Less water: How will agriculture in Southern Mountain states adapt?

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[1] This study examined how agriculture in six southwestern states might adapt to large reductions in water supplies, using the U.S. Agricultural Resource Model (USARM), a multiregion, multicommodity agricultural sector model. In the simulation, irrigation water supplies were reduced 25% in five Southern Mountain (SM) states and by 5% in California. USARM results were compared to those from a "rationing" model, which assumes no input substitution or changes in water use intensity, relying on land fallowing as the only means of adapting to water scarcity. The rationing model also ignores changes in output prices. Results quantify the importance of economic adjustment mechanisms and changes in output prices. Under the rationing model, SM irrigators lose $65 in net income. Compared to this price exogenous, "land-fallowing only" response, allowing irrigators to change cropping patterns, practice deficit irrigation, and adjust use of other inputs reduced irrigator costs of water shortages to $22 million. Allowing irrigators to pass on price increases to purchasers reduced income losses further, to $15 million. Higher crop prices from reduced production imposed direct losses of $130 million on first purchasers of crops, which include livestock and dairy producers, and cotton gins. SM agriculture, as a whole, was resilient to the water supply shock, with production of high value specialty crops along the Lower Colorado River little affected. Particular crops were vulnerable however. Cotton production and net returns fell substantially, while reductions in water devoted to alfalfa accounted for 57% of regional water reduction.

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1. Introduction

[2] Irrigation accounts for 82% of water withdrawals in the six southwestern states of Arizona, California, Colorado, Nevada, New Mexico, and Utah [*Hutson et al.*, 2005]. This region faces increasing competition for water in the wake of rapid population growth, yet new sources of water supply will be costly and difficult to develop [*Colby et al.*, 2007; *Frisvold and Konyar*, 2011]. Historically, the region has been susceptible to severe, prolonged droughts [*Stockton and Jacoby*, 1976; *Meko et al.*, 1995; *Hidalgo et al.*, 2000; *Woodhouse et al.*, 2006]. If such periods of severe drought reoccur, water available for agriculture could decline significantly. There are also concerns that climate change will lead to further drying, making future regional water management even more difficult [*Christensen et al.*, 2004; *Hoerling and Eischeid*, 2007; *Seager et al.*, 2007; *Rajagopalan et al.*, 2009].

[3] This study examines the impacts of reduced water availability on agriculture in the Southern Mountain states. It uses an updated version of the U.S. Agricultural Resource Model (USARM) to simulate impacts of large reductions in water availability in the Colorado and Upper Rio Grande River basins. USARM is a 32-commodity, 12-region U.S. agricultural sector model. Earlier versions of USARM have been documented and successfully applied to examine impacts of U.S. commodity, conservation, and energy policies, as well as impacts of agricultural biotechnology adoption [*Howitt*, 1991; *Ribaudo et al.*, 1994; *Konyar and Howitt*, 2000; *Konyar*, 2001; *Kim et al.*, 2002].

[4] In the simulation, water available to agriculture in the Southern Mountain region (Arizona, New Mexico, Colorado, Utah, and Nevada) is reduced 25%, while water available to California falls 5%, reflecting reductions in Colorado River water use by Southern California agriculture. Southern California has seen recent agreements that will ultimately transfer large amounts of water from agriculture along the Colorado River to San Diego and Los Angeles. While Arizona is a large producer of specialty crops, California is an even larger producer. Together, California and the Southern Mountain (SM) states represent a large enough share of the market to affect national output prices.

[5] The water supply shock simulated here is generic and not necessarily representative of any particular drought, water transfer, or climate change scenario. Previous studies have examined specific scenarios by linking hydrological models to mathematical programming models of agricultural production. *Chen et al.* [2001] assessed the impacts of

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climate change scenarios on agriculture in the Edwards Aquifer region of Texas, while several studies have examined implications of different climate change scenarios for California. Other studies have examined effects of severe, prolonged drought [*Booker*, 1995; *Booker et al.*, 2005] and restrictions on agricultural water use for habitat or fish species protection [*McCarl et al.*, 1999; *Sunding et al.*, 2002; *Ward et al.*, 2006]. The importance of water transfers for reducing adjustment costs is a recurring theme in these studies. Our purpose is to examine the modes by which SM agriculture might adapt to large water shortages and identify producer groups most vulnerable to shortages.

[6] Agricultural producers can reduce water use in different ways and to varying degrees. In some areas, producers can shift from irrigated to dryland crop production. This shift is possible in Colorado and some parts of Utah or northern New Mexico, but it is not a viable option in Arizona. In principle, growers could significantly reduce water use simply by switching between crops. For example, in Arizona, producers applied, on average, 5.8 acrefeet of water per acre to alfalfa and 4.2 acrefeet to cotton, but apply 3.5 acrefeet per acre to wheat [*United States Department of Agriculture* (*USDA*), 2010]. Producers can practice deficit irrigation, reducing the amount of water applied per acre. Finally, they can substitute other inputs for water. The extent to which growers adopt these measures in response to water shortages will depend on the economic returns of doing so.

[7] Section 2 provides background on the balance of water demand and supply in the Southwest, discussing how this balance is sensitive to growing demands for water for urban use and riparian habitat protection as well as recurrence of prolonged drought or climate change. We then provide an overview of the USARM model and discuss how the water supply shock is introduced into the model. In section 5, producer adjustments are examined. These include changes in irrigated acreage, cropping patterns, water-use intensity and input substitution. These adjustments translate into changes in crop yields, production, prices, agricultural employment and net returns as well as changes in consumer benefits and commodity program outlays. These adjustments and their impacts are compared with a "rationing model" approach to estimating response to water shortages. The rationing model assumes producers cannot change crop mix on planted acres, substitute inputs, or reduce water use intensity. It relies on land fallowing as the only means of adapting to water scarcity. The comparison between USARM and the rationing model highlight the importance of more flexible options for reducing irrigator adjustment costs. Although the model aggregates agriculture across the entire SM region, one can make inferences of impacts on a more local level based on production specialization within the region. For example, most specialty crops are grown in Western and Central Arizona, while dryland wheat is produced primarily in Colorado, and cotton is produced in Arizona and New Mexico.

2. Western Water: Growing Demands, Uncertain Supplies

[8] Although agriculture remains the dominant water user in the West, demands for other uses continue to grow. Rapid population growth in the West will increase urban water demand. The Quantitative Settlement Agreement reached between the Imperial Irrigation District and the San Diego County Water Authority and Metropolitan Water District will transfer up to 200,000 acrefeet of water from agricultural to urban users after 10 years, with the option to transfer up to 300,000 acrefeet later [*Imperial Irrigation District*, 2004]. The Central Arizona Groundwater Replenishment District is looking to meet over 200,000 acrefeet in future demand from leases from Indian tribes and irrigation districts along the Colorado River [*Jacobs and Megdal*, 2004]. Future urban water demand could account for close to 25% of current agricultural use by 2030 in fast-growing Arizona and Nevada [*Frisvold and Konyar*, 2011]. Population growth *by itself* is unlikely to require such a large reallocation of water from agriculture in the SM region as a whole, however, because population growth is slower in Colorado, New Mexico, and Utah.

[9] There are additional demands for water to maintain or restore riparian habitats and to protect endangered species. In California, the Bureau of Reclamation is reducing water deliveries to Central Valley agriculture in attempts to protect Chinook salmon and Delta smelt [*Howitt et al.*, 2009a]. Irrigation withdrawals in the Upper Rio Grande Basin may be restricted to protect the endangered Rio Grande silvery minnow [*Booker et al.*, 2005]. Some have proposed reallocating current water uses to protect riparian species in the Lower Colorado [*Pitt*, 2001; *Glennon and Culp*, 2002; *Parrish*, 2003]. Estimates of water needed to restore the Colorado River Delta ecosystem suggest that 50,000 additional acrefeet of water would be needed for base flows with 260,000 acrefeet needed in 1 of 4 years for flood flows [*Wheeler*, 2007]. *Moore et al.* [1996] note that in the 17 western contiguous U.S. states, agriculture is reported as a "factor in decline" in federal decisions to list 50 fish as threatened or endangered under the Endangered Species Act (ESA). Thirty-nine of these fish species have habitat in the SM states. Irrigated agriculture in 38% of SM counties depends on surface water from rivers and streams with ESA-listed fish.

[10] While demands for water in the Southwest continue to grow, there are also growing concerns about the reliability of water supplies. The Colorado River Compact of 1922 apportioned 7.5 million acrefeet (MAF) of water to Upper Basin States (Colorado, New Mexico, Wyoming, and Utah) and 7.5 MAF to Lower Basin States (Arizona, California, and Nevada). However, this calculation was made from observations during an unusually wet period in the river's history. Delegates based allocations on an estimated mean flow of more than 16 MAF [*Hundley*, 1975]. However, tree ring reconstruction analyses suggest long-run annual average flows of 13.2 MAF [*Hidalgo et al.*, 2000] and 13.5 MAF [*Stockton and Jacoby*, 1976]. More recently, *Woodhouse et al.* [2006] suggest higher annual flows, ranging from 14.3–14.7 MAF, still significantly below current apportioned levels. The 1944 Water Treaty between the United States and Mexico apportioned 1.5 MAF more of Colorado River water per year to Mexico, for a total apportionment of 16.5 MAF [*Christensen et al.*, 2004].

[11] In 2008, the Lower Basin states and Mexico used 9.2 MAF of water [*United States Bureau of Reclamation* (*USBOR*), 2008a]. Upper Basin states currently use about

4.1 MAF per year of their 7.5 MAF per year allocation [*USBOR*, 2008b]. Adjusting for evaporation losses from Lakes Mead and Powell and miscellaneous inflows from smaller streams, there are an additional 1 MAF in water losses to the basin [*Barsulgi et al.*, 2009]. This places current consumptive use plus net losses at 14.3 MAF per year, right at the lower range of *Woodhouse et al.*'s [2006] long-run annual average estimates of 14.3–14.7 MAF. While the system can potentially store up to four times annual flow, its ability to continue to do so has been questioned [*Barnett and Pierce*, 2008, 2009; *Rajagopalan et al.*, 2009].

[12] Historically the region has faced periods of severe, sustained drought. The Southwest experienced multiyear droughts from 1953–56 and from 2000–03. In the late 1500s, the Colorado Basin was hit by a severe, multidecade drought. In 1995, the Powell Consortium considered the question of how the region's hydrology and economy would respond to a drought of that magnitude, should it reoccur [*Young*, 1995]. Their simulations suggested that over half of Upper Basin consumptive use demand would not be met in the worst year and that Lake Powell's elevation would fall to the dead storage levels [*Hardy*, 1995]. Under the worst years of this drought scenario, water deliveries to Arizona's Central Arizona Project (CAP) declined 60%, with reductions in CAP agricultural use falling 75%. Agricultural water use in the Upper Basin States fell by more than 50% [*Booker*, 1995].

[13] A second concern, based on climate change scenarios, is that the Southwest is becoming warmer, with reduced surface water availability [*Christensen et al.*, 2004; *Hoerling and Eischeid*, 2007; *Seager et al.*, 2007; *Rajagopalan et al.*, 2009]. *Christensen et al.* [2004] conducted simulations of climate change on management of the Colorado River Basin reservoir system. They considered the likelihood of shortage declarations, which have been avoided to date, based on reservoir levels at Lake Mead. Water users in Arizona's CAP and a few other Western Arizona users possess the most junior water rights to Colorado River water. They would be required to cut back use first in times of shortage. Water supplies to Arizona would be cut back by 320,000 acrefeet under a level one shortage and by 400,000 under a level two shortage. In simulations over the period 2006–2039 that account for climate change, a level one shortage occurred 92% of years and level two shortages were declared 77% of years. Using updated general circulation models (GCMs), *Christensen and Lettenmaier* [2006] obtained more optimistic results. Nevertheless, their simulations projected that level one shortages would occur in 21% of years from 2010–2039, while level three shortages—requiring a 480,000 acrefoot cutback in Arizona—would occur in 10–11% of years. The bulk of these cutbacks would have to be made by irrigators, primarily in the Central Arizona. Climate change would also affect other basins throughout the SM region [*Hoerling and Eischeid*, 2007; *Seager et al.*, 2007].

3. General Description of USARM

[14] U.S. Agricultural Resources Model (USARM) is a nonlinear mathematical programming model designed to simulate farmer behavior under external market and policy shocks. Further description of the model's structure is presented in the Appendix. The model accounts for 10 major field and 22 fruit and vegetable crops in 12 regions covering the 48 contiguous states. Many studies use computable general equilibrium (CGE) modeling to simulate the effects of change in input prices and other external shocks on input use and output [*Goodman*, 2000; *Hertel*, 1997; *Seung et al.*, 2000]. The USARM borrows from the CGE framework, but it is partial equilibrium. Its scope is limited only to the crop sector, with no direct linkage to other sectors in the economy.

[15] Farmers' economic behavior is modeled in a nonlinear programming framework. Each cropping activity is defined by a nested constant elasticity of substitution (NCES) production function with seven inputs, allowing the model to determine endogenously the quantities of inputs used in each activity. The seven input categories are land, irrigation water, labor, capital, fertilizer (N, P, K), chemicals (pesticides, fungicides and herbicides), and energy/other inputs. There are separate production functions for irrigated and dryland crops, which by definition apply no irrigation water. In some regions, because of arid environments and high water requirements, there may be no dryland production of a particular crop (e.g., SM lettuce production).

[16] The NCES functions allow for different substitution possibilities between different inputs and allow acres planted and input applications per acre to vary continuously. Deficit irrigation is possible where less water is applied per acre. This reduces costs, but at the expense of lower yields. The NCES specification is commonly used in CGE models, reflecting possibilities of medium-term adjustments, over about 2–4 years. Planting decisions may change in response to an initial shock, as do uses of variable inputs and aggregate capital. The specification does not allow longer-term adjustments, such as changes in specific irrigation technology (e.g., switching from gravity flow to sprinkler or drip methods).

[17] The smallest decision-making unit is a region. Regions are modeled as aggregate farm units producing crops in their respective areas under dry and irrigated conditions. The model simulates a conditional medium-term sectoral equilibrium in a comparative static setting. Farmer behavior is predicted for a given shock in terms of acres allocated to specific crops in each region (with or without irrigation), the amount of each input used, and changes in aggregate crop prices. Regional agriculture can adjust to shocks by changes on the extensive margin (change in total acres planted) and the intensive margin (choices of crops to grown, whether or not to irrigate, how much to irrigate, and application of other inputs on the land). In the simulation exercise, the SM and California regions response to the water price shock and subsequent price changes, while other regions respond to price changes to reach market equilibrium at regional and national levels.

[18] The model incorporates aggregate (domestic and export) demand equations for each crop that endogenously determine crop prices. Studies often find inelastic demand for agricultural commodities [*Henneberry et al.*, 1999; *You et al.*, 1996; *Onunkwo and Epperson*, 2000; *Nuckton*, 1978]. Demand elasticities will be larger for individual regions than for the national aggregate. However, for many crops, just a few regions account for the bulk of production. So, even regional demands may be inelastic. For example,

Russo et al. [2008] estimated that the demand for California walnuts, alfalfa, cotton, rice, and tomatoes were all inelastic. In analyses of climate change impacts on California, inelastic price responses provide a "revenue buffer" for specialty crop producers—output prices rise as production falls [*Howitt et al.*, 2009b, 2010].

[19] USARM has been updated to account for federal commodity programs, with marketing loan and countercyclical payments explicitly modeled. Earlier versions are documented in the work of *Howitt* [1991, 1995b] [*Konyar et al.*, 1993; *Howitt and Konyar*, 2000]. Loan deficiency payments (LDPs) under marketing loan programs, when in effect, are coupled payments. That is, they encourage greater production at the margin. In contrast, countercyclical payments (CCPs) are based on the difference between the market price and a target price, but payments are based on historic, rather than current, production. CCPs do not affect marginal production decisions, but aggregate production alters the level of CCPs via its impact on market prices.

3.1. Commodity and Regional Coverage

[20] USARM accounts for 96% of all U.S. harvested acreage of the 10 included field crops and about 98% of all U.S. harvested acreage of the 22 fruit and vegetable crops (Table 1). USARM divides the United States into 12 production regions: Appalachian, Corn Belt, Delta States, Lake States, Northeast, Northern Plains, Southern Plains, Southeast, Northern Mountain, Southern Mountain, Upper Pacific, and California. The Southern Mountain (SM) region, which includes Arizona, Colorado, Nevada, New Mexico, Utah, is the primary focus of this study. Despite this regional aggregation, it is possible to make inferences about economic behavior and impacts in individual states within the SM region. For example, dryland wheat and barley production in the SM region occurs almost exclusively in Colorado and parts of Utah and New Mexico, with no such production in Arizona. Conversely, lettuce, melon, and broccoli production in the SM region occurs almost exclusively in Arizona, while cotton production occurs only in New Mexico and Arizona. Potatoes and sugar beets are produced in Colorado.

[21] USARM was originally calibrated to match acreage and price data for 2000 for specialty crops and 2002 for field crops. However, recent relative price changes have significantly altered the crop mix in the region. For example, corn and wheat prices increased, while cotton prices decreased. Thus, relative prices and acreage planted to major crops were adjusted in USARM to reflect the new environment in which there are higher returns and more acres planted to wheat and corn.

Table 1. Commodity Groupings in the USARM Model

Field Crops	Vegetables	Fruits and Nuts
Alfalfa hay	Asparagus	Almonds
Barley	Broccoli	Apples
Corn	Cauliflower	Citrus
Cotton	Cucumbers	Grapes
Rice	Green Beans	Grapes, Raisin
Sorghum	Green Peas	Melons
Soybeans	Lettuce	Peaches
Sugar cane	Onions	Pears
Sugar beets	Peppers	Strawberry
Wheat	Potatoes	Walnuts
	Tomato, Fresh	
	Tomato, Processing	

3.2. Regional Resource Constraints

[22] Variable inputs are supplied elastically at fixed national prices. Initially, total dryland and total irrigated land uses are calibrated to match actual total regional land use patterns in each region in the base period. For each region, a supply curve for agricultural land allows land rent to be determined endogenously for each region. Total water applications to agriculture in each region are constrained to equal total water available for such agricultural applications. The regional constraint is the sum of surface and groundwater available. Consistent with empirical findings that western water use is quantity constrained [e.g., *Moore and Dinar*, 1995], there is a positive shadow value on this constraint. The cost of water is a weighted average for each region, capturing both the purchase price of water and the cost of water pumping. The model does not allow regions to increase total groundwater use above the constraint. Unlike studies that treat total groundwater use and costs as endogenous [e.g., *McCarl et al.*, 1999; *Chen et al.*, 2001], both are exogenous in USARM. The region cannot endogenously apply more groundwater, by pumping more at higher cost. However, the model *could* be exogenously shocked, increasing groundwater supplies and pumping costs simultaneously, to mimic this effect.

3.3. Water Supply Shock

[23] To examine how agriculture responds to a reduction in water availability, the total amount of water available for irrigation in the SM region is reduced by 25%. Water supplies in California are reduced 5% to reflect reductions in Colorado River water available to Southern California, which might occur from agricultural-urban water transfers or streamflow requirements to protect endangered fish. Reduced specialty crop production in California may raise prices received for specialty crops produced in the SM region.

[24] A 25% reduction in the SM region is large, but several studies have examined similar reductions. *Booker* [1995] considered reductions of 50% or more in the Upper Colorado in combination with a 75% reduction in agricultural CAP supplies. *Booker et al.* [2005] considered reductions of 25–50% in the Upper Rio Grande Basin. In Nevada, *Elbakidze* [2006] examined effects of a 27% reduction in the Truckee Carson Irrigation District, while *Seung et al.* [2000] considered a 31% reduction in Churchill County.

[25] A limitation of USARM is the fact that watersheds within a region are not modeled separately. The SM region includes many different river basins and groundwater sources. Surface water from the Upper and Lower Colorado Basins provide water for 35% of irrigation water applied, while groundwater in these basins accounts for 9%. Surface water and groundwater from the Great Basin account for another 16% and 9%. Surface water and groundwater from the Rio Grande, Pecos, Arkansas, and Platte River basins

account for 11% surface and 20% of groundwater water applied in the SM region [*USDA*, 2010]. Implicitly, then the 25% water reduction shock suggests a pervasive reduction throughout the region, but cannot specify exactly where water supplies decline.

[26] One might question the likelihood of reductions in water availability affecting so many river basins at once. However, all states in the region face growing urban demand for water and greater regulatory constraints to increase or maintain instream flows to protect threatened or endangered fish. Furthermore, climate change forecasts suggest that reductions in available runoff will span the entire region [*Hoerling and Eischeid*, 2007; *Seager et al.*, 2007]. Historically, such widespread drought has occurred [*Hardy*, 1995; *Meko*, 1995]. Estimates of tree ring reconstruction of stream gauge data and long-term tree ring reconstructions suggest that sharp reductions in streamflow often occur in the same years in the Colorado and Rio Grande Basins [*Woodhouse*, 2008].

4. Limitations

[27] Before proceeding to model results, we note some limitations of the modeling approach. First, several previous studies have linked economic programming models with hydrologic models [*Booker*, 1995; *Booker et al.*, 2005; *Chen et al.*, 2001; *Harou et al.*, 2010; *Howitt*, 2009b; *McCarl*, 1998; *Medellín-Azuara et al.*, 2008; *Tanaka et al.*, 2006; *Ward et al.*, 2005]. Changes in streamflow or groundwater availability enter as inputs into the economic model and feedback loops allow one to examine how agricultural production decisions affect the hydrological system. Such model integration is quite complex and beyond the scope of this current study. However, such integration in other watersheds provides important insights about factors like return flows, groundwater depletion, potential third-party effects and gains from water transfers. One may regard this study as a first exploration of the agricultural economic component of a more integrated approach. Moreover, these other studies treat agricultural output prices as fixed, ignore market interactions with other regions of the country, or both. Our analysis specifically considers these price and market interaction effects.

[28] Another potential problem is the fact that USARM does not impose specific constraints on the flow of water *within* regions. It therefore does not capture physical or institutional impediments to certain reallocations of water. For example, large increases in water use by crops grown in one state might implicitly suggest unrealistic water transfers across basins or states. Research suggests that costs of such impediments can be significant [*Harou et al.*, 2010; *Howitt*, 2009b; *Medellín-Azuara et al.*, 2008; *Tanaka et al.*, 2006; *Ward et al.*, 2005]. Fortunately, the results of our water shortage scenario do not imply or require such unrealistic water reallocations. Further, state production specialization within the region allows us to make a number of important inferences about more localized effects.

[29] USARM also uses regional averages for water application intensities, which masks state differences in water requirements. For example, average water applications per acre for cotton and wheat are about 4.2 AF per acre and 3.5 AF per acre in Arizona, but 2.2 AF per acre and 2.0 AF per acre in New Mexico. Water applications per acre are 5.8 AF per acre for alfalfa in Arizona, but only 1.5 AF per acre in Colorado. In reality, there are two avenues to reduce regional water applications per acre. One is deficit irrigation (less water applied per acre); another is reduced production in regions with higher water requirements. For example, reduced alfalfa production in Arizona would reduce regional water use per acre for alfalfa. USARM, however, does not explicitly model a reduction in production in states with higher water requirements.

[30] The water supply shock simulation is not a full drought or climate change scenario, although a water supply reduction of this magnitude may well be part of such scenarios. To be complete, drought or climate change scenarios would also include changes in water requirements and water-yield response of irrigated crops as well as changes in yields for dryland crops. Climate scenarios projected decades in the future may also include projections of future crop prices (from population and economic growth) or in yields (from technological progress) [*Medellín-Azuara et al.*, 2008; *Howitt et al.*, 2009b; *Howitt et al.*, 2010]. The USARM results are also medium-term responses to a comparative static shock and do not include longer-term adjustments such as investment in new irrigation technologies or adoption of drought-tolerant crop varieties.

[31] While USARM includes 32 different crops, it does not include livestock or dairy production directly. Allocating land for grazing, for example, is not an option. Previous analyses of climate change impacts on agriculture, found shifting acreage between cropland and grazing land to be an important adaptation to changes in precipitation and water availability [*Reilly et al.*, 2001, 2003]. Pasturing decisions are complex, involving changes in desired herd sizes and grass production on the land. *McCarl* [2006] reports declines in pastureland under climate scenarios with reduced water availability and in scenarios with increased availability.

[32] Although livestock and dairy production are not explicitly modeled, USARM does capture effects on those sectors via changes in consumer surplus measures. In the model, "consumers" may be more correctly thought of as "1st purchasers" of commodities. Thus, lost consumer surplus from higher alfalfa prices captures losses to dairies, while higher corn prices will cause losses to the livestock industry through higher feed prices. Likewise, higher cotton prices will affect cotton gins as first purchasers of cotton.

[33] Despite limitations, results highlight the importance of acreage adjustments, changing crop mix, and deficit irrigation as adaptation strategies. Relatively modest adjustments in production practices and crop mix substantially reduce the cost of water shortages relative to a "land-fallowing only" response. While the region as a whole appears resilient to large water supply shocks, certain crops and subregions appear relatively vulnerable. Results also demonstrate the importance of output price effects, even when water supply shocks are confined to subregions within the United States.

5. USARM Simulation Results

[34] In response to reduced water for irrigation, producers may respond by fallowing land, changing crop mix

on planted acres, shifting between irrigated and dryland production, altering water use on irrigated acres, and altering use of other inputs on planted acres. Below we focus on acreage and water use responses, comparing them with a less flexible rationing model approach that only permits land fallowing as an adjustment. The comparison illustrates the importance of multiple adjustment mechanisms to reduce costs of water shortages. Although the simulations include both a 25% reduction in water use to the SM region and a 5% reduction in California, impacts in California were quite small. Reported results, except where noted, apply only to the SM region.

5.1. Acreage Response

[35] In response to the 25% reduction in water availability, SM irrigated acreage declines by 54,700 acres (a 1.5% decrease) and dryland acreage increases by the same absolute amount (Table 2). The biggest changes in absolute acreage are an expansion of wheat acres and a decline in cotton and alfalfa acres. Dryland wheat expands by 45,800 acres, while irrigated wheat expands by 25,100 acres. Cotton acres fall by over 50,000 acres and irrigated alfalfa acres fall by nearly 24,000 acres. There are modest increases in dryland barley, corn and sorghum and modest decreases in irrigated acreage of these crops.

[36] These results suggest an expansion of total acreage in Utah and Colorado and a decline in total crop acreage in Arizona and New Mexico. Cotton, which accounts for the largest acreage decline, is only grown in Arizona and New Mexico. Arizona has virtually no dryland crops, while Colorado accounts for more than 90% of dryland wheat production. Therefore, expansion of dryland wheat, barley, corn, and sorghum would be primarily in Colorado. Although dryland wheat accounts for the largest absolute increase in acreage of any crop, the change represents only a 2.7% increase in SM dryland wheat acreage. Reduction in cotton acreage would occur in Arizona and New Mexico. This 50,000 acre reduction cannot be made up by expansion of other irrigated crops in these states as irrigated acreage expansion for wheat and corn are less than 25,000 acres for the entire SM region (Table 2). Although some expansion of irrigated wheat acreage could occur in Arizona, this would be smaller than declines in acreage of other crops, implying a net loss in Arizona crop acreage.

[37] Acreage of specialty crops changes very little. Lettuce, broccoli, melons, and cauliflower acreage decline by less than 1%. Citrus acreage declines by 1.2%. SM region acreage of these crops is concentrated almost exclusively in Arizona. Yet, this represents a reduction in fewer than 1000 acres. Overall, results are quite consistent with analyses of California, which found that drier conditions led to relatively large changes in field crop acreage with relatively less change among specialty crops [*Tanaka et al.*, 2006; *Howitt et al.*, 2009b; *Medellín-Azuara et al.*, 2008; *Harou et al.*, 2010; *Howitt et al.*, 2010].

5.2. Water Use

[38] Most of the 2.4 MAF reduction in water use is achieved by a 1.36 MAF reduction in water going to alfalfa. This result is similar to *Moore and Negri* [1992] who used an econometric model of land and water use to simulate the effects of 10% reduction in Bureau of Reclamation water supplies in 17 western states. As in our study, reductions in water applied to alfalfa accounted for the single largest source of water reduction. About 93% of the overall reduction is achieved by reducing water applied to alfalfa, cotton, wheat, corn, and barley (Table 3). Water use per acre of cotton falls 35%, while total water used by cotton falls 53% (Table 4). Other important reductions are to higher-valued crops such as sugar beets and potatoes that are grown in Colorado.

[39] Although regional water supplies fall 25%, crops do not experience an equiproportional reduction in water use. Irrigated wheat's water use per acre falls by 27%, more

Table 2. Change in Acreage in Southern Mountain Region in Response to Water Supply Shock

	Change in Acreage	
	Acres (000)	Percent
	Nonirrigated Crops	
Alfalfa	2.0	1.1%
Barley	0.8	9.0%
Corn	1.9	2.5%
Sorghum	4.3	2.7%
Wheat	45.8	2.7%
Total	54.7	
	Irrigated Crops	
Alfalfa	−23.7	−1.3%
Apples	−0.9	−9.0%
Barley	−6.4	−4.4%
Broccoli	0.0	−0.1%
Cauliflower	0.0	0.0%
Citrus	−0.3	−1.2%
Corn	2.8	0.3%
Cotton	−50.1	−27.2%
Grapes	0.0	−0.3%
Lettuce	−0.4	−0.5%
Melons	−0.2	−0.7%
Onions	0.0	0.0%
Potatoes	−0.2	−0.2%
Sugar Beets	−0.3	−0.8%
Wheat	25.1	7.3%
Total	−54.7	

Table 3. Reduction in Irrigation Water Use in Southern Mountain Region in Response to Water Supply Shock

	Reduction in Acrefeet (Thousands)	Crop's Share of Total Regional Irrigation Reduction	Cumulative Share of Total Regional Irrigation Reduction
Alfalfa	−1361	57%	57%
Cotton	−366	15%	72%
Wheat	−231	10%	81%
Corn	−212	9%	90%
Barley	−76	3%	93%
Lettuce	−70	3%	96%
Citrus	−22	1%	97%
Potatoes	−21	1%	98%
Sugar Beets	−15	1%	98.6%
Melon	−15	1%	99.2%
Onions	−7	0%	99.4%
Apples	−7	0%	99.7%
Broccoli	−4	0%	99.9%
Cauliflower	−3	0%	100.0%
Grapes	0	0%	100.0%
Total	−2408		

Table 4. Change in SM Region Water Use Per Acre and Water Use by Crop in Response to Water Supply Reductions

Crop	Percent Change in Water Use Per Acre	Percent Change in Total Water Use
Alfalfa	−28%	−28%
Apples	−8%	−16%
Barley	−23%	−26%
Broccoli	−12%	−12%
Cauliflower	−22%	−22%
Citrus	−16%	−17%
Corn	−11%	−11%
Cotton	−35%	−53%
Grapes	−4%	−4%
Lettuce	−26%	−27%
Melons	−13%	−13%
Onions	−12%	−12%
Potatoes	−10%	−10%
Sugar Beets	−28%	−28%
Wheat	−27%	−22%

than its 22% reduction in absolute water use. This occurs because of expansion in total irrigated wheat acreage. Water use for cotton, alfalfa, wheat and sugar beets decline by more than 25%, while water use for many crops decline by less than 25%. For many specialty crops, water use falls by considerably less than 25%. Water used for broccoli, citrus, and melons declined by 16% or less.

[40] The acreage and water use responses do *not* imply large, implicit transfers from water surplus subregions to water deficit subregions within the SM region. A major adaptation to meet the water shortage is reducing cotton acreage. This would occur entirely in Arizona and New Mexico and implies no transfer of water. Acreage of irrigated wheat increases, but this could just represent a switch from cotton acreage to wheat acreage in Arizona and New Mexico. In both states, wheat uses less water per acre than cotton. From 2003 to 2008, actual wheat acreage in these states increased relative to cotton acreage in response to relative prices changes. Although irrigated corn *acreage* increases, water applied to corn throughout the region declines. In fact, water use for all crops declines. Water use falls most for field crops with relatively small changes for specialty crops. However, most of the specialty crops in the region are grown along the Lower Colorado River main stem by irrigators with the most senior water rights. Given the prior appropriation doctrine, these irrigators would be among the last to have to reduce their own water use in response to Lower Basin water shortages. Moreover, these irrigators also grow field crops with lower returns than specialty crops, thus they would be more likely to reduce water to field crops before cutting back applications to specialty crops. Conversely, results suggest that the crops where most of the adjustments would occur, cotton, alfalfa, and barley account for a significant share of acreage and water use in Central Arizona, which has junior water rights to Colorado River water. Thus, the model suggests that the least cost regional adjustment to water shortages would require land fallowing and reduced water use in the very region that institutionally would be required to adjust the most to basin-wide water shortages. The net change in alfalfa, wheat, cotton, and barley acreage is small relative to total field crop acreage in Central Arizona.

5.3. Yields and Production

[41] Table 5 shows changes in yields, acreage and production in the SM region. Cotton yields fall by nearly 24%, followed by yield losses of 9% for irrigated barley and wheat, and 4% for alfalfa. Overall, cotton production declines by 44%. This is significantly more than the 27% acreage reduction. It reflects the reduction in other inputs devoted to cotton production and subsequent reduction in cotton yields. Although irrigated wheat acreage expands 7.3%, irrigated wheat production declines 2.5%. Again, this decline results from a decline in other inputs devoted to wheat production and reduced yields. Percent reductions in output of specialty crops are modest, with declines for lettuce (1.5%), broccoli (0.5%), melons (1.4%), cauliflower (0.3%), and citrus (2.3%). Again, apples are an exception, with a production decline of 13%. Unlike other specialty crops, net returns to apple production in the SM are relatively low and production in the region, already small has been steadily declining.

[42] Comparing Tables 4 and 5, one can see that yields fall much less than water use per acre. This occurs because yield elasticities with respect to water are low and because of the functional form of our production functions. With a CES function, the marginal product of water (or any other input) will not fall below zero, but rather approach it asymptotically. The yield curve can have a long "flat" portion where more water can have small, but still positive, effects. This implies that the marginal value product curve for water is also very flat where large amounts of water are used. If the price of water is low, then water use will be at the "flat" portion of the yield and marginal value product curves. Thus, at low water prices and high levels of water use per acre, there is a range where large percentage reductions in water use per acre can be made without sacrificing yield or revenues.

[43] Therefore, low water prices combined with the CES production specification account for the low yield elasticities with respect to water. Several empirical studies support this specification, finding quite low output elasticities for water. *Moore et al.* [1993, p. 16] estimated Cobb-Douglas and quadratic production functions with farm-level data for 13 irrigated crops in the 17 Western States and found, "The output elasticities of irrigation water are highly inelastic for every crop, indicating that *reductions in water supply would have relatively small effects on crop production*" (emphasis added).

[44] Depending on functional form, they found yield elasticities with respect to water for alfalfa (0.138–0.145), barley (0.014–0.020), cotton (0.115–0.126), corn (0.064–0.070), sorghum (0.112–0.115), sugar beets (0.055–0.064), and wheat (0.082–0.083). These elasticities, evaluated at sample means, were consistently small across crops and functional form. *Antle and Hatchett* [1986] found even smaller output elasticities with respect to water, estimating a sequential-decision production function for Imperial Valley wheat. Estimating production functions for winter vegetables, *Just et al.* [1983] reported water output elasticities for tomatoes (0.037), bell peppers (0.046), onion (0.051), melons (0.050), and eggplant (0.079). *Schneider and Howell* [1997] and *Knapp and Schwabe* [2008] suggest that it is possible to reduce water applications with relatively

Table 5. Change in SM Region Output, Yields, and Acreage in Response to Irrigation Water Supply Reduction[a]

	Percent Change in Output	Percent Change in Yield	Percent Change in Acreage
	Nonirrigated Crops		
Alfalfa	1.1%	0.0%	1.1%
Barley	10.1%	1.1%	9.0%
Corn	2.5%	0.0%	2.5%
Sorghum	0.7%	−2.0%	2.7%
Wheat	0.9%	−1.9%	2.7%
	Irrigated Crops		
Alfalfa	−5.4%	−4.1%	−1.3%
Apples	−13.0%	−4.4%	−9.0%
Barley	−13.2%	−9.2%	−4.4%
Broccoli	−0.5%	−0.5%	−0.1%
Cauliflower	−0.3%	−0.3%	0.0%
Citrus	−2.3%	−1.0%	−1.2%
Corn	−1.2%	−1.5%	0.3%
Cotton	−44.3%	−23.6%	−27.2%
Grapes	−0.8%	−0.5%	−0.3%
Lettuce	−1.5%	−1.0%	−0.5%
Melons	−1.4%	−0.7%	−0.7%
Onions	−0.3%	−0.2%	0.0%
Potatoes	−0.7%	−0.5%	−0.2%
Sugar Beets	−3.2%	−2.4%	−0.8%
Wheat	−2.5%	−9.2%	7.3%

[a]$\%\Delta$ *output* = $\%\Delta$ *yield* + $\%\Delta$ *acreage* + ($\%\Delta$ *yield* X $\%\Delta$ *acreage*)/100.

Table 6. Change in SM Region Farm Labor in Response to Reduction in Regional Water Supplies

	Percent Change in Farm Labor	Crop's Share of Regional Labor Reduction
	Nonirrigated Crops	
Alfalfa	1%	–[a]
Barley	10%	–
Corn	3%	–
Sorghum	0%	–
Wheat	0%	–
	Irrigated Crops	
Alfalfa	−5%	31%
Apples	−13%	8%
Barley	−13%	7%
Broccoli	0%	–
Cauliflower	0%	–
Citrus	−2%	–
Corn	0%	–
Cotton	−44%	35%
Grapes	−1%	–
Lettuce	−1%	14%
Melons	−1%	2%
Onions	0%	–
Potatoes	−1%	–
Sugar Beets	−3%	–
Wheat	0%	–
Total Farm Labor	−3%	

[a]Labor for this crop accounts for less than 1% of the total reduction in regional farm labor.

little yield penalty. The implied yield (or output) elasticities with respect to water in USARM are certainly in line with the estimates of these studies. For many of the crops, the elasticities implied by the USARM model are actually larger than those estimated in econometric studies.

[45] One may interpret results as follows. In the model, water applications can fall over a range without much of a loss in revenue. For high-value, specialty crops, water is reduced as long as it has a negligible effect on revenues. In USARM, many specialty crops, such as broccoli, cauliflower, citrus, melons, and potatoes have large net returns per acre, more than $1,000 per acre. Although *marginal* net losses can be low for *small* changes in water use, beyond a point, reducing water to these crops is costly. However, the model stops reducing water to those crops before that threshold is reached. For crops with lower returns per acrefoot (cotton, apples, barley, wheat, and alfalfa), water applications can be reduced further. While this significantly lowers yield and overall production, it has relatively less effect on net income. In sum, the region adjusts to the water supply shock by preserving production of high return crops at the expense of crops with lower returns per acrefoot of applied water.

5.4. Labor

[46] Total regional farm employment falls by 3%, with the greatest percentage reductions in cotton (44%), followed by irrigated barley and apples (13%) (Table 6). Cotton accounts for 35% of reduction in total farm labor, while alfalfa accounts for 31% of the reduction. Although labor use in alfalfa falls only 5%, alfalfa is so widely produced that it accounts for a large share of the region's agricultural labor use. Cotton, alfalfa, and lettuce account for nearly 80% of the total reduction in farm labor use. Even though lettuce experiences a small percentage reduction in production, it is relatively labor-intensive and accounts for a significant share of regional farm labor. Arizona accounts for the bulk of cotton farm labor and virtually all of the regional lettuce labor. Broccoli, cauliflower, melons, and citrus—grown almost exclusively in Arizona—account for about 3% of the regional decline in farm labor. The labor reductions represent on-farm jobs only and do not account for losses in farm-related jobs, such as postharvest processing or transportation jobs or jobs in agricultural input industries.

5.5. Net Farm Income

[47] Net farm income from nonirrigated crops (in Colorado, Utah, and New Mexico) increase by $3.9 million, while net income from growing irrigated crops falls by over $15 million (Table 7). The largest fall in income is in irrigated alfalfa production (nearly $10.5 million) and cotton production (nearly $2.5 million). Irrigated alfalfa accounts for 65% of the total loss in regional net farm income, while cotton accounts for 15%. Cotton faces the largest percentage reduction in net farm income, however, with a 44% loss. Net income from specialty crop production falls little in percentage terms. Income for some specialty crops actually increases.

[48] Two factors explain, in part, why the large water supply shock has a small effect on the net incomes of SM producers. First, producers respond to water shortages by cutting back water use and production for the least profitable activities. This will be production on the least productive land, which has the highest marginal and average production costs. This generates a pivotal shift in supply curves, such that marginal costs at low production levels change very little, so the percentage change in net income can be small.

Table 7. Change in SM Region Net Income in Response to Water Supply Shock

	Net Income[a]	Percent
	Nonirrigated Crops	
Alfalfa	$581	2%
Barley	$31	10%
Corn	$175	3%
Sorghum	$259	2%
Wheat	$2899	3%
Subtotal	$3944	
	Irrigated Crops	
Alfalfa	−$10,455	−2%
Apples	−$130	−9%
Barley	−$811	−6%
Broccoli	$108	1%
Cauliflower	$34	0%
Citrus	−$406	−2%
Corn	−$423	0%
Cotton	−$2481	−44%
Grapes	−$5	0%
Lettuce	$595	6%
Melons	−$307	−1%
Onions	$138	0%
Potatoes	−$332	0%
Sugar Beets	$72	1%
Wheat	−$775	−3%
Subtotal	−$15,178	
Total	−$11,234	

[a]Net income change in $ thousands.

[49] A second reason has to do with the price elasticity of demand for specialty crops. Demands for these commodities tend to be highly inelastic [*Henneberry et al.*, 1999; *You et al.*, 1996; *Hatchett*, 1997; *Onunkwo and Epperson*, 2000; *Nuckton*, 1978]. Rising prices create a "natural hedge" against the water supply shock as part of the cost of the shock is passed on to consumers. We estimate that if SM irrigators were not able to pass price increases on to consumers, their net income losses would have been about $22 million, instead of $15 million.

[50] Although some of the costs of water shortages are passed on to "consumers" in the form of higher prices, many of these "consumers" are agricultural producers as well, primarily livestock and dairy producers. Direct losses nationally to livestock and dairy producers from higher alfalfa and corn prices totaled $47 million. Thus, model results suggest the largest losses to agricultural producers from SM water supply shocks are felt via higher animal feed prices.

5.6. Rationing Model Results

[51] It is interesting to compare USARM results with those of a "rationing model" approach [*Dale and Dixon*, 1998; *Sunding et al.*, 2002; *USBOR*, 2007]. In this approach, the only way growers adapt to water shortages is to fallow land. To adapt to lower regional water supplies at least cost, growers fallow the "lowest-value" crops first. Crops are ranked by net revenue per acrefoot of water applied and acres are fallowed until the water supply constraint is met. *Sunding et al.* [2002] argue that crop mix choices are predetermined in the short-run given climate, installed production technology, preexisting postharvest technology, and infrastructure. Thus, a reasonable response to short-run water shortages may be to simply plant fewer irrigated acres of low-return crops and maintain current production practices on remaining acreage. A comparison between results of a rationing model and USARM illustrates differences in immediate, short-run responses to water shortages and medium term adjustments that would include changing crop mix, irrigation intensity, and use of other inputs.

[52] For the purposes of comparison, rationing model results can be estimated using the net returns per acre data used to calibrate the USARM model. The rationing model provides estimates of the costs of a land-fallowing only response to water shortages and has quite modest data requirements (only estimates of net returns per acrefoot of water and acreage are needed). One drawback of the rationing model approach is that it treats output prices as fixed and thus does not measure how output price increases affect farm income. Another drawback, common to linear programming, is that one gets extreme solutions. For example, production of some lower-return crops ceases completely, while production of higher-value crops is completely unaffected. For a 25% reduction in SM irrigation water availability, under the rationing model, all cotton, barley, and apple production ceases as acres to these crops are fallowed. Some alfalfa acreage is also fallowed to meet the new water availability constraint, although the percentage reduction in alfalfa acreage is small. Acreage and production for other crops remain unchanged. In USARM, cost functions are quadratic in acres planted. This means that marginal returns are lower than average returns and prevents extreme corner solutions. Thus, in USARM, cotton, barley, and apple acreage is not eliminated, although acreage for these crops faces the largest percentage reductions (Table 2). *Chen and Önal* [2012] have recently questioned both the PMP and historical crop mix approaches to model calibration for not allowing sufficient flexibility to adjust to large, unprecedented shocks. To address this concern, they have developed "synthetic crop mixes" using estimated supply elasticities to increase model flexibility. The rationing model implies greater supply contractions in cotton, barley and apples than USARM allows. A more flexible parameterization would yield greater supply reductions for these crops, but lower supply reductions for other crops.

[53] Under the price exogenous, rationing model, the cost of a 25% reduction in water supplies to SM irrigators is $65 million. Under USARM, direct costs to irrigators are $22 million if producers cannot pass price increases on to consumers and $15 million if they can. While losses under the rationing model reflect the direct costs of a land-fallowing only response, the USARM results reflect additional grower responses that include changing crop mix, deficit irrigation, input substitution, Compared to the land-fallowing only response, these other adjustments reduce the costs of water shortages to crop producers by 66%. The ability to pass some costs on to crop purchasers reduces costs by an additional 9% of the $65 million base.

5.7. Prices and First Purchaser Impacts

[54] Most crops in the model experience slight price increases. For 17 of 32 crops, prices rise less than 0.1%.

For 24 of the 32 crops, prices rise less than 0.2%. Only three crops experience price increases of more than 0.5%. Cotton prices rise 1.1%, walnut prices rise 0.6%, and sugar beet prices rise 1.1%. The SM region accounted for about 11–12% of total U.S. production of alfalfa, broccoli, cauliflower, and melons, 16% of onion production, and 24% of lettuce production. The commodities with the larger price effects, however, represent responses to the 5% water reduction in California. Price increases are limited because of supply response in other regions of the country. For example, nationally, alfalfa production falls by only 0.37%; feed grain production changes little—corn production falls 0.01%, barley production falls 0.56%, and sorghum production remains unchanged. Combined, California and the SM region accounted for 14% of U.S. cotton production and 16% of sugar beet production. California accounted for virtually all walnut production. Although, shocks to California were originally included to capture effects on specialty crops, California production adjusted primarily by reducing production of field crops (e.g., cotton, sugar beets). Thus, there were relatively little price effects for specialty crops.

[55] Because of reduced production and higher commodity prices, total first purchaser surplus declines by $129.7 million. About 55% of this loss is borne by first purchasers of cotton and alfalfa. Alfalfa first purchaser surplus falls $36.2 million, while cotton consumer surplus falls $35.6 million. Cotton gins and dairy producers will feel these losses as first purchasers of cotton and alfalfa. Small grain (wheat and barley) first purchaser surplus falls by $5.1 million, while lettuce, citrus, broccoli, melons, cauliflower, onions, and walnuts account for $10.8 million in first purchaser losses. Somewhat surprisingly, corn accounts for 14% of the purchaser losses, at $18.1 million. This occurs even though percent changes in national corn production (−0.01%) and price (<0.05%) are minuscule. This happens because sales from corn are so large, that base consumer surplus is more than $66 billion. The $18.1 million consumer loss represents a reduction of less than 0.03% in corn purchaser surplus. If purchaser losses are proportional to purchaser share of uses, U.S. feed grain purchasers would feel about $10.8 million of this loss, with corn purchasers for biofuels and food production facing the remainder.

5.8. Economic Welfare Effects

[56] Turning to overall welfare effects, the water supply shock redistributes income from first purchasers nationwide to agricultural producers outside the SM region. First purchaser surplus falls by nearly $130 million. Of this, purchasers of alfalfa lose $36 million from higher prices, while feed corn purchasers lose $11 million. As production in the SM region and California contracts, producers elsewhere gain from the higher prices that generates. Producers in other regions are also able to increase their sales volumes slightly. Thus, producer surplus in the SM region falls by $11 million (from $15 million in irrigator losses and a $4 million gain in nonirrigated net income). Producer surplus in the rest of the United States, however, increases by $101 million (Table 8). Government payments fall by about $30 million, because these decline when market prices rise. Changes in government payments need to be deducted because they contribute to producer surplus. Failure to account for them would lead to double counting in overall welfare calculations. The change in welfare, ΔW is calculated as

Table 8. Welfare Impacts of the Water Supply Shock

Changing Parameter	$ Millions
Total Consumer (First Purchaser) Surplus	−130
First Purchaser Surplus, U.S. Alfalfa	−36
First Purchaser Surplus, U.S. Feed Corn	−11
First Purchaser Surplus, U.S. All Other	−83
Total Producer Surplus	90
Other Producer Surplus	101
SM Producer Surplus	−11
Government Payments	−30
Welfare	−10

$$\Delta W = \Delta CS + \Delta PS - \Delta GP,$$

where ΔCS = change in consumer surplus, ΔPS = change in producer surplus and ΔGP = change in government payments. The water supply shock reduces net welfare nationally by $10 million (Table 8). Aggregate welfare effects are modest because large, national first purchaser losses are counteracted by large gains in producer surplus outside the SM region. These losses are direct impacts, excluding indirect or induced impacts on income or employment of adjustment costs that might result from responses such as cotton gins closing.

6. Conclusions

[57] This study examined how large reductions in irrigation water supplies might affect crop agriculture in the Southern Mountain region of the United States. Agriculture can reduce water use by fallowing land, switching to less water-intensive crops, reducing water applications per acre, or substituting other inputs for water. U.S. Agricultural Resources Model (USARM) simulations quantified the importance of such adjustments for reducing the costs of water scarcity. Estimates from a rationing model suggested that a 25% reduction in irrigation water supplies to the Southern Mountain (SM) region would reduce irrigator income by $65 million. The rationing model permitted fallowing as the only response to water shortages. When USARM simulations allowed growers to adjust more flexibly—including other responses beyond fallowing—irrigator losses fell to $15 million, a reduction of 77%.

[58] Deficit irrigation proved to be a key response to water shortages. Losses to producers were relatively modest, in part because crop yield elasticities with respect to water applications were low in USARM. These low elasticities implied that, up to a point, water use intensity could be reduced significantly with relatively little penalty to net farm income. Irrigators cut water applications most to crops with the lowest returns. Although the elasticity parameters in USARM were low in an absolute sense, they were larger than elasticities estimated in the available published literature. Given the important implications of the simulation results, this suggests that more research is needed to develop more and better estimates of water-yield elasticities under actual, on-farm production in the Western United States.

[59] Our model simulations only considered the impacts of water reallocation out of agriculture and thus did not include all impacts one might expect in a full drought or climate change scenario. For example, yields of dryland crops were assumed to remain unchanged. Thus, our analysis may be optimistic by overstating the scope for producers to shift to dryland production in response to water shortages. Again, this suggests that more research is needed to estimate drought or climate change impacts on dryland production in the West.

[60] Two other future research needs are modeling impacts to the livestock sector and linking economic models of regional agriculture to hydrological models. Livestock sales account for roughly a third of Southern Mountain agricultural sales. Previous studies have found changes in water availability to have important impacts on allocation of land between crops and pasture, herd size and livestock producer returns [*Reilly et al.*, 2001, 2003; *McCarl*, 2006]. Our own results suggest that higher alfalfa and feed grain prices account for a significant share of the economic welfare losses of water shortages. Previous studies have also demonstrated that integrating hydrological and economic models can provide important insights about factors like return flows, groundwater depletion, potential third-party effects and gains from water transfers.

[61] While models examining costs of water shortages often assume that output prices are fixed, our results demonstrate the importance of output price effects and impacts on consumers. Here, consumers may be thought of as first-purchasers of crops. In many cases, these are agricultural producers themselves, purchasing alfalfa for dairies or corn for livestock feed. First purchaser losses were significant, about $130 million. Nationally, losses to purchasers of alfalfa and feed corn totaled $47 million alone. Rising prices generated $101 million in producer surplus gains for growers outside the SM region. Supply responses by producers in other regions were important in limiting price increases.

[62] Thus, while SM agriculture, as a whole, was resilient to the water supply shock, livestock and dairy producers were vulnerable, as were producers of some SM crops. Among these were cotton, barley, alfalfa, and apples. Regional farm employment fell by 3%. Employment impacts would be felt relatively more in Arizona because labor demand fell more for crops grown primarily in Arizona than for other crops grown in the SM region. For similar reasons, regional acreage reductions were modest overall, but would be proportionally greater in Arizona.

[63] As a holder of junior water rights to Colorado River deliveries, the Central Arizona Project, and its irrigators, would be among the first affected by severe regional water shortages. Results suggest that field and forage crops would be the first to contract in the face of water shortages, while producers would maintain production of higher-valued specialty crops. This implies that field and forage crop production in Central Arizona would be relatively vulnerable to severe water shortages in the Southwest. Dairies in Central Arizona would also be negatively affected from higher prices of alfalfa. However, agriculture along the Colorado River main stem would continue to be a national center of specialty crop production, even in the face of large regional water shortages.

Appendix A: U.S. Agricultural Resources Model

A1. Objective Function

[64] The objective function represents the aggregate consumer (domestic and foreign) and producer welfare for all regions and activities:

$$
\begin{aligned}
\Pi = & \sum_i \left[\alpha_i \sum_w \sum_r q_{iwr} + 0.5\delta_i \left(\sum_w \sum_r q_{iwr} \right)^2 \right] \\
& - \sum_i \sum_w \sum_r \tau_{iwr} q_{iwr} \\
& - \sum_r \left[v_{r1} \sum_i \sum_w x_{iwr1} + 0.5\omega_{r1} \left(\sum_i \sum_w x_{iwr1} \right)^2 \right] \\
& - \sum_i \sum_w \sum_r \eta_{iwr1} x_{iwr1} \\
& - \sum_i \sum_w \sum_r \sum_j \left(\rho_{iwrj} x_{iwrj} + \varphi_{iwrj} x_{iwrj}^2 \right)
\end{aligned}
\quad \text{(A1)}
$$

[65] This formulation ensures a competitive market equilibrium solution. The first expression in brackets measures the area under the crop-specific linear market quantity-dependent demand equations for each crop i. The variable q_{iwr} represents the output of crop i, produced under cultivation condition w ($1 =$ dry and $2 =$ irrigated), in region r. The coefficient τ_{iwr} accounts for marketing and transportation costs. The third expression allows the land rents to be endogenous at the regional level, where v_{r1} and ω_{r1} are the intercept and slope of regional linear land supply equations. The coefficient η_{iwr1} accounts for the difference between the regional average land rent and the crop activity specific land rents in that region.

[66] The last term in the objective function is a quadratic cost function, where ρ and φ are the coefficients, and the variable x_{iwrj} is the amount of input j ($j = 1, \ldots, 7$ with $1 =$ land input) used in the cropping activity i, w, r. This function is quadratic in the land input and linear in the others. The quadratic cost function captures the fact that as more land is allocated to a specific crop, the marginal cost increases as marginal lands with lower yield potential come into production. It also allows for the exact calibration of the model solutions to the base year levels of crop acreage following *Howitt*'s [1995a, 1995b] Positive Mathematical Programming (PMP) method. The PMP approach eliminates the need to use upper and lower bound constraints on the activity levels when simulating policy scenarios. Another popular approach to avoid over-specialization is to calibrate the model to replicate historical crop mixes and allow for convex combinations of those crop mixes [*McCarl*, 1982; *Önal and McCarl*, 1991].

A2. Nested CES Production Functions

[67] The regional total output from each cropping activity q_{iwr} (indices are dropped for brevity) is defined by the following nested-CES production function with seven categories of inputs:

$$Q = C\left\{\beta_F\left[C_F\left(\sum_{j=1}^{2}\beta_j x_j^{\gamma_F}\right)^{1/\gamma_F}\right]^{\gamma} + \beta_V\left[C_V\left(\sum_{j=3}^{7}\beta_j x_j^{\gamma_V}\right)^{1/\gamma_V}\right]^{\gamma}\right\}^{1/\gamma}. \quad (A2)$$

[68] The function consists of two nests. The first nest, in the first set of brackets, includes the allocable inputs, land and water. The second nest, in the second set of brackets, is for the remaining five variable inputs: agricultural chemicals, fertilizers, labor, capital, and energy/other inputs. Each nest is in itself a CES function. A nested-CES function is more flexible than a regular CES function because there can be more than one elasticity of substitution between inputs. In agricultural crop production, the ability to substitute inputs varies significantly [*Debertin et al.*, 1990; *Hertel et al.*, 1989; *Rendleman*, 1993; *Ray*, 1982].

[69] In the nested CES production function, the nests can be thought of as hierarchies. Equation (2) has the higher nest parameters on the outside. The scalar C is the top-nest scale parameter, and β_F and β_V are the top-nest share parameters for allocable and variable inputs. Moving to the lower nests, C_F and C_V are scale parameters for allocable and variable input nests, respectively. The quantity of input j allocated to each cropping activity is indicated by x_j, where the j values of 1 and 2 correspond to allocable inputs of land and water, and the remaining values of j (from 3 to 7) correspond to variable inputs. The parameter β_j is the share parameter of the jth input. In addition to index j, input quantity x is indexed over i, w, and r, which are dropped here for brevity. The coefficient $\gamma = (s - 1)/s$, where s is the top-nest elasticity of substitution coefficient. Finally, $\gamma_F = (s_F - 1)/s_F$ and $\gamma_V = (s_V - 1)/s_V$, where s_F and s_V are the elasticity of substitution between the allocable inputs and the elasticity of substitution between the variable inputs. For the dryland cropping activities, the allocable input nest has only the land input as its argument.

A3. Resource Constraints

[70] In the following discussion, indices on x are reintroduced: i (crop), w (irrigation condition), r (region), and j (input). Regional irrigation water constraints limit the total irrigation water used by all irrigated crops ($w = 2$) in a region to the actual total irrigation water ($j = 2$) used in the region in the base year, $\underline{X}_{2r2}$. This constraint is specified as

$$\sum_i x_{i2r2} \le \underline{X}_{2r2} = \underline{S}_{2r2} + \underline{G}_{2r2} \quad (A3)$$

where $\underline{S}_{2r2}$ is total surface water availability and $\underline{G}_{2r2}$ is total groundwater availability.

[71] The regional irrigation land constraint restricts the total land allocated to irrigated cultivation to the total actual base year irrigated acreage

$$\sum_i x_{i2r1} \le \sum_i \underline{X}_{i2r1} \quad (A4)$$

A4. Empirical Specification

[72] The coefficients of the demand equations, α_i and δ_i, are derived by solving crop specific linear demand equations, where a crop's aggregate demand elasticity and the base year aggregate market price and quantities are given. The coefficient τ_{iwr} is measured as the difference between the national market and the regional price of each crop in the base year. Parameter τ reflects the deviation of a region from the average transportation and marketing costs. In the policy runs, the national level market price for each crop is endogenously determined. During the solution, τ maps the national crop prices to their regional levels, maintaining the deviation of regional crop price from the national average.

[73] The coefficients of the regional land supply equation, v_{r1} and ω_{r1}, are calculated by solving a region specific linear equation, where the regional average land rents, land in crop production, and land supply elasticity are given. The supply elasticity is derived from a special run of a model presented in the work of *Lewandrowski et al.* [1999]. The coefficient η_{iwr1} is calculated as the difference between the crop specific land rent in each region and the average land rent for that region. The method of calculating the cost function coefficients ρ and φ (for land only) is based on *Howitt*'s [1995a, 1995b] PMP approach. First, a linear programming problem is solved. In this problem, the objective function is linear net profit. Output prices, regional resource use, and the acreage of each activity are constrained at their base year levels. From the solution, the shadow value of each activity specific acreage constraint, λ, is obtained. The slope coefficient for each activity φ_{iwr1} equals $2\lambda_{iwr1}/x^*_{iwr1}$, where x^* is the base year acreage of the respective activity. To get ρ, we subtract λ from the per acre cost of the land input. For the nonland inputs, φ and λ are zero, so $\rho_{iwrj} = c_{iwrj}$ for $j = 2$–7.

[74] The elasticity of input substitution coefficients of the nested-CES function (equation 2) are derived from several empirical sources. The values of the substitution parameter between land and water are obtained from *Hatchett* [1997]. In this study, separate elasticities for truck crops, row crops, and alfalfa for California are estimated. Due to the lack of empirical estimates for the other states, and the fact that the range of irrigation technologies is similar across regions, the California elasticities for irrigated activities are used in all regions.

[75] The values of the input substitution parameters for the top nest, i.e., the allocable and variable inputs nest, and the substitution parameter for the inputs in the variable input lower nest 2, are based on *Hertel et al.* [1989] and *Rendleman* [1993]. *Rendleman* [1993] estimates own-price and cross-price elasticities of derived demand for several inputs used in the production of food grains, feed grains, oilseed crops and cotton. His input categories, with the exception of 'energy/other' inputs, closely resemble ours. For the 'energy/other' category, we rely on estimates from *Hertel et al.* [1989]. From the Allen partial elasticities of substitution found in the work of *Hertel et al.* [1989] and *Rendleman* [1993], we calculate Morishima elasticities of substitution. Morishima elasticities are relevant for the type of CES function we use here [*Blackorby and Russell*, 1989]. The pairwise Morishima elasticities are weighted by each input's cost share in the variable input nest to come

up with a single crop- and region-specific elasticity of substitution for nest 2. The elasticities of substitution for the top nest, i.e., between allocable and variable input nests, are calculated in a similar fashion, using original estimates from the three empirical sources.

[76] The values of the remaining parameters of equation (2) (C, β_F, β_V, C_F, C_V, and β_j) are obtained by solving the first-order conditions of a profit maximization problem defined by equations (1)–(4). The known quantities are elasticity of input substitution, base year levels of acreage, output, input use under each activity, and regional crop prices, along with shadow values of the regional land and irrigation water constraints.

[77] To summarize, in the first stage, a linear programming problem is solved. The shadow value estimates from the solution, along with input substitution coefficients and the base year levels of the variables, are used to calculate coefficients ρ and φ in equation (1) and coefficients C, β_F, β_V, C_F, C_V, and β_j in equation (2). In the second stage, the model defined by equations (1)–(4) is solved. The crop prices are endogenous in the second model. Both models are written in GAMS software and solved sequentially with the MINOS optimization algorithm on a PC [*Brooke et al.*, 1992]. The base year solution of the second model exactly replicates regional base year acreage and input use in each cropping activity and output price.

[78] USARM was originally calibrated to match acreage and price data for field crops in 2002 and specialty crops in 2000. Recent relative price changes, however, have significantly altered the crop mix in the region. Output prices for major field crops were changed to reflect changes in relative prices in 2007. For example, corn and wheat prices were increased, while cotton prices were reduced. Thus, relative prices and acreage planted to major crops have adjusted to reflect the new environment with more acreage planted to wheat and corn and less to cotton.

A5. Data

[79] The primary budget data on the field crops, except alfalfa hay and sugar cane, are extracted from the results of the most recently available Cost of Production Surveys. The surveys are conducted by the USDA agencies NASS and ERS every 5–8 years for each commodity. Occasionally, the surveys leave out states with significant acreage. This also occurs for alfalfa and sugar cane. In these instances, the data are obtained from the crops budgets published by various State Cooperative Extension Service offices. State-level acreage, yield, and market prices were obtained from USDA's National Agricultural Statistics Service (NASS), Historical Data, Crops County Data Files.

[80] A total of 396 detailed cost of production budget estimates from 35 states, covering 22 vegetable and fruit crops were collected. The crops were aggregated into 22 groups. Most of the 396 budgets are authored by State Cooperative Extension economists or crop specialists. In a few cases, state growers' association experts provided budgets. In some states, most notably, Arizona, California, Florida, Idaho, Oregon, Texas, and Washington, multiple budgets for the same crop were collected to capture the diversity in the states' growing conditions. The model captures 97.8% of the actual year 2000 acreage of the included vegetable and fruit crops.

[81] Domestic and export elasticities for the field crops are obtained from R. C. Green and J. M. Price (Estimates of short-run price elasticities for major U. S. field crop and livestock commodities using FAPSIM, unpublished report, U. S. Dept. of Agr., Econ. Res. Serv., 1987), *Hertel et al.* [1989], and *Knapp and Konyar* [1990] For the vegetable and fruit crops, usually only aggregate demand elasticities were available [*Henneberry et al.*, 1999; *You et al.*, 1996; *Hatchett*, 1997; *Onunkwo and Epperson*, 2000; *Nuckton*, 1978]. Elasticities were disaggregated into domestic and export elasticities using the following procedure. Total output, domestic consumption, export quantity, market prices, and aggregate demand elasticities are given. Using these data and employing a maximum entropy approach, domestic and export demand elasticities were solved optimally such that the resulting elasticities guarantee market clearance in the two markets as well as that the individual elasticities sum up to the aggregate elasticity.

[82] Data on program acres and yield by state were obtained from USDA, Economic Research Service (ERS) data files (available at http://ers.usda.gov/Data/BaseAcres/Download.aspx). Available data include base acres designated under the 2002 Farm Act, by commodity, including base acres updated to 1998–2001 plantings under the 2002 Farm Act as well as state-level program yields used to determine direct and CCP payment rates for each program commodity. *Young et al.* [2005] describe the data and programs in detail.

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