (δ = 0.1). Next, lacking data, they assume that the natural level of nitrogen in the receiving water body equals zero. Finally, they assume a maximum acceptable concentration of nitrogen of 10 mg / liter, based on the standard recommended by the U.S. EPA. Below, we follow this approach for the Yuma grey water footprint. Given assumptions for δ, c_{max} and c_{nat}, the formula simplifies to:

$$GWF = 10 \frac{AR}{\mathrm{Y}}$$

To calculate the grey water footprint of Arizona durum wheat production, we use the same USDA NASS values of durum wheat yields for *Y* that were used for the green and blue water footprint calculations. The next step is to develop estimates of nitrogen fertilizer application rates.

Nitrogen Application Rates

According to the University of Arizona Cooperative Extension publication, *Nitrogen Fertilizer Management in Arizona* (Doerge et al., 1991) for wheat and barley, "[w]ith good management, a total of about 150 to 230 lbs. N per acre is usually needed for optimum production." In the mid-1990s, Cooperative Extension specialists reported that it was "the standard practice" to apply 204 lb. / acre of nitrogen (Husman and Ottmann, 1996; Ottman et al., 1997). Results from an annual survey of durum wheat producers were regularly reported in the University of Arizona *Forage and Grain Report* (Ottman, 2005; 2006; 2007; 2008). Each report published results of the survey conducted the previous year. The 2004 survey captured 47% of wheat growers, accounting for 40% of Arizona durum wheat production. Subsequent surveys captured 50% growers representing 57-59% of state production. Nitrogen application rates were 210 lb. / acre in 2004, 213 lb. / acre in 2005, 224 lb. / acre in 2006, and 224 lb. / acre in 2007.

For durum wheat yields of 100 bushels / acre (6,000 lb. / acre), Ottman and Thomas (2006) and Ottman (2020) report a baseline nitrogen application rate of 211 lb. / acre to achieve 13% grain protein and 222 lb. / acre to achieve 14% grain protein. Protein rates of 13% or higher are desirable for buyer needs (Ottman, 2024) (such as pasta production). Ottman (2020) notes, "[i]nsufficient N application reduces grain yield and results in unacceptable grain protein content." Application rates of 246-259 lb. / acre were reported for a baseline yield of 116 bushels / acres with protein percentages of 13% and 14%. Durum wheat yields over our period of analysis averaged roughly 102 bushels / acre.

Different researchers and extension specialists have made a variety of observations about standard practices that Arizona growers follow in durum wheat production. Wang et al. (2010) reported that 200 lb. N / acre "is considered the standard N rate for most growers." Discussing different experimental treatments, Liang et al. (2014) stated, "The 269 kg ha-1 rate is similar to farmers' rate." This is 240 lb. / acre. A USDA study grew durum wheat for two years in Central Arizona using five fertilizer and ten irrigation rates to compare yields and estimate how efficiently the wheat used nitrogen (O'Brien, 2017). They found that "[f]or maximum yield, the optimal fertilizer rate was 225 pounds of nitrogen per acre." But they also found that when they factored in fertilizer costs, more isn't always better. The economic rate, with the fertilizer cost included, was about 175 pounds of nitrogen per acre. These various observations were made across different years and different parts of the state. Rather than assume a single N application rate, we calculate grey water footprints based on a range of values that match rates reported by the above different sources. We consider a low rate of 200 lbs. / acre, a mid-range rate of 220 lb. / acre, and a high, upper bound rate of 240 lb. / acre.

Grey Water Footprint Estimates

Based on different assumed N fertilizer application rates, the grey water footprint ranges from 324 m^3 / MT to 408 m^3 / MT (Table 18). The Central Arizona data source with the low green-blue footprint (CAIDD) has a slightly higher grey water footprint than the other Arizona source (from the Maricopa Agricultural Center). This happens because estimated yields were lower in CAIDD. Because the grey water footprint goes down as yields go up, lower yields mean a larger footprint. While Arizona durum wheat green and blue water footprints were low relative to other wheat producers, grey water footprint estimates are relatively larger. Mekonnen and Hoekstra (2014) report a global average of 208 m^3 / MT across wheat producers.

Table 18. Grey Water Footprint Estimates for Durum Wheat in Arizona Under Alternative Nitrogen Fertilizer Application Rates

	Nitrogen (N) fertilizer application rates		
	200 N / acre	220 N / acre	240 N / acre
	Grey water footprint (m^3 / MT)		
Western AZ (weighted average)	324	356	388
Central AZ Low (Green-Blue)	340	375	408
Central AZ High (Green-Blue)	329	363	395

Implications for Nitrogen Fertilizer Management

Our earlier analysis found that Arizona durum wheat production relies on nearly no green water. The production system is fine-tuned to the Arizona desert environment so that there is little room for improvement of its green-blue water footprint. Arizona's green-blue water footprint is far lower than most other wheat producers and among the lowest in the world. In contrast, Arizona durum wheat's grey water footprint is an area where improvement is more possible. As noted above, USDA research found that the profit maximizing rate of N applications was lower than the yield maximizing rate (O'Brien, 2017). The profit maximizing rate also appears lower than standard practices of many growers.

Wang et al. (2013) note:

> *"Many growers in Arizona use fixed N fertilizer programs to manage durum wheat crops. In these programs, N fertilizer can be under- or over-applied in the field due to different crop growth and N demand from year to year. When crop yield is high due to favorable growing conditions, N fertilizer applications from fixed programs are often not sufficient enough for the crop to attain the desirable 13% protein content. When crop yield is low, N fertilizer is*

often over-applied in fixed programs, resulting in protein contents higher than the desirable 13% without economic gains from N fertilizer application. In either case, growers' profitability is reduced."

So, programs that apply a fixed amount of N may either over- or under-apply, depending on yield potential and crop needs. Misapplication can lower farm returns.

Another way to think of the grey water footprint (GWF) is

$$GWF = \frac{\delta\ (N_{applied} - N_{uptake})}{(c_{max} - c_{nat})} \frac{1}{Y}$$

where $N_{applied}$ is the amount of N applied per acre (or hectare) and N_{uptake} is the amount of N taken up and used by the crop. The difference between the two represents excess N that can potentially reach water bodies. The extent of this depends on the leaching fraction, δ.

There are a variety of fertilizer management practices that can allow growers to better match N applications to plant nutrient requirements in durum wheat production. Soil nitrate testing and nitrogen balance approaches (replacing N removed by the crop while accounting for soil and water contributions) provide a baseline for reducing unnecessary applications (Ottman, 2020). Stem nitrate analysis has been shown to reliably estimate the minimum N required for optimum yield and protein content, enabling adjustments to fertilizer rates N during the growing season, rather than relying on pre-determined application programs (Doerge et al., n.d.). Nitrogen reference strips improve decision-making by providing a spatially explicit benchmark for sufficient-N conditions. By comparing crop growth and color in reference strips versus the surrounding field, growers can visually assess N sufficiency and avoid over-application in low-demand environments (Wang, 2012). Split applications and fertigation timed to coincide with peak crop uptake stages increase nitrogen use efficiency and reduce losses associated with large, single applications (Ottman, 2024). Precision agriculture technologies, including canopy reflectance sensors and variable-rate application systems, extend these principles by enabling site-specific N management based on real-time crop status. This reduces over-application and improves fertilizer targeting (Andrade-Sánchez & Ottman, 2014). These management techniques can lower the grey water footprint of durum wheat production by matching applications to crop needs and so, reduce surplus N, reduce the rate at which N leaches into water bodies, or both.

Improving fertilizer management in Arizona durum wheat production has the potential to be a win-win strategy, both improving farm profitability and water quality. Improving the efficiency of applications can increase yields and crop quality (both increasing farm revenues). Avoiding over-application of fertilizer reduces grower costs. Improved fertilizer management can also reduce environmental problems of nitrogen reaching water bodies (which the grey water footprint indirectly measures).

The Total Water Footprint of Arizona Durum Wheat Production

We may now combine our range of grey water footprints with our earlier green and blue water estimates to calculate ranges for the total water footprint of Arizona durum wheat (Table 19). The total footprint ranges from 1,090 m^3 / MT to 1,327 m^3 / MT. Table 19 compares our estimates to those of other studies of Arizona and the Colorado Basin. The blue water estimates of Antonelli and

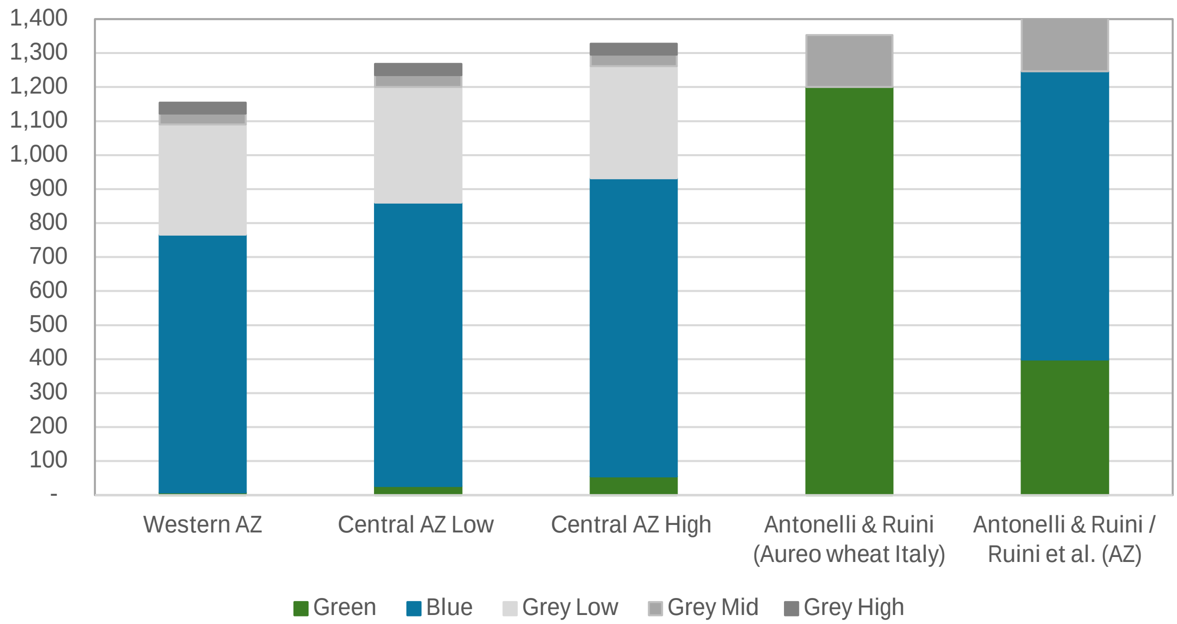
Ruini (2015) and Ruini et al. (2013) lie within the bounds of our blue water footprint estimates. The grey water estimate of Mekonnen and Hoekstra (2010b) lies within our range of estimates. As discussed earlier, the estimates of Antonelli and Ruini (2015), Ruini et al. (2013), and Mekonnen and Hoekstra (2010b) are based on impossibly high estimates of local Arizona precipitation.

Table 19. The Total Water Footprint for Durum Wheat in Arizona Under Alternative Nitrogen Fertilizer Application Rates with Comparisons to Other Studies

	Green	Blue	Grey	Total Water Footprint
Western AZ (N = 200 lb. /acre)	8	758	324	1090
Western AZ (N = 220 lb. /acre)	8	758	356	1123
Western AZ (N = 240 lb. /acre)	8	758	388	1155
Central AZ Low (N = 200 lb. /acre)	27	833	340	1200
Central AZ Low (N = 220 lb. /acre)	27	833	375	1235
Central AZ Low (N = 240 lb. /acre)	27	833	408	1268
Central AZ High (N = 200 lb. /acre)	55	878	329	1262
Central AZ High (N = 220 lb. /acre)	55	878	363	1295
Central AZ High (N = 240 lb. /acre)	55	878	395	1327
Antonelli & Ruini / Ruini et al. (AZ)	399	848	156	1403
Mekonnen & Hoekstra (CO River Basin)	2636	366	338	3340

Antonelli and Ruini summarize the results of the pasta company Barilla's Aureo Wheat Programme. This program involved shifting their sourcing of durum wheat for their pasta production. Specifically, sourcing was shifted away from Arizona durum wheat and to the Aureo variety grown in Italy under entirely rainfed production. They claimed that the shift away from Arizona durum wheat led to cumulative blue water savings of 35 million m^3 since program inception in 2011, with 40 million m^3 savings per year in the fully implemented program. While a switch to rainfed durum wheat production obviously reduces the blue water footprint of production, Antonelli and Ruini (2015) do not discuss the impact of this shift on the total water footprint of production. They report a total water footprint of Aureo wheat as 50 l / kg (same as 50 m^3 / MT), less than the Arizona variety. They do not state what the Arizona value is, but their figure 9 matches the values from Ruini et al. where they estimated a total water footprint for Arizona durum wheat of 1,403 m^3 / MT and a blue water footprint of 848 m^3 / MT, and a grey water footprint of 156 m^3 / MT. From this total water footprint of 1,403 m^3 / MT and the 50 m^3 / MT difference, we can infer that the total water footprint of Aureo wheat is 1,353 m^3 / MT. Our total water footprint estimates from Arizona range from 1,090 to 1,155 m^3 / MT for Western Arizona durum and range from 1,200 to 1,353 m^3 / MT for Central Arizona durum (Figure 44). All of these ranges are below the Aureo wheat footprint. Our estimates are 5%-22% lower than those of Antonelli and Ruini (2015) and Ruini et al. (2013).

Figure 44. The Total Water Footprint for Durum Wheat in Arizona Compared to Estimates for Arizona and Italy from Antonelli & Ruini (2015) and Ruini et al. (2013)



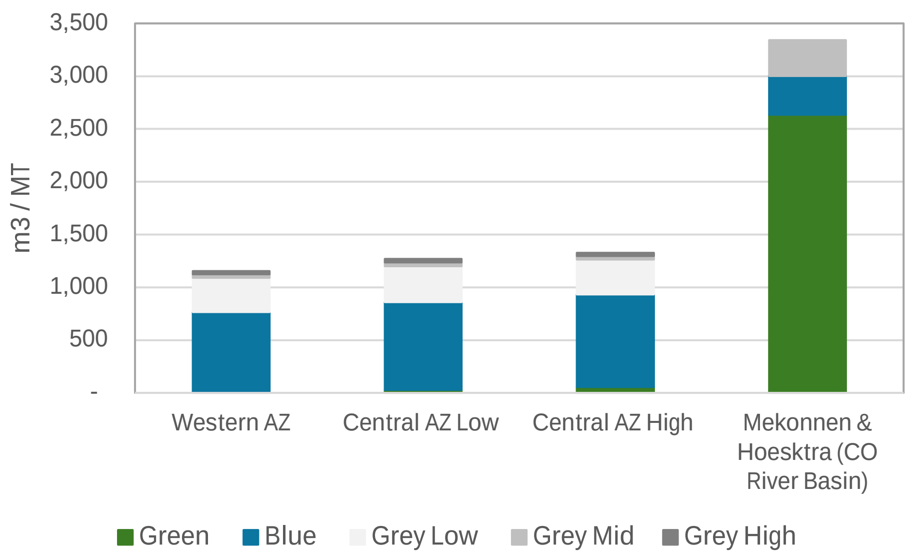
So, what were the impacts of Barilla's Aureo Wheat Programme on their total water footprint? Their estimated blue water savings of 35 million m^3 since program inception in 2011 imply that 41,274 MT of wheat was sourced from Italy instead of Arizona. Based on our range of Arizona durum wheat's total water footprint, the program actually increased Barilla's water consumption by 1.1 million to 10.9 million m^3 since the program's inception in 2011. Antonelli and Ruini's estimated blue water savings of 40 million m^3 per year in a fully operational program imply that 47,170 MT of wheat was sourced from Italy instead of Arizona. Based on our water footprint range for Arizona durum wheat, the program would increase Barilla's water consumption by 1.2 million to 12.4 million m^3 annually. If all the reduction in wheat that would have been sourced from Arizona came from Central Arizona, the increase in water use would range from 1.2 million to 7.2 million m^3 annually. If all the reduction in wheat sourced from Arizona came from Western Arizona, the increase in water use would range from 9.3 million m^3 to 12.4 million m^3 annually.

Antonelli and Ruini (2015) emphasize savings of blue water but ignore impacts on overall water use. They and other researchers have emphasized blue water use and under-emphasized green water use. Some standard arguments are that green water has a low opportunity cost. Water used for crop production cannot be used for other things. The loss from not using water for other things is the opportunity cost. It has argued (without producing estimates) that these costs are inherently low (Aldaya et al., 2010; Antonelli and Ruini, 2015; Mekonnen and Hoekstra, 2010a, 2010b). It is claimed that green water used for crops does not compete with other uses and that diverting water away from natural ecosystems has few negative environmental consequences (Aldaya et al., 2010).

The notion that rainwater is not scarce and competed over has been increasingly challenged (Wichelns, 2017). Green water (from rainfall) is the dominant input in rainfed systems and sustains terrestrial ecosystem structure and function (Falkenmark & Rockström, 2006; Rockström et al., 2009). Rainfed agriculture is already constrained by green water scarcity, defined as the inability of precipitation and soil moisture to meet crop water demand. This scarcity is expected to intensify under climate change (Rosa and He, 2023; Rosa et al., 2025). Increased crop use of green water can reduce ecosystem services associated with natural vegetative cover (Scanlon et al., 2005; Norman et al., 2026). Converting vegetation can degrade soil structure and water regulation capacity, reduce biodiversity, and weaken ecosystem resilience (Foley et al., 2005; Tilman et al., 2001). Water footprints are simple measures of water productivity (how much water is used to produce something). Consequently, it is too indirect a measure to weigh the environmental consequences of shifting production from one watershed to another (Wichelns, 2017). To understand the environmental and economic consequences, one needs detailed information about the specific agricultural, environmental, and economic features of watersheds. We can say, though, that Barilla's Aureo Wheat Programme increased Barilla's overall water footprint.

Mekonnen and Hoekstra's green water estimates implicitly assume that rainfall in wheat growing areas of the Colorado River Basin (with 89% of production in the Sonoran Desert) is nearly 5 acre-feet per acre. Mekonnen and Hoekstra's overestimation of green water is so large that their total water footprint estimate is roughly triple the size our estimates based on local weather and production data (Figure 45).

Figure 45. The Total Water Footprint for Durum Wheat in Arizona Compared to Mekonnen & Hoekstra (2010)



International Comparisons

Figure 46 compares Arizona durum wheat's total water footprint with those of 26 major wheat producing countries. Country data come from Mekonnen and Hoekstra (2010a, b), who report a global average total water footprint of wheat production overall of 1,830 m^3 / MT, with a global average of 1,868 m^3 / MT for irrigated wheat production. By comparison, our estimates vary based on location within Arizona and assumed fertilizer application rates range from 1,090 m^3 / MT to 1,327 m^3 / MT. These values place Arizona durum wheat's water footprint 29-42% below the global average for irrigated wheat. Depending on Arizona estimates, Arizona's water footprint is lower than either 19 or 20 of the 26 wheat producing countries.

Figure 46. The Total Water Footprint for Durum Wheat in Arizona Under Alternative Nitrogen Fertilizer Application Rates Compared to 26 Major Wheat-Producing Countries

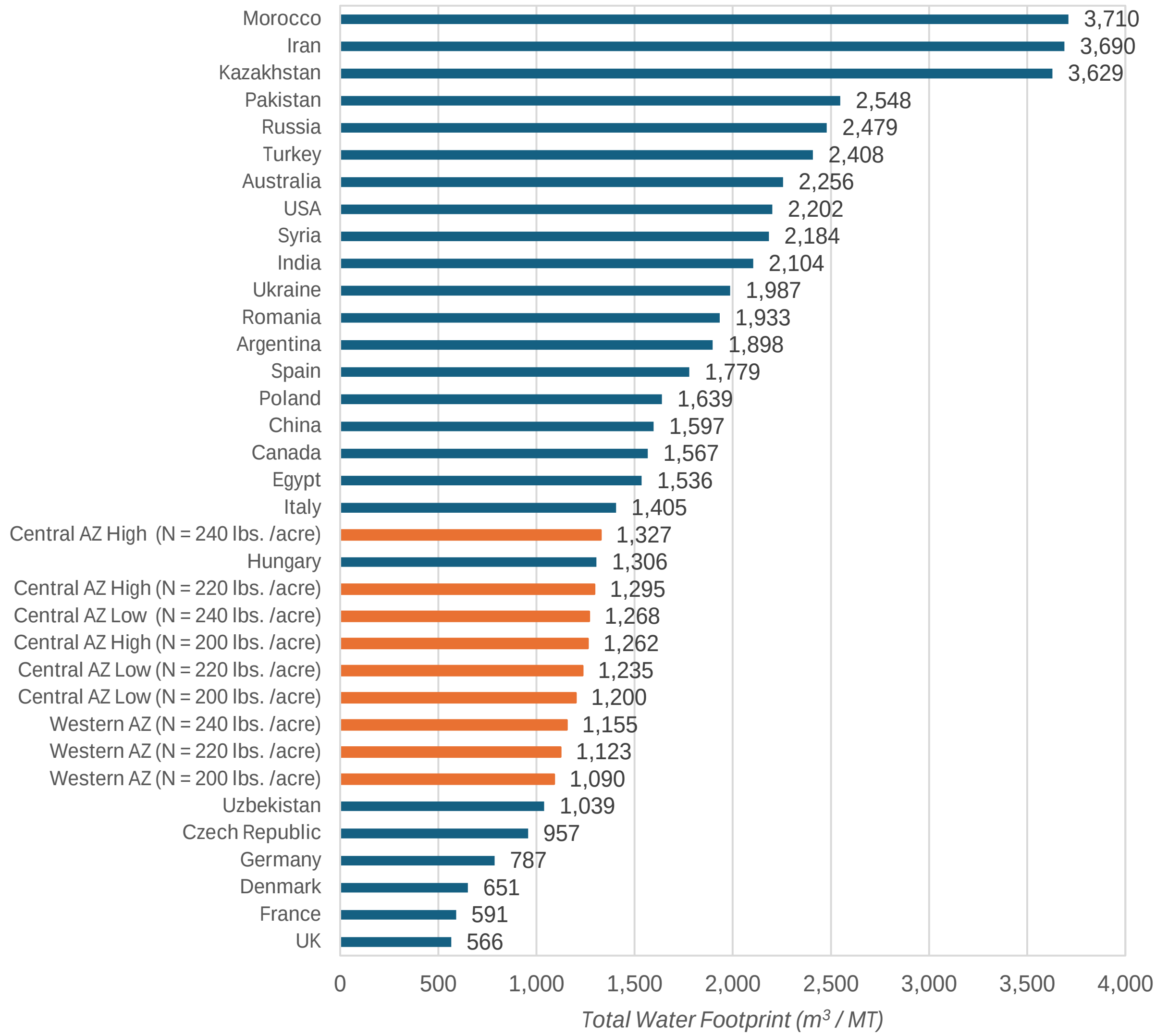
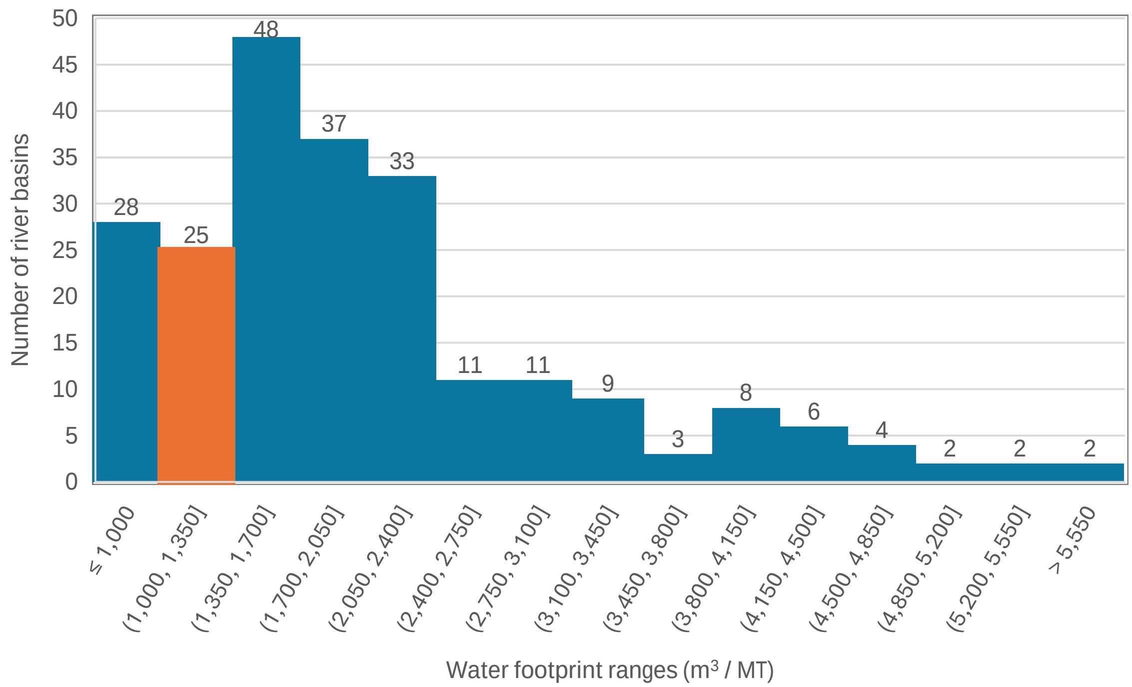


Figure 47 compares our Arizona total water footprint estimates with those of 220 wheat-producing river basins globally. River basin estimates come from Mekonnen and Hoekstra (2010b). Values for the Colorado River Basin were excluded because of the problems with their Colorado River estimates, discussed above. The figure displays the distribution of water footprint values across river basins, with Arizona's nine estimates falling between 1,000 and 1,350 m^3/MT, shown in orange. Within this range, Arizona's estimates account for 9 of the 25 total observations. Globally, there are 16 river basins (7% of the total) in the same range as Arizona, while 28 river basins (13%) are in a lower range than Arizona. In contrast, 176 river basins (80%) have a larger total water footprint of wheat production than Arizona.

Figure 47. The Total Water Footprint for Durum Wheat in Arizona Compared to Footprints in 220 Wheat-Producing River Basins



Summary of Water Footprint Findings

We summarize our water footprint analysis of Arizona durum wheat production as follows.

- Previous estimates of the water footprint of wheat production in the Colorado River Basin and Arizona developed green water estimates that assume an implausibly high level of rainfall. These also lead to significant overestimates of Arizona's overall water footprint.
- Green water footprint estimates, developed here and based on more accurate, local precipitation and crop yield data, suggest that Arizona durum wheat has a lower green water footprint than any of 26 major wheat producing countries or across 220 river basins.
- Green water measures effective precipitation consumed by crops, while blue water measures consumption of irrigation water. We developed 15 combined green-blue water footprint estimates across western and central Arizona. Of these, 14 were below the 20th percentile across all wheat production globally, meaning that 80% of global wheat production used more water per unit of wheat produced. The remaining estimate was below the 25th percentile, meaning that 75 % of global wheat production used more water per unit of wheat produced.
- Arizona's grey water footprint (measuring water needed to assimilate nitrogen from fertilizers reaching water bodies), in contrast, was greater than the global average. There are a variety of fertilizer management practices that can allow growers to better match nitrogen fertilizer applications to plant nutrient requirements in durum wheat production. Improving fertilizer management in Arizona durum wheat production has the potential to be a win-win strategy, both improving farm profitability and water quality.

- The pasta firm, Barilla, instituted its Aureo Wheat Programme with the intent of lowering its water footprint of pasta production. A key feature of the program was sourcing more wheat from Italy and less from Arizona. While the program reduced Barilla's blue water footprint, it increased its overall water footprint of pasta production, increasing water consumption by 1.2 million m^3 to 12.4 million m^3 annually in the fully implemented program.
- Arizona durum wheat's total water footprint was lower than the water footprints of 80% of global river basins producing wheat. Arizona's footprint was 29-42% below the global average for irrigated wheat.

Economic Contribution of Small Grains

The contribution of small grains to Arizona's economy goes beyond on-farm production to generate subsequent rounds of economic activity in other industries. These effects are known as *indirect* and *induced multiplier effects*. *Indirect effects* measure economic activity generated by small grains operations' demand for inputs or supplies. These effects represent business-to-business transactions that occur in other local non-agricultural industries that provide goods and services as inputs to production. *Induced effects* measure the economic activity generated when households employed by small grain farms spend their earnings on local goods and services.

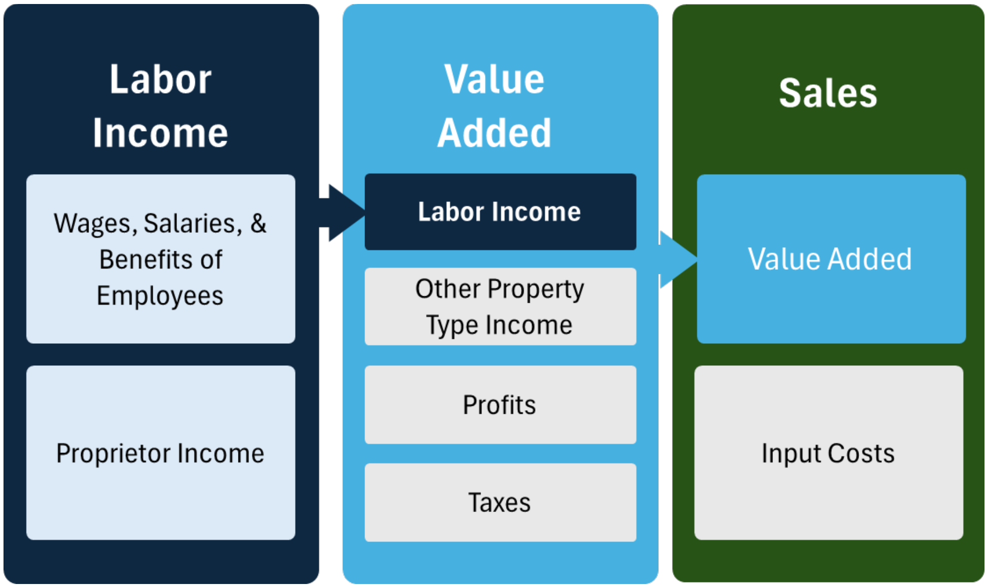
This study uses the IMPLAN input-output model (IMPLAN Group, LLC, 2024) to estimate the total (direct, indirect, and induced multiplier effects) contribution of small grains to Arizona's economy in 2024. Small grains sales are calculated by adding durum wheat and barley sales. Several modifications were made to the 2024 IMPLAN model to reflect Arizona's production patterns better. Appendix A offers detailed information on the adjustments made to the model, as well as all the assumptions and considerations.

Economic contributions are limited by a phenomenon known as leakage. Leakage occurs when a business purchases inputs or a household purchases consumer goods and services from outside Arizona. When this occurs, that spending has "leaked" out of the state economy, and the circulation of those dollars ceases, resulting in a dampening effect.

Economic contributions can be measured using a series of interrelated metrics. **Sales (or gross output)** is an intuitive measure analogous to the way we transact money in our day-to-day lives. While sales provide an easy-to-understand, cumulative measure of economic activity, it can double-count certain transactions that involve local use of locally sourced supplies. This is particularly the case within agriculture because many agricultural products are used as production input for other agricultural operations. One of the best examples is the use of locally produced feed crops by the dairy industry. One business' revenues are another's expenditures, leading to a double counting of the value of the feed when using sales or output as a measure of economic activity.

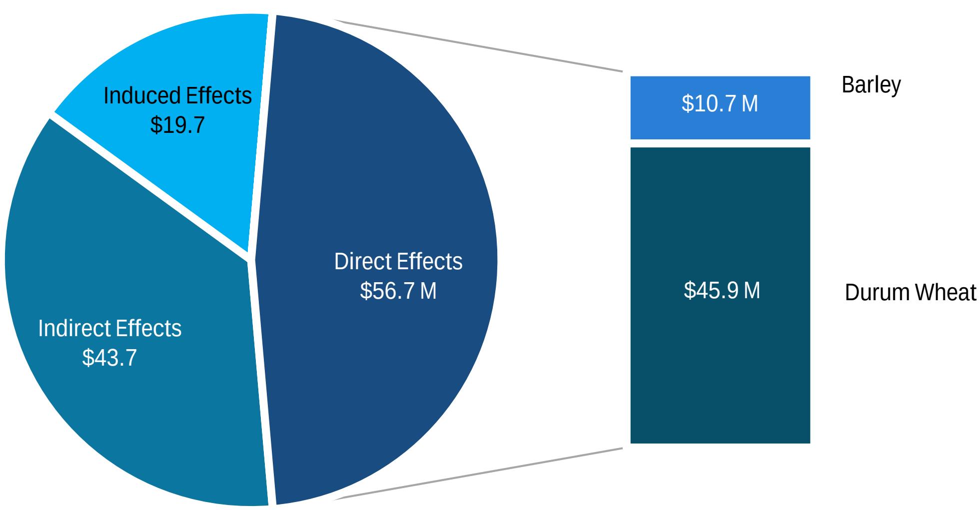
An alternative measure is **value added,** which measures the value created by an industry over and above the cost of inputs to production. It is analogous to gross domestic product (GDP) and only counts the net new value of production that occurs in an economy. Value added includes labor income, other property type income, profits, and taxes. Labor income can further be broken down into wages, salaries, and benefits paid to hired employees, as well as income to proprietors who own businesses. Figure 38 illustrates the relationship between sales, value added, and labor income. Because these measures are interrelated, they are not additive.

Figure 46. Components of Economic Output (Sales)



The total contribution of small grains farming to Arizona's economy in 2024 was more than $120 million in sales (output), including multiplier effects. Small grains production directly contributed $56.7 million in sales. Of the total, $45.9 million comes from durum wheat and $10.7 million from barley sales (Figure 39).

Figure 47. Economic Contribution of Small Grains to Arizona State Sales, 2024 (Sales, in Millions of 2024 USD)



Arizona's small grains production supported $26.2 million in labor income, including multiplier effects. The production of durum wheat and barley directly and indirectly supported 466 jobs, of which 149 jobs were directly in small grain production, and 316 were in other Arizona industries.

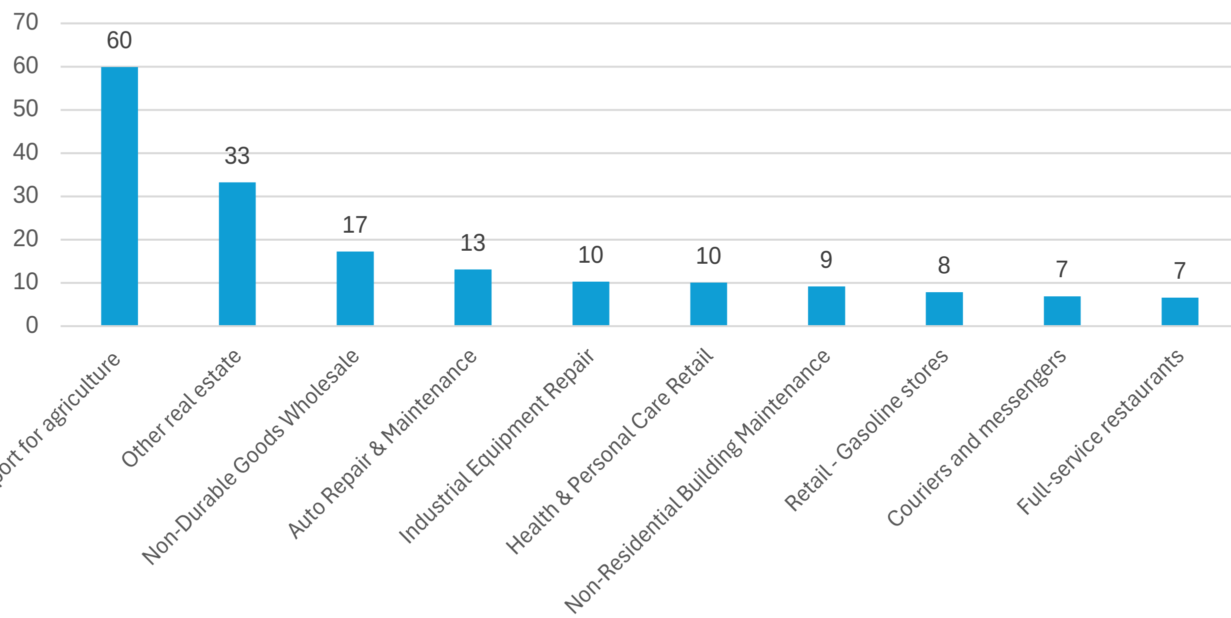
Including multiplier effects, the value added (Gross State Product) generated by small grains was nearly $54 million in 2024 (Table 20).

Table 20. Economic Contribution of Small Grains to Arizona's Economy, 2024 (in 2024 US Dollars)

Effect	Employment	Labor Income	Value Added	Output
Direct	149	$6,075,000	$17,170,000	$56,700,000
Indirect	219	$14,059,000	$24,255,000	$43,675,000
Induced	97	$6,083,000	$12,218,000	$19,651,000
Total	466	$26,217,000	$53,643,000	$120,026,000

The results show that the indirect and induced employment effects exceed the direct employment estimate. This is consistent with the nature of small grain production as capital and input-intensive rather than labor-intensive. Small grain farming relies heavily on purchased inputs, including fertilizers, chemicals, fuel, machinery services, and custom harvest operations, which generate economic activity and employment in upstream supplier industries (see Figure 48).

Figure 48. Top Industries by Employment Supported by Small Grain Farming in Arizona, 2024



The 2024 estimates reflect a year of relatively low small grain production and sales in Arizona (see Section 1). To provide a broader perspective, we also estimated the economic contribution using 2022 production and sales, and the 2022 IMPLAN model, as 2022 was a year with higher production levels and one in which both the activity data and the spending pattern modifications derive entirely from the 2022 Census of Agriculture. The resulting multipliers are stable across both years, particularly the output multiplier, which is identical at 2.1 in 2022 and 2024. Appendix B provides all the estimation details.

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Appendix A: Model Assumptions and Methodology

Estimating the economic contribution of small grains production in Arizona required modifications to the default 2024 IMPLAN model. The standard IMPLAN parameters are calibrated using national averages and do not adequately reflect the specific productive structure that characterizes Arizona agriculture. For this reason, the model was updated across all primary agriculture sectors.

Output (Sales)

Agricultural output by sector was estimated using 2024 ERS Cash Receipts data, cross-checked with USDA NASS production statistics, and AMS data. Table A1 presents the estimated output for each primary agriculture sector in Arizona.

Table A1. Estimated Sales of Primary Agriculture Sectors, 2024 (in 2024 US Dollars)

Primary Agriculture	Estimated Value
Grain farming	$100,591,000
Small grains (durum wheat and barley)	$56,700,000
Vegetable and melon farming	$1,386,919,000
Fruit farming	$77,748,000
Tree nut farming	$150,545,000
Greenhouse, nursery, and floriculture production	$214,073,000
Cotton farming	$148,401,000
All other crop farming	$778,154,000
Beef cattle ranching and farming, including feedlots and dual-purpose ranching and farming	$1,502,702,000
Dairy cattle and milk production	$1,057,906,000
Animal production, except cattle (including poultry and eggs)	$133,984,000
Total Primary Agriculture	**$5,551,023,000**

Value Added

IMPLAN value-added-to-output ratios were compared with those calculated directly from 2022 Census data. The Census ratio was constructed using the market value of production and total production expenditures from Table 75 of the 2022 Census of Agriculture, which provides expense detail by NAICS code at the state level. Where the two sources produced similar ratios, IMPLAN defaults were used. Where they are significantly different, the Census-derived ratio was used. Modifications were applied to grain farming, cotton farming, all other crop farming, beef cattle ranching, and dairy cattle production. Note that we assume that no significant changes in the production structure and functions occurred between 2022 and 2024, given that 2022 is the most recent Census data available.

Labor income was recalibrated using the expense shares reported by NAICS code in Table 75 of the 2022 Census of Agriculture. Proprietors' income (PI), other proprietor income (OPI), and taxes on proprietor income (TOPI) were calculated from updated output values using IMPLAN ratios, except for vegetables and melons and fruit farming, where the ownership structure in Arizona differs from the national pattern embedded in IMPLAN, as most of the farms are family owned (Duval et al., 2024).

Employment

Employment estimates for all the primary agricultural sectors were calculated using multiple approaches to cross-validate results. The primary approach used the 2024 Quarterly Census of Employment and Wages (QCEW) data, combining average employment figures with the number of establishments as a proxy for the number of farm proprietors. As a cross-check, total annual wages were converted to employee compensation using IMPLAN conversion factors. A third approach estimated employment by applying a modified production function to the updated output values and using IMPLAN to translate output into employment contributions. The three estimates were compared and reconciled before finalizing the employment figures used in the model (see Table A2).

Estimating the number of jobs supported directly by the small grains industry is challenging because employment data are aggregated by industry at a level slightly less detailed than needed to segment small grains from other grains' employment. Furthermore, employment data only reflects employment at establishments specializing in grain production. According to the Bureau of Labor Statistics, 20 individuals were employed in wheat farming (NAICS 11114) at 8 establishments in Arizona. Seventy-three (73) individuals were employed in all other grain farming (NAICS 11119), which includes barley. In total, there were 93 jobs in oilseeds and grain farming in Arizona in 2024 (QCEW, 2024). However, this estimate does not capture the jobs generated by the production of small grains in other types of farms. As mentioned previously, most of the state's small-grain production occurs on farms that specialize in other crops, such as vegetables, melons, and alfalfa hay. To account for the total number of jobs generated by the total small grain's output, we estimated the number of jobs using the customized 2024 input-output model, based on the value of production of small grains and the updated labor/output ratios. The industry generated an estimated 149 jobs, and this value was used for the economic contribution analysis.

Table A2. Job Estimates for Arizona Agricultural Industries

Primary Agriculture	Estimated Number of Jobs
Grain farming	265
Small grains	149
Vegetable and melon farming	5,773
Fruit farming	489
Tree nut farming	1,043
Greenhouse, nursery, and floriculture production	1,156
Cotton farming	598
All other crop farming	5,149
Beef cattle ranching and farming, including feedlots and dual-purpose ranching and farming	5,234
Dairy cattle and milk production	2,906
Animal production, including poultry and eggs	700
Total Primary Agriculture	**23,313**

Spending Patterns

Spending patterns for primary agriculture sectors were modified using production expense data from the 2022 Census of Agriculture, which provides itemized expenditure totals by economic sector. For the grain farming sector specifically, the Census spending pattern was validated through a structured comparison with four independent crop budget studies representing wheat and barley production in Arizona and California. Using the 2022 Census of Agriculture as a baseline, the primary budget sources used for the comparison were the Yuma County Durum Wheat and Barley, and the La Paz County Durum Wheat budgets published by the University of Arizona Cooperative Extension (Quintero et al., 2025; Quintero, 2026), and the second was the Sacramento Valley Irrigated Wheat budget published by the UC Davis Agricultural Issues Center (Mathesius et al., 2016).

Each source's expense share was calculated as a percentage of the total reported cost for that source to preserve the real weight of each item within each source's full cost structure and to avoid distortions from differing levels of cost disaggregation across sources. Table A3 presents the results.

Table A3. Comparison of Grain Farming Expenses Across Four Data Sources.

Expense	AZ Census Grains (2022, $1,000)	Yuma Durum Wheat (2026, $/acre)	Yuma Barley (2026, $/acre)	La Paz Durum Wheat (2024, $/acre)	SAC Valley Wheat (2016, $/acre)	Items included
Total	$83,129	$1,066	$931	$1,256	$1,034	Total reported cost
Fertilizers	15.8%	16.5%	14.8%	29.02%	8.1%	Fertility program, spreader, injection system
Seed	7.6%	6.9%	5.0%	2.19%	9.1%	Seed costs only
Chemicals	7.4%	2.4%	5.0%	3.53%	2.1%	Herbicides, insecticides, fungicides
Utilities	10.6%	12.6%	12.1%	15.28%	4.3%	Electricity and water
Hired labor	13.1%	15.5%	15.6%	14.10%	8.1%	Hired farm labor, irrigation labor, and operation labor
Fuel & machinery	16.5%	7.7%	7.8%	7.33%	7.7%	Fuels/oils and repairs & maintenance; machinery; fuel, lube, repairs
Harvest & hauling	4.6%	8.7%	9.7%	11.19%	2.9%	Harvest custom and hauling custom
Cash land rent	11.3%	23.5%	26.8%	13.49%	5.8%	Annual cash rent; share rent 20% on 50% acreage

Based on this comparison, the Census spending pattern for the grain farming sector was used as the primary basis for the model. While the expense categories are not perfectly consistent across all sources (which is expected given differences in geography, crop mix, farm size, and cost disaggregation), the overall structure of production costs is similar. Hired labor and utilities show the strongest alignment across all Arizona sources, ranging from 13–16% and 11–15% of total costs, respectively. Fertilizers are consistent between the Census (15.8%) and the Yuma budgets (14.8–

16.5%), with La Paz as an outlier due to the use of a more expensive nitrogen source at $360/acre. The most notable divergences are in cash land rent, which is substantially higher in the Yuma per-acre budgets (23–27%) than in the Census aggregate (11.3%), consistent with Yuma County ranking first in cash rental rates for irrigated agricultural land among all counties in the Colorado River Basin and 15th nationally in 2022 (Duval et al., 2024). The Sacramento Valley budget, included as an external reference, shows a similar cost distribution for the categories most comparable across sources.

These shares were used to adjust the default spending patterns of the 2024 IMPLAN model. This adjustment assumes that the structure of production expenditures did not change significantly between 2022 and 2024, an assumption supported by the stability of input cost shares observed across the budget sources reviewed.

Economic Contribution Analysis

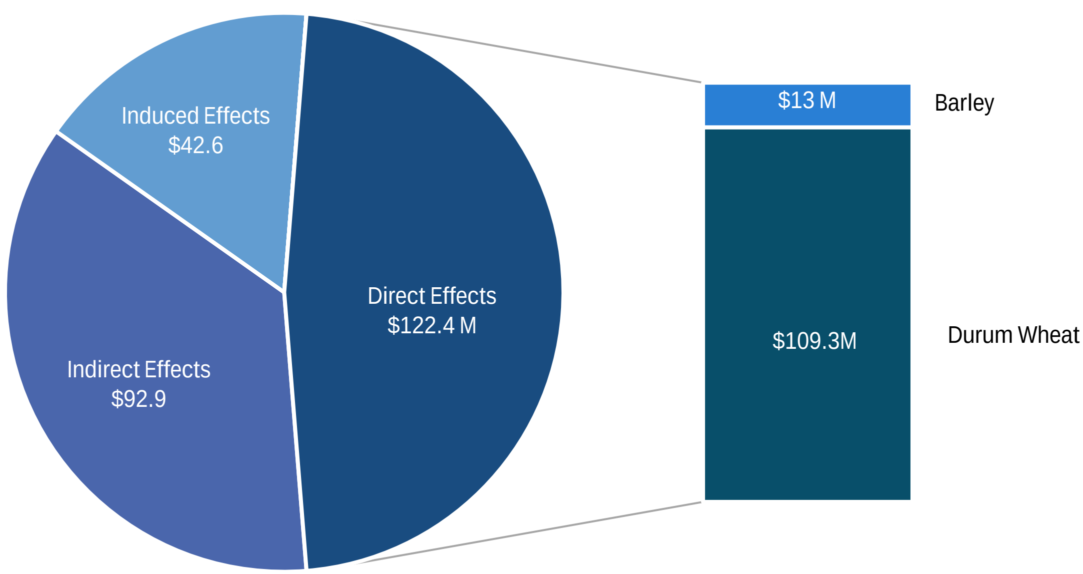
After the customization of the model, we apply the economic contribution analysis to grain farming, using the estimated output of small grains only. To avoid double accounting, the Regional Purchasing Coefficient (RPC) of Grain Farming was set to zero. The results are expressed in 2024 dollars.

Appendix B: Sensitivity Analysis

The economic contribution estimates presented in this report are based on 2024 sales and employment data. Since production and cash receipts of small grains have declined in recent years (see Figures 2 to 5), we also estimated the economic contribution for the year 2022, with the objective of comparing the resulting multipliers and providing a series of benchmarks, observing year-to-year variability in production and cash receipts.

To do this, we used the 2022 IMPLAN model, customized using the 2022 Census of Agriculture and following the most recent statewide agricultural economic contribution (Montanía et al., 2025). According to Figure B1, in 2022, the total contribution of small grains farming to Arizona's economy was estimated at $257.9 million (output), including multiplier effects. Small grains production directly contributed $122 million in sales. Of the total, nearly $110 million was from durum wheat and $13 million from barley sales

Figure B1. Economic Contribution of Small Grains to Arizona State Sales, 2022 (Sales, in Millions of 2022 USD)



In 2022, Arizona's small grains production supported $55.9 million in labor income, including multiplier effects. The production of durum wheat and barley directly and indirectly supported nearly 970 jobs, of which approximately 286 jobs were directly in small grain production, and 683 were in other Arizona industries. Including multiplier effects, the value added (Gross State Product) supported by small grains was nearly $113 million in 2022.

Table B1. Economic Contribution of Small Grains to Arizona's Economy, 2022 (in 2022 US Dollars)

	Employment	Labor Income	Value Added	Output
Direct	283	$15,126,000	$38,537,000	$122,404,000
Indirect	458	$27,666,000	$49,527,000	$92,999,000
Induced	225	$13,149,000	$24,923,000	$42,570,000
Total	966	$55,941,000	$112,987,000	$257,973,000

Table B2 presents the comparison between the multipliers obtained through the two customized models. The resulting multipliers are consistent across both years. The output multiplier is identical at 2.1, and the value-added multiplier differs by only 0.2, providing confidence in the robustness of the model structure. The remaining multipliers are of comparable magnitude, and any differences are expected, given the methodological distinctions between the two model versions rather than reflecting instability in the underlying economic relationships. Note that the 2022 IMPLAN model includes 543 industries, while the 2024 model is composed of 528 industries.

Table B2. Comparison Between Multipliers (2024 Model vs. 2022 Model)

	2024 Multipliers	2022 Multipliers
Employment	3.1	3.4
Labor Income	4.3	3.7
Value Added	3.1	2.9
Output	2.1	2.1