Watering the West: Exploring Agricultural Water Use in the Colorado Basin States

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Abstract

Water resources in the arid western US are under pressure, especially within the Colorado Basin states. Excluding thermoelectric withdrawals, these seven states account for nearly a third of all water withdrawals in the contiguous United States, with over three-fourths of this water going toward agriculture. Agricultural water use footprints and flows through the system were characterized using a variety of datasets from the United States Department of Agriculture (USDA), the United States Geological Survey (USGS), and the Bureau of Land Management (BLM), revealing that the majority of irrigation water in the Colorado Basin goes toward vegetables (10.4%), orchards (27%), and especially animal feed crops (53.5%) (i.e., hay, corn grain, corn silage, pasture, and soybeans). Outside California and Arizona, animal feed crops account for 72% of irrigated acreage and 44% of water usage within the basin. Furthermore, it was determined that most basin states are reliant upon feed imports, especially California. This investment in water yields 35.34 billion kilograms of animal products, amounting to 28% of milk, 15.5% of beef, 8.6% of egg, 3.1% of chicken, and 1.8% of pork production in the US. A 20% reduction in the two major feed crops, hay and corn silage, could reduce water consumption in the basin states by over 4 million acre-feet, which is sufficient to satisfy long-term Colorado River conservation needs, at the cost of under 9% of milk and beef production. Moreover, re-orienting production to higher value horticultural crops could increase farm sales while lowering water use.

Keywords: Colorado Basin, agriculture, irritation, animal feed

1 Introduction

Much of the American West is dependent upon Colorado River water, yet consumptive use typically exceeds natural water flows. Moreover, Lake Powell and Lake Mead, the two major reservoirs for Colorado River water, have been in decline since the onset of a long-term drought, dating to the year 2000 [28]. Thus, if water use in this area remains the same, the unlikely occurrence of multiple subsequent years of wetter conditions will be required in order to refill Lake Powell and Lake Mead as well as the basin [23]. Indeed, falling water levels in Lake Mead triggered the first mandatory cuts to water withdrawals in 2021, while a consensus proposal was announced in May 2023 to cut river water withdrawals by 3 million acre-feet through 2026. Given the near certainty of a future of long-term curtailments in river water use, it is essential that all Colorado Basin actors be aware of where their water is going, and what it is getting in return [27].

The most significant source of water for this region is the Colorado River. This resource has a rich history of providing water to Native tribes in its surrounding areas; however, the Colorado River Compact of 1922 would forever change the river's use [2, 15]. The agreement separated the Colorado Basin into upper (Nevada, New Mexico, Utah, Wyoming) and lower (Arizona, California, Nevada) sections, allocating each 7.5 million acre-feet of the river's water, which is generally agreed to be an unsustainable number [27]. This compact was later adjusted in 1964 to allocate based on specific states instead of general regions alone, granting 4.4, 2.8, and 0.3 million acre-feet to California, Arizona, and Nevada, respectively [2].

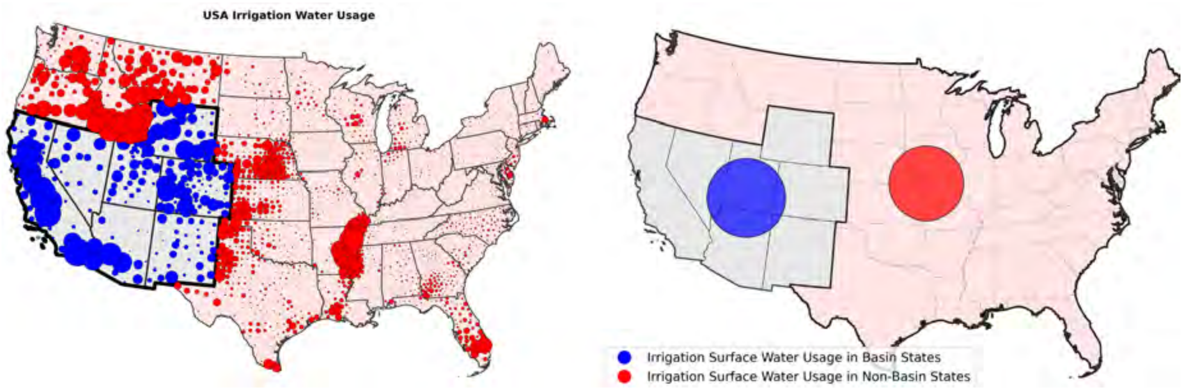

Figure 1: The left panel shows total 2015 irrigation water usage (Maf/yr) by county, based on USGS data [16]. Dot size scales with irrigation water usage, with Colorado Basin counties highlighted in blue and remaining counties in red. Note that the Colorado Basin states account for 40.5% of total irrigation water in the contiguous US. The right panel compares irrigation surface water (Maf/yr) in the Colorado Basin states to the rest of the contiguous US. Note that the Colorado Basin states are responsible for 45.5% of total irrigation surface water in the contiguous US [16].

Recently, the government has discussed cutting back on Colorado River allocations to southwestern states. Originally, it was planned to reduce water allocations to the Lower Basin states (California, Nevada, and Arizona) by 2 million acre-feet. However, this plan has been adjusted with the Lower Basin states practicing self regulation in order to save a total of 3 million acre-feet by 2026. An official decision is to be decided by the end of this year.

Water resources in the US are projected to be increasingly stressed in the coming decades due to population growth, economic expansion, climate change, and shifting rainfall patterns. If these projections prove accurate, the Colorado Basin states may be disproportionately affected, due to their heavy reliance on ground and surface water resources [17]. Water use in the western US is dominated by irrigation for agriculture, and irrigation withdrawals are overwhelmingly concentrated in the West in general. In particular, the seven Colorado River Basin states (Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) account for a large proportion of overall irrigation water as well as nearly half of all irrigation surface water as illustrated in Figure 8.

Within the Colorado Basin itself, major irrigated crops include orchards, hay, corn, vegetables, cotton, wheat, rice, barley, sorghum, beans, and soy. Of major crops, almost 90% of total irrigated acreage is devoted to hay, vegetables, orchards, and corn (including both grain and silage). Hay alone accounts for about 40% of irrigated crop acreage [6]. In addition, irrigated pastureland is also a substantial user of water in the basin states [24]. Irrigated agriculture, especially the irrigation of animal feed crops, is currently a significant driver of river flow depletion in the western United States [21]. Across the western US, the most produced crop by far is hay and haylage, with over 234 million tons [6] being produced per year in the Colorado Basin alone. Note that this crop is solely produced for animal feed and is not directly consumed by humans.

Richter et al. [21] estimated that cattle feed crops are responsible for the majority of river water consumption in the western United States, implying that beef and dairy production is a dominant driver of water shortages in the West. These authors argue for reducing cattle feed production to alleviate water stress, also implying that long-term water sustainability will require less beef consumption.

It is widely observed in literature that animal production represents an inefficient conversion of land, energy, and water resources to an edible product, with human-consumable calories constituting a large proportion of animal feed [25, 8]. Moreover, much land that is devoted to feed could be used for human-consumable crops. Conversion efficiencies in terms of energy and protein fed and retained in final animal products were examined at the scale of the total US by Shepon et al. [25]. They found that beef is by far the least efficient protein source, retaining only about 3% of feed energy and protein in the final product, while dairy, eggs, poultry, and pork had efficiencies on the order of around 10%. Across studies, [19, 13, 20], beef is uniquely inefficient in converting feed to edible product, with beef cattle requiring far more feed per unit of edible weight than other livestock [19].

These results support the general idea that a dietary shift away from beef toward other animal products, and especially plant-based foods, could increase agricultural efficiency and spare large amounts of inputs, including land, fertilizer, energy, and water [20]. The water footprint of beef and other animal products has been previously examined, but typically at national scales without sub-national regionalization. Broom [9] compared land and water usage across four model beef production systems, finding large variations in the irrigation requirements. Thus, the irrigation footprints of animal products are likely highly variable, with many existing estimates having limited applicability to the American West. It is notable, however, that Sawalhah et al. [22] recently calculated the water footprint of rangeland beef in New Mexico to be 28,203 liters per kilogram of meat (3,379 gallons per pound), of which 18% is blue water and the remainder green water.

Given the long-term need to reduce water consumption in the Colorado Basin states and the fact that most such water is used for irrigation, especially irrigation for cattle feed crops, we sought to extensively characterize the water footprint and detailed final outputs of agriculture within this region. In addition to compiling overall irrigation estimates by county, we estimated irrigation rates for individual crops at both state and county level from a combination of the 2013 USDA Irrigation Survey [24], the WATNEEDS model [11], and USGS [16] data. This allowed a highly detailed characterization of the water footprint of all major crops by state.

In addition, we tabulated animal product production across the basin from a combination of USDA Census, Survey, and Slaughter Report data [6]. With this, we were able to estimate total feed requirements from forage (pasture, hay, corn silage) as well as corn grain and soymeal by state. We also estimated total feed production across private pastureland, BLM public grazing allotments, and feed crops, determining that the basin states are not self-sufficient in feed and require significant imports of corn grain, soy, and forage. Moreover, we provide a thorough characterization of the flow from feed crop to final animal product for the basin as a whole.

We calculated the per-unit water impact of different crops and animal products as well as potential water savings from simple shifts in production. Overall, we found that feed crops are the greatest users of water in the basin, going almost exclusively toward cattle feed; although, high-value orchard and vegetable crops are also major water users, especially in California and Arizona. Reducing hay and corn silage irrigation by 5% would save well over 1 million acre-feet of water per year, meeting short-term water conservation goals, but at a cost of about 2% of milk and beef production. More ambitious decreases of 20% would meet longer-term goals at a modest cost to the basin and overall US agricultural output.

2 Methods

2.1 Overall Agriculture and Water Characterization

Data on total harvested acres, irrigated harvested acres, and production for major crops was obtained from the 2017 USDA Census of Agriculture [6]; this data was available for all states and most counties. Irrigation and other water withdrawal totals at county scale were obtained from the USGS [16]. All production data was converted to kilograms, and all water withdrawal data was converted to millions of acre-feet per year. Total harvested land, production, and water withdrawals were compared between the seven basin states as well as to the rest of the contiguous US (see Figures 2 and 6 in Results). Irrigated pasture acreage was not generally available from the USDA Census of Agriculture, so we used 2013 estimates (state-level only) from the 2013 USDA Irrigation Survey [24]. Note that we considered the following crops/crop categories in further detail: barley, corn (silage and grain), hay, orchards, rice, sorghum, soy, vegetables, and wheat. Additionally, data on BLM grazing allotments, including permitted animal unit months (AUMs) and allotment polygons were obtained from the BLM Rangeland Administration System Reports system [1].

2.2 Climate Data

Mean temperature and precipitation for the year 2015 in all US counties was obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate at a Glance: County Mapping dataset [18].

2.3 Crop and Location-Specific Irrigation Rates

Crop and state/county-specific irrigation rates were estimated using several methods. First, we attempted a purely statistical approach using county-scale data. Predictors included 2015 irrigated acreage for all major crops, 2015 mean annual temperature, and 2015 mean annual precipitation, while output was total irrigation water. Linear regression and random forest regression models were trained, and the latter gave excellent in-sample predictions (see Figure 5). Crop acreages were then doubled and predicted irrigation totals were examined in order to infer county and crop-specific irrigation rates. Unfortunately, implied rates were not plausible, in many cases being negative or orders of too large magnitude.

As a result, we instead combined 5 arcminute resolution gridded estimates of annual blue water requirements for irrigated crops from the WATNEEDS model [11] and the 2013 USDA Irrigation Survey [24] to estimate irrigation rates. The WATNEEDS model provided estimates for 23 crops and 3 crop categories. When a crop was not represented exactly, the following surrogates were used: (1) “Citrus” was used for all orchard crops, (2) “Fodder grasses” was used for all hay, (3) ”Barley” was used for oats, and (4) “Others annual” was used for vegetables.

Mean irrigation requirements (in feet of water) in the WATNEEDS dataset for each county and each state were calculated; if no irrigation in a county was recorded, the state average was used. If no irrigation of a crop for a state was recorded at all, the crop/state pairing was excluded. WATNEEDS blue water requirements are reasonably similar to irrigation rates recorded by the USDA, but are somewhat larger on average, with irrigation rates for wheat and vegetables in particular somewhat higher than observed (even when increasing USDA rates by 33%, as below).

Therefore, the WATNEEDS estimates were normalized such that the state mean from WATNEEDS equaled the USDA Irrigation Survey value. Each county estimate was then scaled in proportion to the deviation from the state mean. In the absence of county-level estimates for blue water requirements in irrigated pastureland, state-level figures were adopted on irrigated pastureland area and rate directly from the USDA. Finally, total predicted irrigation water applications were compared across the basin states to withdrawals reported by the USGS, with the former found to be about one-third lower. Therefore, all crop irrigation rates were crudely adjusted upward by 33%. Note that the USDA Irrigation Survey provides irrigation rates and acreages for alfalfa hay and other hay as separate categories. Since hay is treated as a lumped item elsewhere in this work, irrigation rates for alfalfa and other hay were weighted by irrigated acreage to obtain a single rate for all hay.

We estimated both live and edible animal product production across the US in 2017 for eggs, milk, beef cattle, poultry, and pigs. Total slaughtered live weights in 2017 of cattle, poultry, and pigs were obtained from the USDA Slaughter Reports [7]. Totals were tabulated for all states when possible; however, several states had missing data.

2.4 Animal Production

In order to analyze the feed requirements of animal agriculture in the Colorado Basin, state level data was extracted from the USDA Economics, Statistics, and Market Information System Slaughter Reports [7].

This data included crops grown in the state, layers and broilers in the state, and the number of livestock in the state. Note that in order to protect the privacy of several local farmers, pieces of data were withheld in these categories; consequently, estimates from previous censuses were used in order to fill the missing data. In addition to this data, 2017 animal agriculture production data was drawn from the USDA Economics, Statistics, and Market Information System as well as USDA Quickstats in order to determine the total live weight of animal slaughter (in lbs) and milk production (in lbs)[14, 7].

Cow and pig slaughter report data was incomplete for several contiguous states. In response, information for these states was taken from the available slaughter reports closest to the year 2017. For cow report data, the 2015 USDA slaughter reports were used for Minnesota and Oregon, the 2013 slaughter report was used for Georgia, the 2003 slaughter report was used for Illinois, and the 2022 slaughter report was used for Iowa. For pigs, the 2015 slaughter report was used for Arizona and Mississippi, the 2014 slaughter report was used for North Carolina, South Dakota, and Virginia, and the 2007 slaughter report was used for Kansas and Kentucky. In addition, chicken slaughter liveweights were withheld for half of the states; as such, predictions of slaughter numbers were made based on USDA census broiler headcounts and average chicken weight at death (a factor of 35) [6].

Egg estimates were also extracted from the USDA census data where the number of layers was multiplied by a conversion factor of 3/4 (average number of eggs per day) [6]. Previous years were used to fill in missing data points for states where this information was withheld. When this was not possible, however, the USDA census information on the number of operations that had different ranges of layer chickens was used to calculate a low estimate of possible egg numbers per year, which we believed was better than no estimate. In the case of Arizona, we used an estimate of 9 million layers owned by Hickman's Egg Farm, the largest producer of eggs in Arizona, from a local paper [29]. In order to convert the number of eggs produced to weight, we multiplied the average weight of an egg (0.06 kg) by the total number of eggs in each state.

2.5 Animal Feed Requirements

In order to analyze the efficiency of water use with respect to animal agriculture, we needed to calculate the water intake of each animal. To achieve this, we needed to know the amount of feed each animal consumes. Caloric estimates of animal needs, specifically feed intake and metabolizable energy estimates, were used from Shepon et al. [25]. To calculate forage estimates, USDA and BLM data for pastureland acres and animal unit months was used. For our best estimate of total forage in the US, production assumptions were necessary; we assumed one ton of feed per acre production for the USDA grazed cropland data, 0.25 of a ton of feed per acre for BLM data, and 900 lbs of feed per animal unit month. These were added to create a general forage estimate [19][25] [1]. High and low estimates were done for forage; however, this did not change overall results significantly, so a factor of 0.25 tons was used to convert from private pastureland to production for all further calculations. This data was used for determining a best guess estimate of caloric and protein requirements for cattle in each of the basin states.

We used a system of equations in order to approximate corn and soy requirements (in kg) since broiler, layer, and pig diets generally consist of a majority of corn and soy. Using estimates from Peters et al.[19], it was possible to include corn and soy diet approximations for beef and dairy cows as well. This was possible through the use of information on the metabolizable energy each kilogram of corn and soy produced as well as by using estimates from Shepon multiplied by our calculated live weights and metabolizable energy they require for each kilogram of live weights. These estimations were used to approximate the total corn and soy requirements for animal agriculture across the United States. Note that Delaware and Maryland were combined into one category as well as the New England states (Connecticut, Maine, Massachusetts, New Hampshire, and Vermont) due to beef and chicken slaughter live weights being given as totals of these areas. These results were compared against the Commodity Flow Survey net exports for feed products to ensure accuracy [10].

The Commodity Flow Survey from Census Bureau provided data commodities weight shipped across the United States. Two sections of commodity products were used, such as Cereal Grains, including seed (02) and Animal Feed, Eggs, Honey, and Other Products of Animal Origin (04). In order to find the export for certain states, we set the origin state as the target state and excluded transport within the state. Similarly, import data was gathered by setting the destination state as the target state. The total weight of import subtracted from the total weight of export gave the net exports of cereal grains, animal feed, and products of animal origin for each state. A negative net export shows the amount of animal feed and product of animal origin imported from other states while a positive net export shows the amount that the state exported to other states.

In order to compare the cattle energy requirement (in kcal) with poultry, pig, and egg feed requirements (in kg) in the Colorado Basin states, we needed to convert cattle energy requirement to feed requirement (in kg). Assuming that all production of hay, corn silage, and pasture in the Colorado Basin states goes toward cattle feed, we used the proportion of each cattle feed crop multiplied by their conversion factor of metabolize energy [25]. The sum of these provided an average conversion factor of 2203 kcal/kg from energy requirement to feed requirement in the basin states. From there, we used the total energy requirement for cattle divide by the energy conversion factor to get the feed requirement for cattle in kilograms.

2.6 Sankey Flow Chart

A Sankey flow chart was created to visually depict the complex process through which water indirectly transforms into edible kilograms for human consumption (refer to Figure 8 in Results). On the left, we give total mass (in kg) of major agricultural products harvested at the crop phase, including orchard, vegetable, and different feed crops as well as estimated forage produced by pasturelands. The rightmost elements give final human-edible weights (in kg). The intermediate flows depict the flux of feed mass to animal liveweight and final edible weight (in kg). Note that for cattle, all pasture, hay, and corn silage is aggregated to the lumped category, "forage feed." Corn feed is the sum of locally produced corn, as well as estimated imports; soy feed is similar. These base feed categories are then distributed to "cattle feed," "pig feed," "chicken feed," and "egg feed." Cattle feed in turn is divided between milk and beef.

These fluxes were determined from the feed requirements determined in Section 2.4 of Methods, and the agricultural production data presented in Section 2.1 of Methods. To more fairly compare milk to other animal products, we adjusted for the fact that milk is much more dilute. Fat and protein-corrected milk has a digestible energy content of roughly 700 kcal per kg, while beef is 2500 kcal per kg. Therefore, we created an adjusted milk category that was fourfold smaller than the physical milk output. Thus, the adjusted milk category is equivalent to beef on an energy per weight basis, making for a more fair comparison.

While analyzing the production of orchards and vegetables, the 2017 USDA Census did not provide production weights for these crops. To overcome this limitation, we used USDA data giving total fruits, tree nuts, and vegetables production (in weight) at the national scale [3, 4]. To obtain the fraction of orchards and vegetables harvested in the basin states, we divided the acreage of harvested orchard and vegetable crops in the seven states by the total amount of acres of the same respective categories in the whole contiguous US. These percentages were then multiplied by the total weight of orchard and vegetable production to estimate the production of each state in the basin. Based on the USDA's statement that over 90% of tree nuts are harvested in California [5], we were able to multiply this percentage by the total weight of nuts produced in the nation to obtain the quantity of nuts produced in kilograms in California as well as fruits in the basin states by subtracting the new weight of nuts from the weight of orchard production.

3 Results

3.1 Overall irrigation footprint

Based on USGS figures [16], total irrigation water for the seven basin states sums to a total of 53 million acre-feet, while irrigation in the rest of the contiguous states amounts to 78.3 million acre-feet. However, the basin states account for only 8.5% of total harvested cropland in the contiguous United States, and 19.5% of crop sales by value [6].

3.2 Irrigation and Cropping Patterns within the Basin States

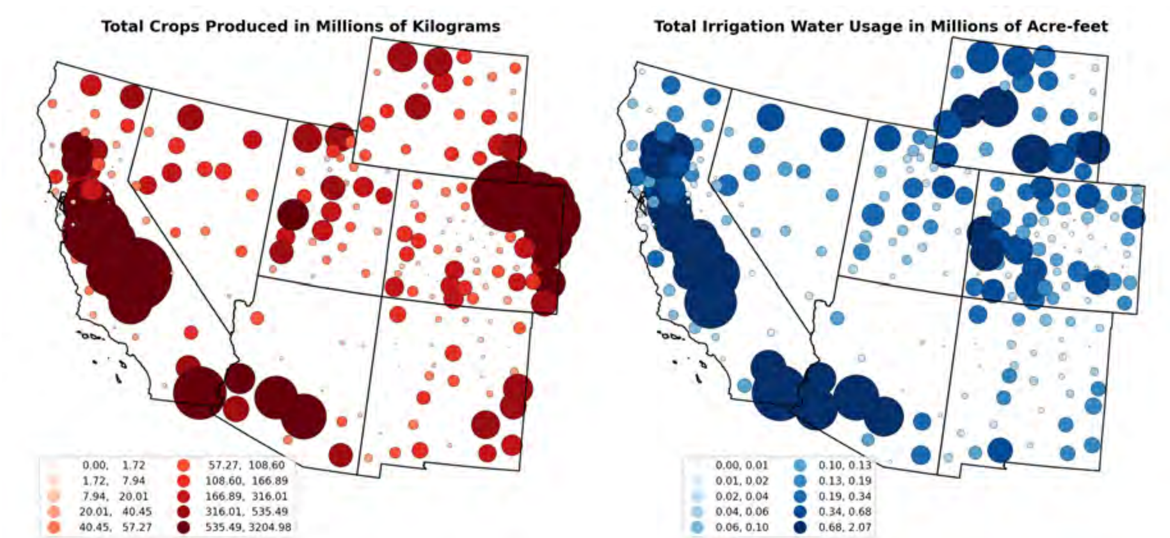

Figure 2: The left panel shows the comparison of county level crop production (kg) in 2017. The right panel shows the comparison of statewide crop irrigation (af/yr) in 2015. Note that bubble size scales with each respective total per county. Data was gathered from the USDA [6] and USGS [16] respectively.

Spatial patterns for total county-level irrigated cropland were characterized alongside total irrigation water [16, 6]. In general, there is a strong visual correlation between these two metrics, as illustrated in Figure 2. However, notable exceptions include parts of Wyoming and Colorado, particularly the northeastern region of Colorado.

3.3 Agricultural Crops and Water Usage

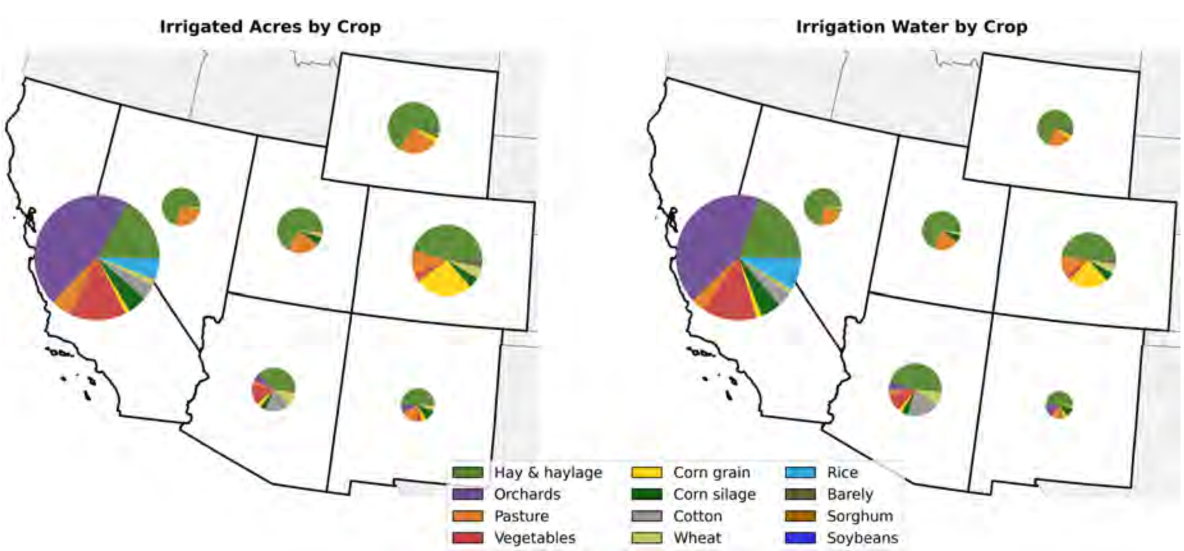

Figure 3: The left panel shows 2017 proportions of irrigated acres separated by crop. The right panel shows 2015 proportions of irrigation water use separated by crop. Note that pie chart size scales with each respective overall total per state.

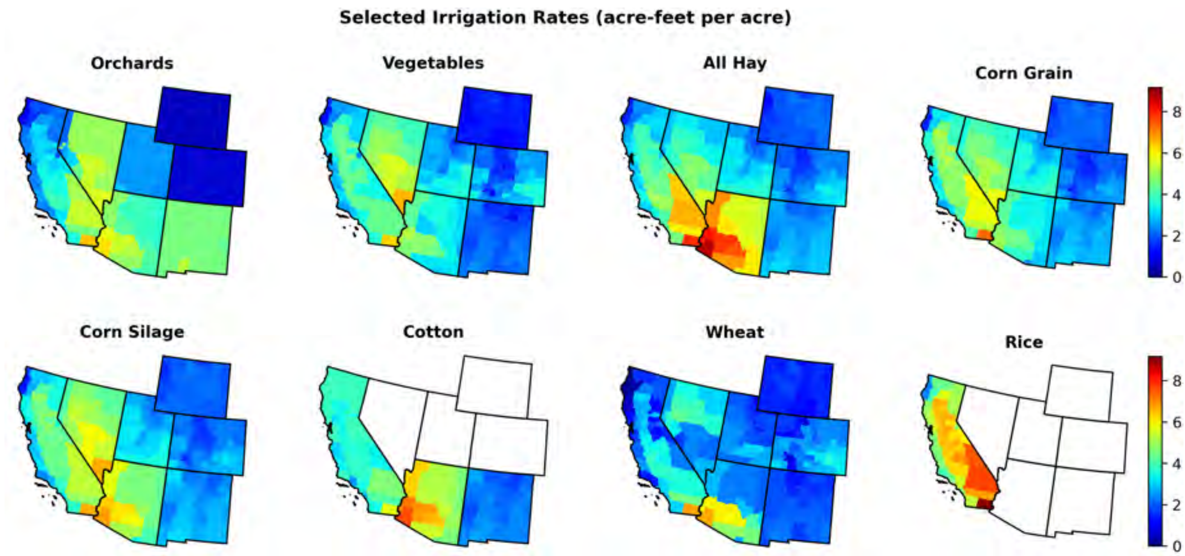

Figure 4: Calculated county and crop-specific irrigation rates for eight selected crops (in acre-feet).

California is a clear outlier in terms of both irrigated acreage and water use, contributing to 39.74% of total irrigation water and 52.17% of irrigated acres in the basin. Colorado comes in second place in both categories, making up 16.8% of irrigated acres and 11.31% of irrigation water in the basin. Figure 3 depicts the relative acreage and water withdrawals for each state disaggregated by major crop, inferred from state-level irrigation rates described below. Hay and haylage account for the vast majority of land and water in all states except California, where orchard crops are dominant.

3.4 Crop and Location Specific Irrigation Rates

As described in Methods, crop-specific irrigation rates were estimated for each county and state using a combination of results from the WATNEEDS model [11], the 2013 USDA Irrigation Survey [24], and 2015 USGS water withdrawal data [16]. County-level irrigation rates for eight representative crops are depicted in Figure 4. Irrigation rates were generally highest in the southwestern parts of Arizona and California, and lowest in Wyoming. Hay, which is predominantly alfalfa hay in the basin states, was consistently irrigated at higher rates than most other crops.

3.5 Forest Regression Model

Figure 5 depicts the results of the county-level random forest regression. As stated in Methods, the model shows significant correlation with regard to average temperature, average precipitation, and individual crop harvest to total irrigation water in a region, having an R^2 value of 0.95. Unfortunately, further analysis of the model revealed unlikely if not impossible results such as doubled production of a certain crop reducing the amount of irrigation water used. As such, this model was not extensively used.

3.6 Crop Value

As shown in Figure 6, analysis of 2017 crop sales reveals that hay is by far the most produced crop yet one of the least valuable crops. A similar trend can be seen in corn, wheat, and rice. In contrast, crops that are grown for human consumption such as fruits, nuts, and vegetables, all see significant increases in their value when compared to production. This indicates that the majority of land and water goes toward crops that are not substantially profitable on their own.

3.7 Animal Production

It was found that the Colorado Basin states were responsible for 15.5% of the United States production of beef in 2017, with Colorado responsible for half of the basin states total. In addition, the Colorado Basin states produced 27.4 billion kgs of milk, accounting for 28% of the United States dairy production with California alone yielding two-thirds of the basin's dairy production. In contrast, the basin states yielded smaller shares

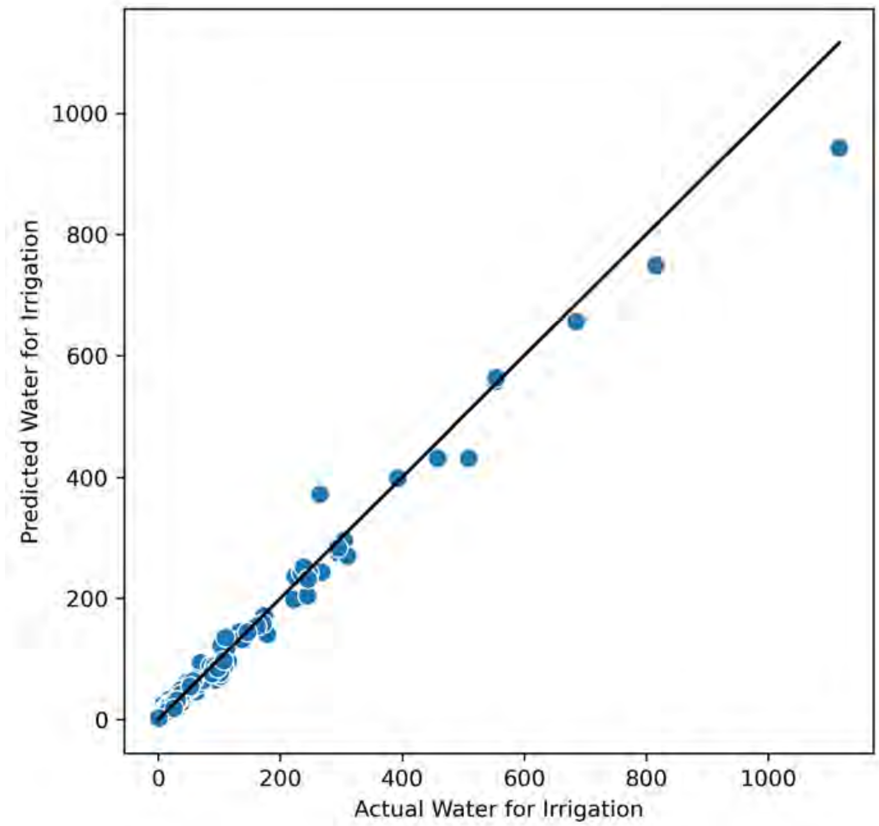

Figure 5: The county-level forest regression model for total irrigation water (af/yr), comparing actual irrigation water used per county [16] to the estimated irrigation water use created by the model using average county-level temperature (in Fahrenheit), precipitation (in inches), and individual crop harvests (in acres).

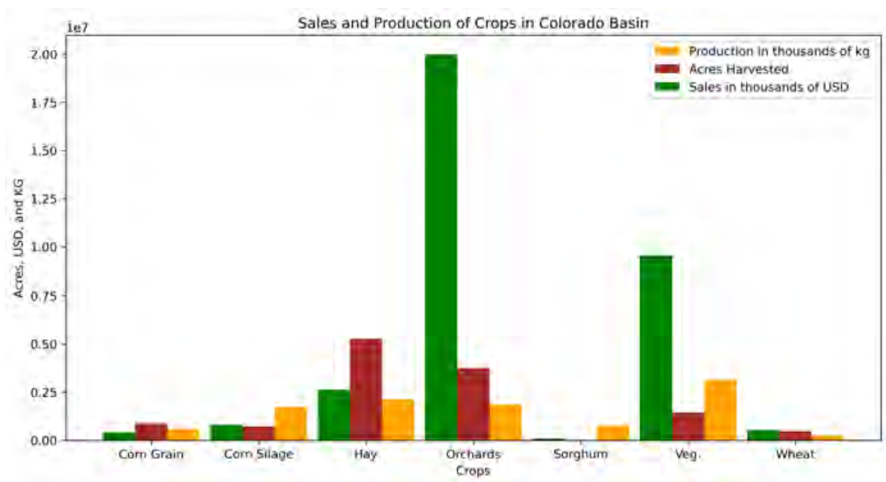

Figure 6: Total 2017 crop production (acres) and sales (USD) of the top crops in the Colorado Basin.

in production for eggs, chicken, and pork, producing 8.6% of the eggs, 3.1% of the chicken, and 1.8% of the pork produced in the US as shown in Table 1.

	AZ	CA	CO	NV	NM	UT	WY	All Basin	US	Basin Fraction
Cow	345.16	803.54	1575.98	0.82	1.803	387.71	2.62	3117.64	20060	0.1554
Milk	2287.73	18090	1904.09	322.27	3732.72	1006.82	62.82	27406.45	97945	0.2798
Chicken	0.07	703.68	1.78	0.018	0.092	0.154	79.69	785.49	25124	0.0312
Pig	0.22	271.63	2.29	0.14	0.32	473.54	0.52	279.87	15221	0.0183
Egg	131.4	233.15	74.52	0.26	1.67	73.59	0.48	515.09	5967	0.0863

Table 1: Animal production by individual states, the Colorado States in lump, and the United States in million kg. The last column shows the fraction of animal production in the Colorado Basin States compare to the United States.

3.8 Feed Requirements and Imports/Exports

As explained in Methods, we found that the Colorado Basin States produced 80.09 billion kg of forage (hay, corn silage, and pasture) and required 83.69 billion kg of forage for cattle feeds. This shows that the Colorado Basin states need to import around 3.6 billion kilograms of forage from other states in order to satisfy the need of cattle feed.

Overall, the Colorado Basin states require 45% more corn than they produce for their animal agriculture industry. California only produced 6% of its corn requirements while Colorado and Wyoming produced 25% and 86% more corn than what they needed, respectively. California grew less than 1% of the necessary soy requirements needed to sustain its animal agriculture, likely importing the deficit from the midwestern states. All other states grew either no soy or negligible amounts with regard to respective soy feed requirements.

3.9 Animal Feed

In analyzing animal feed requirements, we found that the Commodity Flow Survey results roughly matched the estimation of corn and soy production deltas (see Figure 7). This highlights that the majority of the Colorado Basin states are not fully self-sufficient in producing animal feed and instead must import the necessary feed from midwestern states.

Note that Colorado and Wyoming produce enough corn but not enough soy to feed their pigs, layers, and broilers. In contrast, all remaining Colorado Basin states are in deficits for both corn and soy. Due to how the caloric and protein requirements were estimated for cattle in each state, it was not possible to separate the data by crop with the same level of certainty as for corn and soy due to variations in feed ratios (i.e. some cows are pasture finished before slaughter while others are feed finished with corn and soy meal).

Regardless, it was possible to find whether each state can meet general caloric and protein requirements for its cattle and dairy production. This shows that some of the basin states, although calorically sufficient, do not meet the necessary protein requirements for their cattle and dairy production; these states included Arizona, New Mexico, and Utah. Overall, the Colorado Basin states have an energy deficit of 8.028 trillion kilo-calories and protein deficit of 8.7 billion kilograms for cattle and diary production.

3.10 Water Footprint for Animal Products.

In analyzing water usage for each crops and the feed requirement for each animal, it was found that beef and milk intake 25.33 million acre-feet of the irrigation water compared to 53 million acre-feet for irrigation within the Colorado Basin states. Overall, 49.33% of the irrigation water in the Colorado Basin states goes to animal feed for beef and milk cattle. Based on the type of feed beef cattle and milk cattle eat, we found that 13.7 million acre-feet of irrigation water goes to animal feed for beef cattle and 11.63 million acre-feet of irrigation water goes to animal feed for milk cattle. That is, every pound of beef that people in the Colorado Basin states consume requires 1626.6 gallons of water, and every pound of milk consumed requires 62.75 gallons of water.

3.11 Kilograms of Crops to Consumable Goods

The Sankey diagram demonstrates the flow of kilograms from harvested crops to final products in the Colorado Basin states. This detailed visualization enables a clear understanding of how different crops are allocated within the agricultural system and highlights the significant role they play in supporting animal agriculture. The flow from beef cattle feed to consumable beef yields only 2.7% of the starting kilogram amount, demonstrating the effect the beef industry has on the United States' food production. An important note is that the majority of corn feed is used for beef cattle feed even though there is higher kilogram yield for consumable pig, poultry, and eggs (17%, 21.6%, and 42% of starting kilogram amounts respectively). The inefficiency of consumable beef can be observed by comparison with the feed to consumable ratios of the other

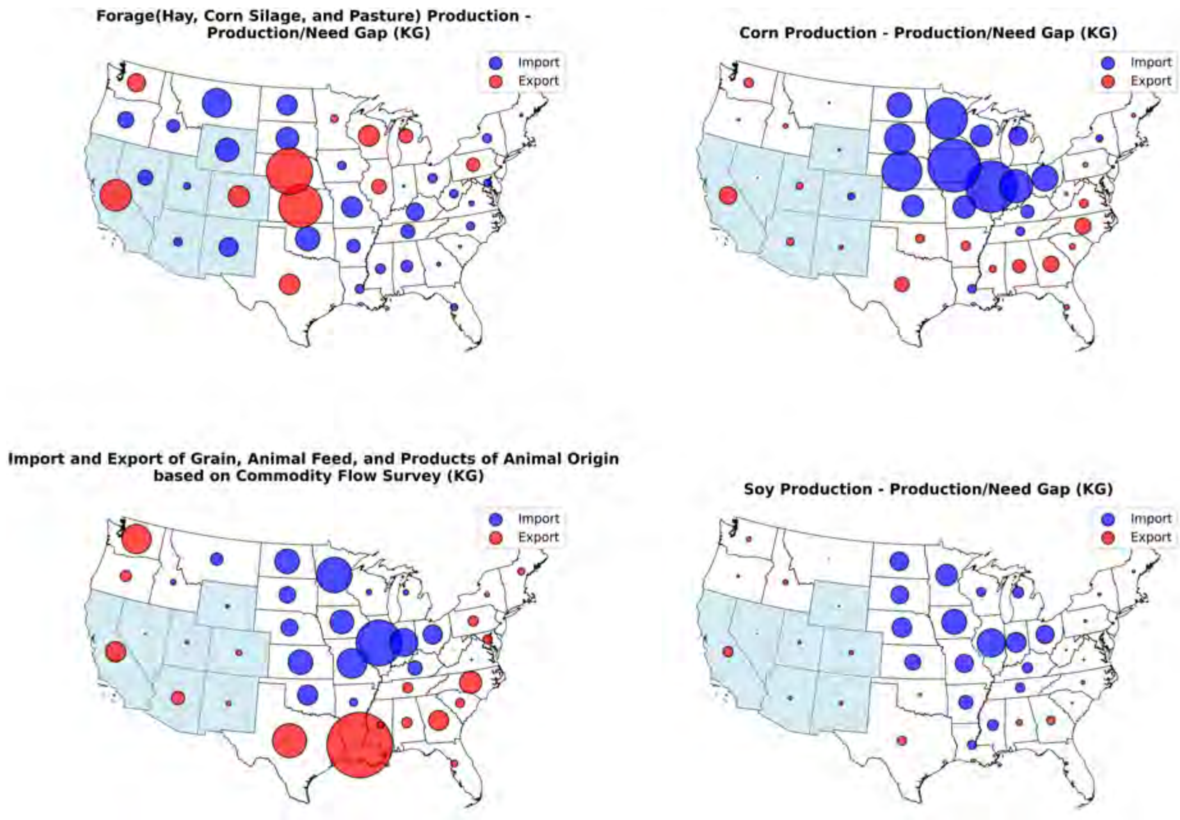

Figure 7: The net exports of forage, corn, and soybean in the US are in blue while the net imports of these crops are in red. Circle size scales with the proportion of net export/import.

animal products. Moreover, the efficiency of harvested vegetables, grains, fruits, and nuts to consumable goods can be acknowledged since this is usually a direct path from farm to table.

The development of the Sankey flow chart has allowed for a thorough analysis of the intricate transformation process from water to edible kilograms for human consumption. By incorporating data on harvested crops, animal feed requirements, and adjustments for milk production, a comprehensive picture of the agricultural supply chain within the basin has been achieved.

3.12 Water Savings from Crop Shifts

We calculated that reducing hay and corn silage irrigated acreage across the basin by 5% would overall spare just over 1 million acre-feet, with a consequent decrease in feed reducing beef and milk production by about 2.2% each. A more ambitious 20% decrease in hay and corn silage would spare 4.13 million acre-feet at the cost of 8.7% of beef and 8.9% of milk output. Note that these calculations use crude basin-wide averages: more targeted fallowing could be of greater efficacy.

4 Discussion

Land, water, and animal production datasets for both the Colorado Basin states as well as the overall United States were aggregated in order to investigate the flow of water in this region. It was found that the Colorado Basin states use nearly as much irrigation surface water as the remaining contiguous states, and the vast majority of this water is used for agriculture.

In fact, the analysis revealed that 53.5% of total irrigation water in the region goes toward animal feed crops alone. These results reflect those of Richter et al. [21], who estimated that 55% of total water in the Colorado Basin goes toward animal feed crops.

Forage estimates are dependent on how much farmers graze and possible overgrazing of BLM lands as well as the quality of feed and the kilograms of feed gleaned per acre. This makes the productivity of pastureland a major source of uncertainty. A best guess estimate was used for the calculations and additions to the water model. Several high and low estimates were created to determine if this would change the final water model

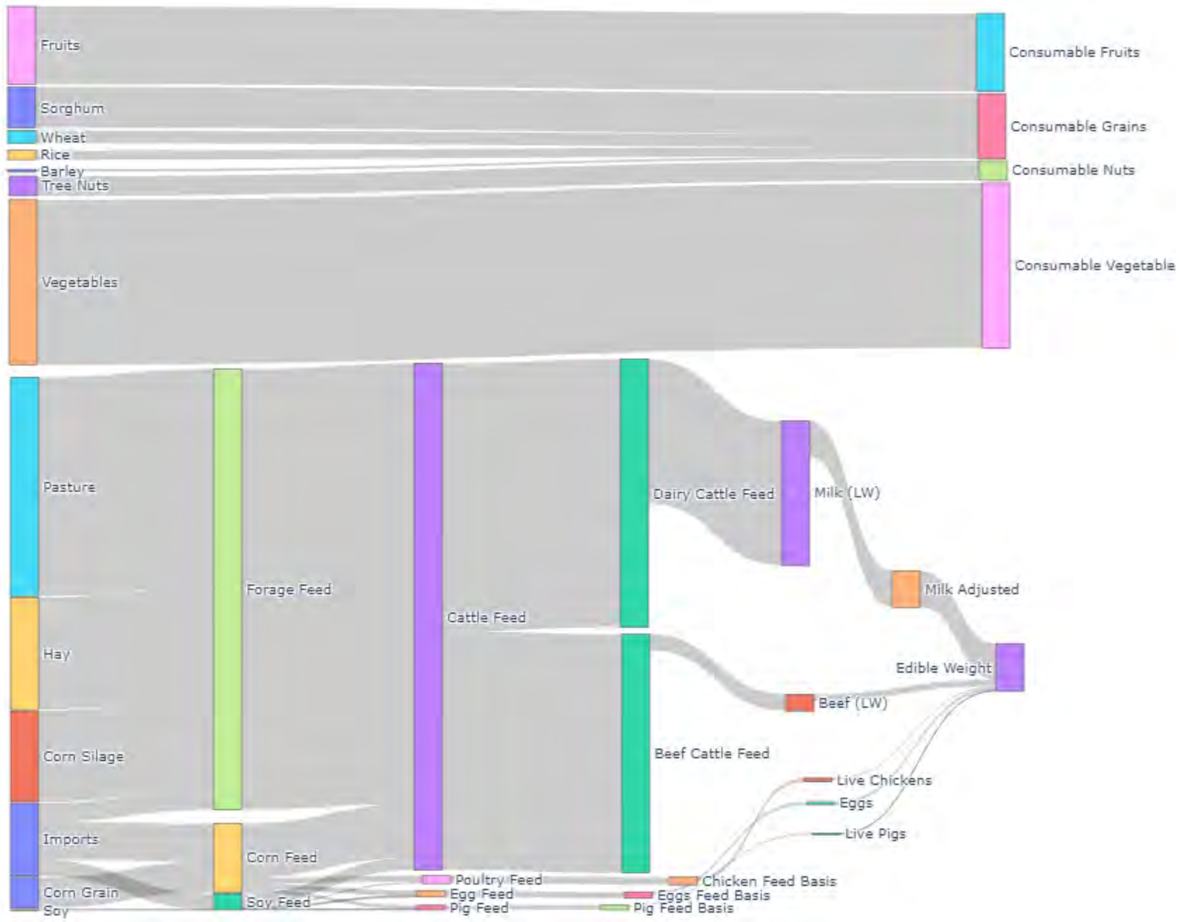

Figure 8: The flow from crops harvested (kg) to human consumption (kg).

result significantly, which it not. Compared to the pasture estimate results of Eshel et al. [12], our best estimates were within 1.5 percent. However, it is still difficult to determine how accurate these estimates are with regard to pastureland production per state.

In addition, the quality of feed and amount of metabolizable energy cannot be certain, which affects each state's feed requirements. Animal unit months were used to determine feed gained from BLM land and were converted to lbs of feed grazed per acre [26]. This is based on farmers grazing the land to its full extent and not overgrazing or undergrazing the land. It is possible more feed requirements are being met by calories if farmers allow their cattle to overgraze. For these reasons, the graze and pastureland estimates constitute reasonable guesses, and the best guess was integrated into the water model.

Results from the Sankey diagram show that the majority of crop feed within the Colorado Basin states is used for the beef industry despite beef being the worst meat in terms of kilogram output. This aligns with the results of Shepon et al. [25] which state that beef is by far the least efficient energy source, especially in comparison to poultry. As such, the argument made by Shepon regarding the movement from beef consumption to other meat sources is still applicable, especially with regard to the Colorado Basin states, and could help with the overall kilogram yield of human products.

Many complications regarding available data affected the accuracy of this report. For example, most recent data was used from the USDA, USGS, NOAA, and BLM; However, it was not always possible to use data from the same year (2017). In these cases, data from the closest possible year was substituted to estimate 2017 data; in particular, water data was collected from 2015. This was also done for desired data such as almond production/harvest, total sales of hay excluding other field crops, and live weights for poultry, hog, and cattle slaughter. Given the ongoing variation of the data at hand, these estimations increase uncertainty in the accuracy of the water model.

Future work should run more simulations in order to determine further possibilities in agricultural changes. Applying the model to other states would also be beneficial in creating an overall understanding of US agricultural water use and how reducing certain crops could aid in reaching long-term conservation goals. This would also be helpful in identifying other areas of the United States that contribute to high water usage and proposing potential solutions.

5 Conclusion

More than three-fourths of all water used in the Colorado River Basin states go toward irrigation. We estimate that approximately 53.5% of this water goes to cattle feed crops, including irrigated pasture. Approximately half of this feed and embodied water goes toward milk, while the other half goes toward beef, a uniquely inefficient transformation of feed and associated water to final edible product. While pastureland forage production is uncertain, it is likely that the basin states are not fully self-sufficient in forage production, and also import significant amounts of corn and soy feed. We have characterized the likely flow of feed crops through the animal production system of the basin states, finding non-ruminant production to be a minor component that is almost entirely dependent on imported feed. Modest reductions in cattle feed crop production could yield substantial savings in water: a 20% decrease in hay and corn silage would save over 4 million acre-feet of water, at the cost of less than 9% of basin milk and beef production. Chronic overdrawing of western water resources is a fundamental challenge for the future, and will necessarily involve shifts in irrigation practices. These challenges can be better met with a fuller understanding of how irrigation water is ultimately used, along with the value of different end-uses to the US food system.

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