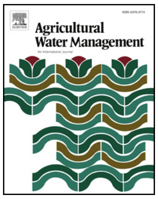
Agricultural Water Management 243 (2021) 106438

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat



A decade of irrigation water use trends in Southwest USA: The role of irrigation technology, best management practices, and outreach education programs

Isaac K. Mpanga[a,*], Omololu John Idowu[b]

[a] *Cooperative Extension, University of Arizona, Camp Verde, AZ, 86322, United States*

[b] *Extension Plant Sciences /Plant & Environmental Sciences, New Mexico State University, MSC 3AE P. O. Box 30003, Las Cruces, NM, 8003, United States*

ARTICLE INFO

Keywords:
Irrigation
Water
Harvested cropland
Best management practice
Sprinklers
Dripsystems

ABSTRACT

Irrigation water is crucial for farm operations in the world, with irrigated lands contributing about 40% to food and fiber production. In semi-arid regions such as the Southwestern United States, the demand for irrigation water has increased due to population growth, rising temperatures, and severe drought events in the region. Irrigation plays a vital role in the economies of southwestern states and requires comparative studies to understand the current situation and propose possible improvement strategies. This study investigated the trend of irrigated cropland, the quantity of irrigation water use, irrigation technology, scheduling decisions, and irrigation outreach using data from 2007 and 2017 United States Department of Agriculture (USDA) National Agriculture Statistics Service (NASS) census. Harvested cropland in the region remained the same with minimal increase in total irrigated land (1%) and the quantity of irrigated water used (2%). However, gravity irrigation methods reduced significantly by 12%, with a 71% increase in the use of drip irrigation systems. The increase in the adoption of soil moisture sensors (55%), plant sensors (107%), government schedules (29%), and supplier's schedules (50%) for irrigation scheduling decisions, did not translate to a reduction in irrigation water use at the regional level. However, at the state level within the same period, Arizona recorded an increase in irrigated cropland by 10% and harvested cropland by 9%, with a reduction in the quantity of irrigation water used (-5%). The gains in Arizona could be associated with the combined effects of improved irrigation technologies and the use of best management decisions, which could serve as a model for prudent water use in the southwest. There is a need to increase the effort in science-based education and extension programming on integrated approaches that emphasize both irrigation technology and the best management practices, which include seed selection for drought-tolerant crops.

1. Introduction

Irrigation farmlands provide about 40% of food and fiber used in the world, with increasing demand for irrigated acreage due to climate variabilities and rising food demands of the growing population (Evans and Sadler, 2008). Drought spells and rising temperatures are occurring, especially in semi-arid and arid regions of the southwestern United States, where annual evaporation and transpiration exceed the rainfall. Southwest is the hottest part of the nation (USGCRP, 2014). The United States Environmental Protection Agency (EPA), in 2014, reported average temperatures in the southwest increased by 2 °F (1.12 °C) from 2000 to 2013 relative to the long-term average from 1895 – 2013. The over-allocation of surface waters and the 20 year-long droughts have affected the Colorado River watershed (USGCRP, 2014), which is a major source of water supply for the southwest. The prolonged continuous droughts and over-allocation of the river waters may lead to an official water shortage declaration in most of the southwestern states. Though a state like Arizona has a great history of robust, innovative groundwater regulation, such a declaration may affect irrigation water supply with potential pressure on groundwater withdrawal and likely increases in prices of water rights and farm produce (Lahmers and Eden, 2018). Irrigation is a crucial component for crop production in the southwest, especially in states like Arizona, where more than 90% of croplands are irrigated, with about 74% of the total water used in Arizona going into agriculture (Arizona Department of Water Resources, 2020). Crop production contributes significantly to the economies in the southwest, hence the need to understand advances made in irrigation water use for crop productions in terms of irrigation

---

* Corresponding author.
E-mail address: mpangai@arizona.edu (I.K. Mpanga).

https://doi.org/10.1016/j.agwat.2020.106438
Received 18 June 2020; Received in revised form 6 August 2020; Accepted 7 August 2020

technology and best management practices (BMP), which includes seeds selection for prudent water management.

According to Carey and Zilberman (2002) and Genius et al. (2014), developing intensive extension and educational programs on irrigation could give producers the right information to transition from unsustainable traditional irrigation practices to smart irrigation technology that may lead to water saving in agriculture. Studies have shown that reducing water withdrawals as a result of smart water use systems in agriculture could increase water supply for other uses such as municipal and environmental applications (Ward and Pulido-Velazquez, 2008; Rockström et al., 2007; Huffaker and Whittlesey, 2000; Hussain et al., 2007), which could be a great strategy in mitigating water shortages. Based on this assumption, we asked the question - could the adoption of smarter irrigation methods in the southwest reduce total irrigation water use in agriculture, thus increasing water availability for other purposes such as municipal and environmental applications without compromising field crop yields?

This study aimed to elucidate a decade of trends of irrigation water use, irrigation technology, and irrigation outreach programs in the southwest, using the United States Department of Agriculture (USDA) census data of 2007 and 2017 in a comparative approach. The study hypothesized no differences in irrigation water use, irrigation technology, and irrigation outreach programs in the southwestern states between 2007 and 2017.

2. Materials and methods

2.1. Study area demographics and precipitation pattern in 2007 and 2017

The locations selected for the study within the southwestern USA include Arizona-AZ, California-CA, Nevada-NE, New Mexico-NM, Colorado – CO, and Utah-UT (Fig. 1).

The number of farms, average farm size, and significant crops grown in the southwest are represented in Table 1. Based on precipitation ranking pattern in the USA, Arizona, recorded below-average in 2017, which is a reduction from near-average in 2007 while UT, CO, and NM registered near-average in both years. However, CA and NV recorded above-average in 2017, which is an improvement from below-average in NV and much-below-average in CA in 2007 (National Oceanic and Atmospheric Administration (NOAA) annual report, 2007 and, 2017).

2.2. Data collection

The USDA, agriculture census data (2007 and 2017) were obtained online at (www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Farm_and_Ranch_Irrigation/index.php) for the study. Data were collected for the following parameters: irrigated lands, harvested irrigated land, the quantity of water used, types of irrigation, methods for water delivery, and methods used to decide irrigation schedules (USDA-NASS; 2008; 2013; 2018).

Fig. 1. Study area (**a**- orange color) (US EPA 2017).

2.3. Data analysis

The years 2007 and 2017 represented the main treatments by the states (Arizona-AZ, California-CA, Nevada-NE, New Mexico-NM, Colorado – CO, and Utah-UT) as the replicates. A *t*-test was then performed in a pairwise comparison, assuming equal variance at $p = 0.005$ using 2007 data as the baseline.

Percentage changes were calculated using the 2007 and 2017 data points in the formula reported by Mpanga et al. (2020) below, to understand the trend of selected parameters.

$$\%\Delta = \frac{Y_2 - Y_1}{Y_1} \times 100$$

where $\%\Delta$ = percentage change, $Y_1 = 2007$ data, and $Y_2 = 2017$ data

2.4. Study limitations

Some limitations of the study included missing or withheld data from the USDA for privacy reasons. However, it did not limit the ability to address the study objective.

3. Results

3.1. Harvested irrigated cropland in the southwest from 2007 to 2017

Harvested irrigated croplands recorded no significant changes from 2007 to 2017 in the southwest. However, quantitatively at the state levels, increases were recorded in Arizona (9%), California (6%), Nevada (7%), and Utah (5%) with reductions in New Mexico and Colorado at 21% and 15% respectively with no statistical difference in any of the categories at the regional level (Fig. 2). California was the highest producer of crops with a yearly average of 2,832,799 ha in the region, followed by Colorado with about 1,011,714 ha. In comparison, the remaining four states (AZ, NE, NM, and UT) were below 404,685 ha each (Fig. 2).

3.2. Total irrigated cropland and quantity of water used in the southwest from 2007 to 2017

The total irrigated cropland in the southwest increased marginally by 1% from 2007 to 2017 with no significant difference. At the state level, increases were recorded in AZ (10%), CA (7%), NE (15%), and UT (3%), while NM and CO decreased by 25% and 14% respectively with no statistical differences at $p = 0.05$ between 2007 and 2017 (Fig. 3a). The result in Fig. 3a is consistent with harvested cropland in Fig. 2. The quantity of water used, however, decreased in most of the states (AZ [-5%], NM[-29%], CO[-15%], UT[-4%]) except CA and NE, which increased by 8% and 34% respectively with a 2% increase at the regional level (Fig. 3b). Arizona and Utah showed water saving by 5% and 4% with gains in irrigated cropland by 10% and 3%, respectively, without statistical differences (Fig. 3 a & b).

3.3. Irrigation methods for water distribution

The USDA census reported data on the types of water distribution systems such as gravity, sprinkler, and drip irrigation systems for 2007 and 2017 (USDA, NASS 2008, and 2018). According to Fig. 4, at the regional level, the use of gravity as an irrigation water delivery system in the southwest reduced significantly by 12% ($p = 0.05$) and sprinklers by 8% from 2007 to 2017. The use of drip, trickle, and low-flow micro-sprinklers increased by 71%, but with no statistical difference at $p = 0.05$ (Fig. 4a), which could be due to the high variability in the measured values at the state level.

There was 71% increase in the use of drip irrigation systems for water delivery from 2007 to 2017 at the regional level by AZ, CA, NE, and UT, with NE and UT contributing the most (45, 74, 431, and 187%

Table 1
Number of farms, and average farm size in 2017 (USDA, 2019) with major crops grown in the southwest of the United States (Arizona-AZ, California-CA, Nevada-NE, New Mexico-NM, Colorado – CO, and Utah-UT).

State	Total number of farms	Average farm size (hectares)	Major crops grown in the state
AZ	19,100	553	Leafy greens, corn, alfalfa, cotton, fruits
CA	70,500	141	Specialty crops (grapes, nuts, fruits, vegetables)
NE	3400	726	Alfalfa, potatoes, small grains, corn, onions
NM	25,000	659	Pecans, hay, onions, chile, cotton, corn, wheat
CO	38,900	331	Alfalfa, corn, small grains
UT	18,400	238	Hay, wheat, fruits, and vegetables

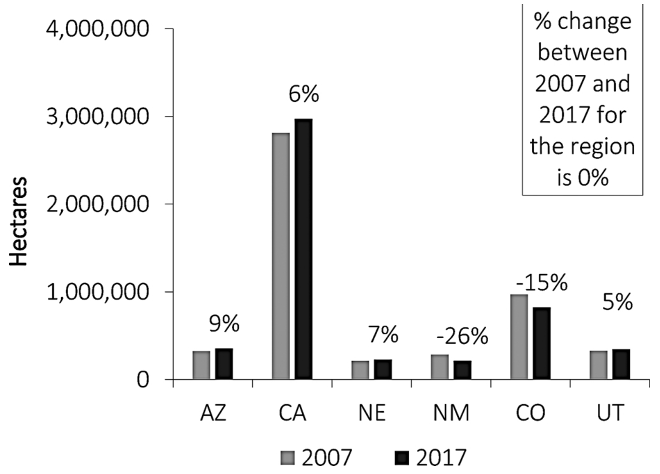


Fig. 2. Harvested cropland in the southwestern USA from 2007 to 2017. (Percentage figures above the bars represent changes from 2007 to 2017. Data obtained from USDA, NASS 2007, 2012, and 2017 Agriculture Census Data. (Percentage figures above the bars represent changes from 2007 to 2017.

respectively) to the increase in the use of drip systems in the southwest (Fig. 4b). The reasons for these increases in the use of drip systems relate to associated benefits such as cost saving for irrigation water, sustainable of water use, potential yield increase, and other advantages such as reduction in weed pressure and soil bone diseases.

3.4. Methods used in making irrigation scheduling decisions

At the regional level, the use of any method was most familiar with about 80, 000 farms, followed by conditions of the crop with 60,000 farms, how soil feels with 30,000 farms, while the rest of the methods together made up less than 20,000 farms, with the use of computer simulation the least used in the region (Fig. 5a). Comparing 2007 and 2017 data, irrigation scheduling by plant sensing methods increased by 107%, while scheduling by soil moisture sensors increased by 55% across the states, although the use of both methods are still relatively low when compared to other scheduling methods (Fig. 5a). Decisions based on information from government and the water supplier schedules increased by 29% and 50%, with minimal increases in any method and conditions of crops (Fig. 5a), but no reported statistical difference in all at $p \leq 0.05$. The regional increases in the use of techniques such as soil moisture and plant sensors, commercial or government schedules, and water supplier companies were influenced by AZ, NE, and NM states with either negative or very minimal contributions from CA, CO, and UT (Fig. 5b). There were decreases in the use of methods such as soil feel (-10%), personal calendar (-12%), computer simulations (-50%), and when the neighbors start irrigating (-10%) (Fig. 5a).

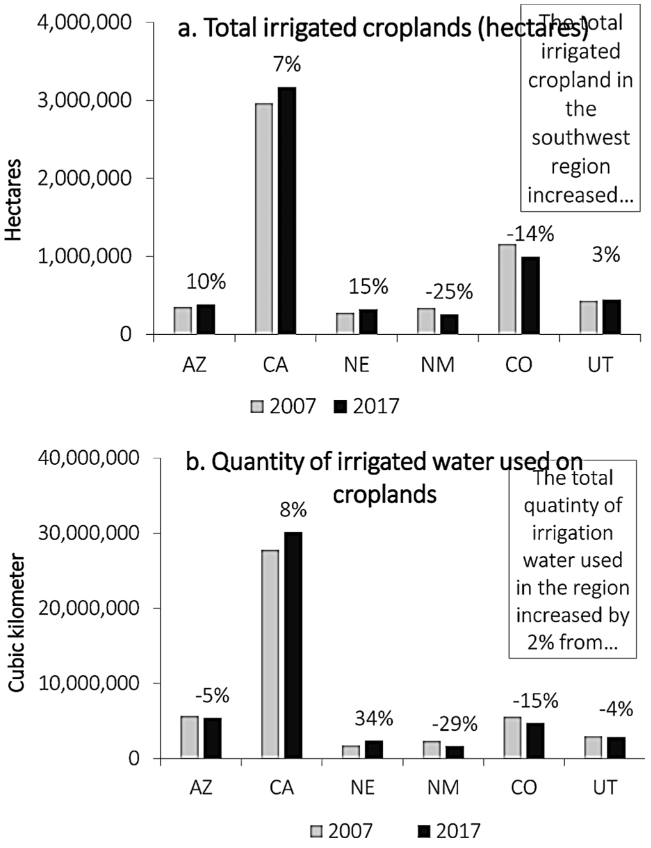


Fig. 3. Total irrigated cropland (**a**) and the quantity of water used (**b**) in the southwestern USA from 2007 to 2017. Data obtained from USDA, NASS 2007, 2012, and 2017 Agriculture Census Data. (Percentage figures above the bars represent changes from 2007 to 2017.

3.5. Irrigation information sources to farmers on how to reduce irrigation costs and conserve water

All outreach programs (including university extension, state and federal agencies, private and media report) as sources of information for growers on how to minimize irrigation cost and conserve water declined between 2007 and 2017, except for the electronic information services such as internet sources, which increased by 38% during the same time period (Table 2).

4. Discussions

This study focused on irrigation practices in crops within the southwest of the United States with comparative analysis of 2007 and 2017 USDA census of agriculture data. Across the region of southwest, there was no increase in harvested irrigated cropland, while total irrigated lands increased by 1%, the quantity of irrigated water also increased by 2% with no significant differences. At the state level, AZ

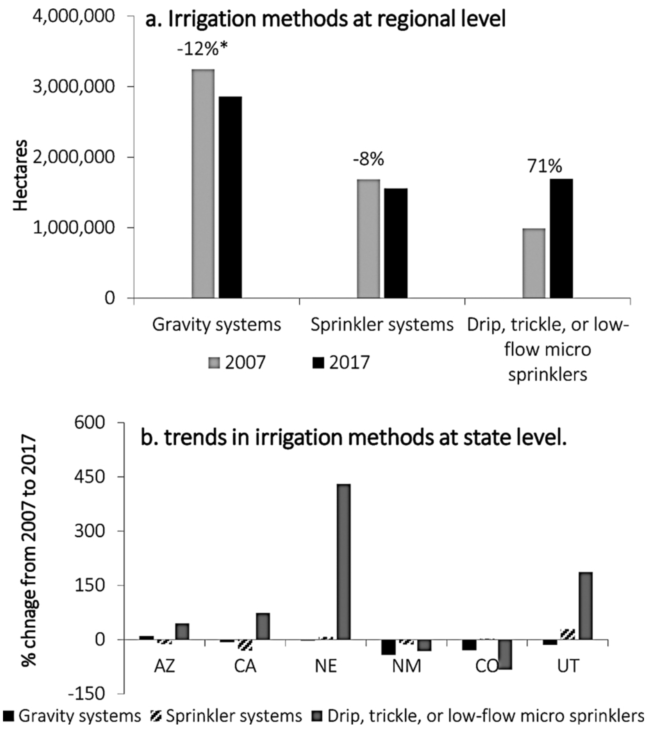


Fig. 4. Irrigation methods at the regional (a) and state (b) levels in the southwestern USA for 2007 and 2017. (Percentage figures above the bars represent changes from 2007 to 2017. Data obtained from USDA, NASS 2007, 2012, and 2017 Agriculture Census Data. (Percentage figures above the bars represent changes from 2007 to 2017, * = significant difference at *t*-test with $p \leq 0.05$).

could serve as a model for irrigation water use improvement, where the quantity of irrigated water decreased (-5%) (Fig. 3b), while the irrigated and harvested cropland increased by 9% and 10% respectively (Figs. 3a and 2) even under a worse precipitation condition in 2017 compared to 2007. (NOAA, 2007 and 2017). The increased efficiency was probably due to the combined effect of irrigation technology and best management practices (Figs. 4a, b, and 5b) as discussed below using Fig. 6.

4.1. Southwest precipitation ranking and irrigation water use in 2007 and 2017

The precipitation pattern did not seem to reduce the amount of irrigation water use in the southwest. For example, the quantity of irrigation water use reduced in AZ, NM, UT, and CO from 2007 to 2017 while there was an increase in CA and NV (Fig. 3b). However, precipitation ranking in AZ reduced from 2007 to 2017. CA and NV recorded a rise in precipitation ranking while UT, CO, and NM remained relatively the same in both years (NOAA, 2007and 2017). Though the precipitation events did now seem to reduce the amount of water use in the region, they play a vital role in refilling the water table after withdrawals (Gardner and Heilweil, 2009). In some cases, farmers may not have the technology and technical irrigation information that will help them understand and adjust irrigation systems to reduce watering during rainfall days. The number of farmers using soil moisture and plant sensors in making irrigation scheduling decisions compared to other methods (Fig. 5a) is a clear evidence that fields could still be irrigated sooner than expected after precipitation events, since most farmers are not using any quantitative method for establishing soil and crop conditions prior to irrigation water application. On the other hand, the increase in precipitation events in the CA and NE could be the driving force behind the increase in the irrigation water use for both states due to more water availability. Unfortunately, the increases in the irrigation water use did not translate into increase in harvested cropland in those two states compared to what was observed in Arizona and Utah. Therefore, understanding the trends in irrigation technology use, best management practices, and irrigation outreach programs is required to support decisions and policy on sustainable irrigation water use in the southwest.

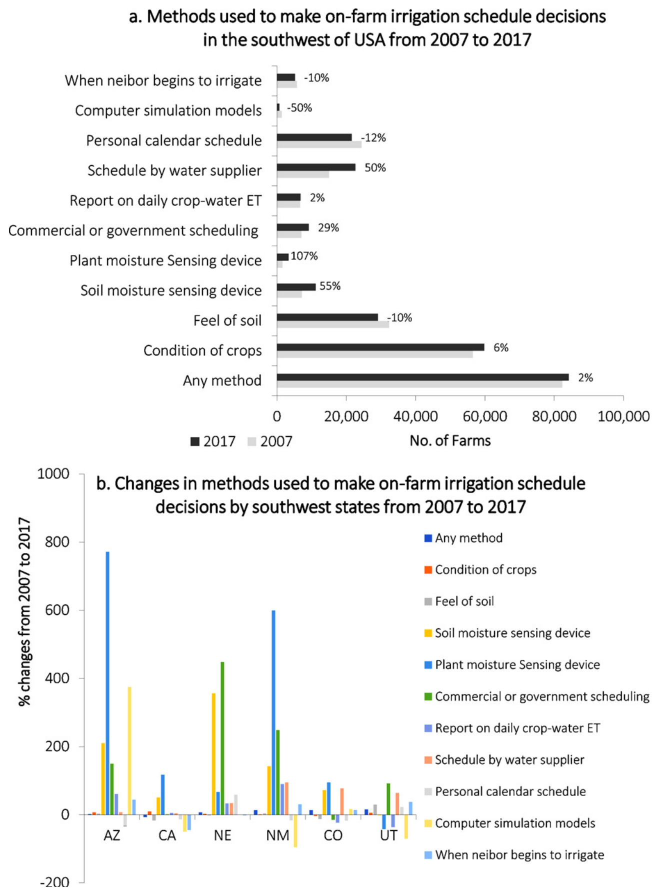


Fig. 5. Methods used by farmers to make on-farm irrigation schedule decisions at the regional (**a**) and state (**b**) levels in the southwest of the USA from 2007 to 2017. Data obtained from USDA, NASS 2007, 2012, and 2017 Agriculture Census Data. (Percentage figures above the bars represent changes from 2007 to 2017.

4.2. Irrigation technology

Growers increased acreage under more efficient systems such as drip (subsurface and micro irrigations) (Fig. 4a and b). In Fig. 4, drip irrigation increased by 71% with significant reduction in gravity methods over the study period. This demonstrates farmers efforts in sustainable water use by transitioning to modern and smart irrigation technologies. Micro-drip, subsurface drip, and pipes reduce water losses to surface evaporation and deliver water by target applications to the plants. This finding is in line with the study by Lahmers and Eden (2018), which reported that the southwest of U.S. made improvements in water use efficiency through improved irrigation technologies. Disadvantages of these irrigation systems compared to open ditches include the initial cost of installation, labor, and maintenance (Fig. 6). Technologies, such as sensors and computer simulations, could reduce delivery waste and on-farm leakages as farmers are now able to deliver water to crops through precision scheduling (Fig. 5a & b, Arizona Department of Water resources, 2020; Fan et al., 2018). Generally, irrigation and water use efficiencies are much higher with subsurface drip systems than the furrow irrigation method (Encisco et al., 2015; Mansour, 2015 and Mansour et al., 2016). Transitioning to a more

Table 2
Irrigation information sources used by farmers on how to reduce irrigation costs and conserve water in the southwestern USA. Data obtained from USDA, NASS 2007, 2012, and 2017 Agriculture Census Data.

	2007	2017	% change from 2007 to 2017
Extension agents or university specialist	20,101	18,109	−10
Private irrigation specialists or consultants	16,191	15,550	−4
Irrigation equipment dealers	10,535	9784	−7
Irrigation district or water supplier	12,437	11,988	−4
NRCS, districts, other federal or state agents	10,540	8945	−15
Media reports	8687	5579	−36
Neighboring farmers	26,689	20,163	−24
Electronic information service (internet links)	5896	8159	38

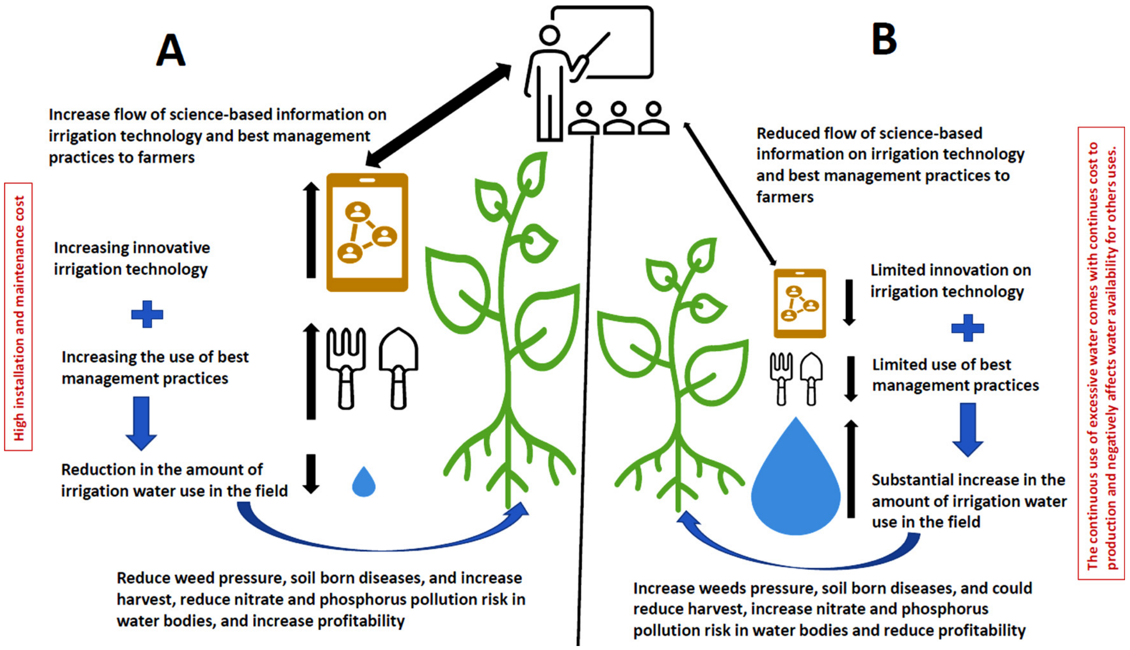


Fig. 6. An ideal approach on how the integrated use of irrigation technology, and best management practices through effective science-based extension and education information flow, could influence irrigation water management and sustainable water use positively (A) and negatively (B). The black arrows show increase (arrow pointing up) or decrease (arrow pointing down) and wide (wider = more information flow) and (narrow = limited information flow).

efficient irrigation system will become more pivotal in the southwestern region, as the impacts of climate change becomes more severe (Fuller and Harhay, 2010). Thompson et al. (2009) highlighted the potential of subsurface drip irrigation as a potential solution to the problem of low water use efficiency in the southwest. The authors also highlighted other added benefits of the subsurface drip systems, including reduced nitrate leaching into the groundwater, higher crop yields, better weed control, crop health (Fig. 6), and flexibility in harvesting specialty crops. All these benefits will improve the bottom line of farmers in the region. As mentioned earlier, installation costs could be a major drawback to the adaptation of these more efficient irrigation methods. This issue could be addressed through the provision of credit facilities to help farmers in the region with the installation of more efficient irrigation systems and by governmental policies that prohibit inefficient irrigation methods such as flood irrigation currently prevalent in the southwestern states.

4.3. *Best management practices*

The method used in making irrigation scheduling decisions play a vital role in making sure the right amount of water is delivered at the right time using the appropriate method. In Fig. 5b, the use of sensors and computer simulations were more prevalent in Arizona, which could be a contributing factor to the water use efficiencies observed in the state, which has also been reported by Yadav et al. (2020) in a technical report with vegetable production in California. Other best management practices introduced through agricultural water conservation include canal lining, laser leveling technology, level basin irrigations, sprinkler irrigation, drip or trickle irrigation, and tailwater re-use systems. Agronomic practices such as crop rotations, also considered as best management practices, contribute to higher water use efficiency (Huang et al., 2003). Mpanga et al. (2020) reported increases in sustainable practices such as conservation agriculture (CA) (no-till, cover cropping, and reduced tillage) in Arizona, could also have contributed to higher water use efficiencies recorded in the state. These practices reduce runoff, improve soil structure for higher water holding capacity, and reduce water evaporation from the soil surface. Hatfield and Dold (2019) reported that depending on climate and soil conditions, cultural practices such as mulching, row spacing, crop rotation, mixed cropping, and agroforestry strategies could increase water use efficiency. Land fallowing could also be used as a conservation strategy. Land fallowing of 1500 acres was tested in 2014 at the Yuma Mesa Irrigation and Drainage District, and this led to savings of about 7000 acre-feet per year of Colorado River water (Lahmers and Eden, 2018).

Crops with higher water use efficiency could be one of the contributing factors to an increase in harvested cropland and a decrease in water use from 2007 to 2017 in Arizona. For example, nut crop production has been on the rise with changes from flood to micro-irrigation systems. In Arizona, alternative crops with higher water use efficiencies such as industrial hemp (*Cannabis sativa*) or guayule (*Parthenium* *argentatum*) are being promoted. Hemp could partially replace cotton for fiber production if the demand for hemp fiber emerges, while guayule is a desert-adapted industrial crop that produces rubber for manufacturing tires (Lahmers and Eden, 2018). The genetic traits, crop species, and variety selections could be another best management practice that can increase water use efficiency in the southwest (Hatfield and Dold, 2019). Breeding techniques such as improving root architecture to access subsoil water and early vigor for rapid soil surface cover will improve water use efficiencies (Condon, 2020). For example, barley cultivars requiring either low or high irrigation input were grown in Arizona under regular and deficit irrigation. The low-irrigation types performed better under drought because of early vigor and flowering, more significant root growth at lower soil depth, and more effective water use during the grain filling stage (Carter et al., 2019). At the plant cell level, osmotic adjustment is the main drought-responsive trait that prevents cellular dehydration under drought stress, apart from developmental and phenological attributes (Blum, 2005). Therefore, species and variety selection are critical to achieving water use efficiency and increased yields under dry conditions such as in the southwest.

4.4. Outreach and educational programs to growers

In most cases, growers need frequent and consistent information and extension service delivery in comprehensive formats on new technologies and practices that can reduce irrigation costs and conserve water. This aspect is very critical for the successful introduction of innovations to growers for adoption. According to Table 2, agricultural extension efforts have reduced over time in the southwest, leaving farmers to depend more on internet links for their irrigation and water conservation information. However, internet sources in many cases may not provide reliable and credible scientific support for the farmers. According to Levidow et al. (2014), to build a sense of responsibility across the entire water-supply chain for improvement in efficient water use, consistent exchange of knowledge is necessary between all stakeholders, which can only be achieved through outreach activities. Based on the results presented in Table 2, most educational activities on irrigation water use requires more efforts in the southwest, to promote smart innovations and technologies on irrigation and water conservation technologies (Fig. 6).

5. Conclusion

Though there was no significant gain in the southwest as a region on prudent irrigation water management, however, the gains made in Arizona and Utah between 2007 and 2017 could serve as a model (Fig. 6A) in the southwestern region. The gains made in Arizona were associated with improved irrigation technologies and the use of best management decisions. To improve water conservation and promote efficient use of water resources in the southwest, an integrated approach that combines both the irrigation technology and best management practices should be a priority for the region. In addition, more research, extension, and outreach programs that address the needs of agricultural stakeholders and water issues using integrated approaches, should be promoted in the region.

Funding

None.

Availability of data and material

(All data used are available at the United States Department of Agriculture (USDA) census website). https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Farm_and_Ranch_Irrigation/index.php (date accessed 06/17/2020)

references

Avramova et al. (2018), Blum (2009), Cernusak (2018), Mingbin et al. (2003)

Declaration of Competing Interest

The authors report no declarations of interest.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2020.106438.

References

Arizona Department of Water Resource (2020). https://new.azwater.gov/conservation/agriculture (Accessed: Feb 2020).

Avramova, V., Meziane, A., Bauer, E., Blankenagel, S., Eggels, S., Gresset, S., 2018. Carbon isotope composition, water use efficiency, and drought sensitivity are controlled by a common genomic segment in maize. Theor. Appl. Genet. 132, 53–63. https://doi.org/10.1007/s00122-018-3193-4.

Blum, A., 2005. Drought resistance, water-use efficiency, and yield potential—are they compatible, dissonant, or mutually exclusive? Aust. J. Agric. Res. 56 (11), 1159–1168. https://doi.org/10.1071/AR05069.

Blum, A., 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field Crops Res. 112, 119–123. https://doi.org/10.1016/j.fcr.2009.03.009.

Carey, J.M., Zilberman, D., 2002. A model of Investment under uncertainty: modern irrigation technology and emerging markets in water. Am. J. Agric. Econ. 84 (1), 171–183. https://doi.org/10.1111/1467-8276.00251.

Carter, A.Y., Hawes, M.C., Ottman, M.J., 2019. Drought-tolerant barley: I. Field observations of growth and development. Agronomy 9 (5), 221. https://doi.org/10.3390/agronomy9050221.

Cernusak, L.A., 2018. Gas exchange and water use efficiency in plant canopies. Plant Biol. https://doi.org/10.1111/plb.12939.

Condon, G.A., 2020. Drying times: plant traits to improve crop water use efficiency and yield. J. Exp. Bot. eraa002. https://doi.org/10.1093/jxb/eraa002.

Encisco, J., Jifon, J., Anciso, J., Ribera, L., 2015. Productivity of onions using subsurface drip irrigation versus furrow irrigation systems with an internet-based irrigation scheduling program. J. Int. Agron. https://doi.org/10.1155/2015/178180.

Evans, R.G., Sadler, E.J., 2008. Methods and technologies to improve efficiency of water use. Water Resour. Res. 44, W00E04. https://doi.org/10.1029/2007WR006200.

Fan, Y., Wang, C., Nan, Z., 2018. Determining water use efficiency of wheat and cotton: a meta-regression analysis. Agric. Water Manage. 199, 48–60. https://doi.org/10.1016/j.agwat.2017.12.006.

Fuller, A.C., Harhay, M.O., 2010. Population growth, climate change and water scarcity in the southwestern United States. Am. J. Environ. Sci. 6 (3), 249.

Gardner, P.M., Heilweil, V.M., 2009. Evaluation of the effects of precipitation on groundwater levels from wells in selected alluvial aquifers in Utah and Arizona, 1936–2005. U.S. Geological Survey Scientific Investigations Report 2008-5242. pp. 28. Available at. http://pubs.er.usgs.gov/sir/2008/5242.

Genius, M., Koundouri, P., Nauges, C., Tzouvelekas, V., 2014. Information transmission in irrigation technology adoption and diffusion: social learning, extension services, and spatial effects. Am. J. Agric. Econ. 96 (1), 328–344. https://doi.org/10.1093/ajae/aat054.

Hatfield, L.J., Dold, C., 2019. Water-use efficiency: advances and challenges in a changing climate. Front. Plant Sci. 10, 103. https://doi.org/10.3389/fpls.2019.00103.

Huffaker, R., Whittlesey, N., 2000. The allocative efficiency and conservation potential of water laws encouraging investments in on-farm irrigation technology. Agric. Econ. 24 (1), 47–60. https://doi.org/10.1111/j.1574-0862.2000.tb00092.x.

Hussain, I., Turral, H., Molden, D., Ahmad, M.D., 2007. Measuring and enhancing the value of agricultural water in irrigated river basins. Irrig. Sci. 25 (3), 263–282. https://doi.org/10.1007/s00271-007-0061-4.

Lahmers, T., Eden, S., 2018. Water and Irrigated Agriculture in Arizona, 2nd ed. Arroyo, Tucson, Arizona, USA.

Levidow, L., Zaccaria, D., Maia, R., Eduardo, V., Mladen, T., Alessandra, S., 2014. Improving water-efficient irrigation: prospects and difficulties of innovative practices. Agric. Water Manag. 146 (2014), 84–94. https://doi.org/10.1016/j.agwat.2014.07.012.

Mansour, H.A., 2015. Design considerations for closed circuit design of drip irrigation system. Closed Circuit Trickle Irrigation Design: Theory and Application. pp. 61–133.

Mansour, H.A., Abd El-Hady, M., Bralts, V.F., Engel, B.A., 2016. Performance automation controller of drip irrigation systems using saline water for wheat yield and water productivity in Egypt. J. Irrig. Drain. Eng. 142 (10).

Mingbin, H., Mingan, S., Lu, Z., Yushan, L., 2003. Water use efficiency and sustainability of different long-term crop rotation systems in the Loess Plateau of China. Soil Tillage Res. 72, 95–104.

Mpanga, I., Neumann, G., Schuch, U.K., Schalau, J., 2020. Sustainable agriculture practices as a driver for increased harvested cropland among large-scale growers in

Arizona: a paradox for small-scale growers. Adv. Sustain. Syst., 1900143. https://doi.org/10.1002/adsu.201900143.

National Oceanic and Atmospheric Administration (NOAA) (2007; https://www.ncdc.noaa.gov/sotc/national/200713 2017). Annual reports (Accessed on the 08/03/2020).

Rockström, J., Lannerstad, M., Falkenmark, M., 2007. Assessing the water challenge of a new green revolution in developing countries. Proc. Natl. Acad. Sci. U.S.A. 104 (15), 6253–6260. https://doi.org/10.1073/pnas.0605739104.

Thompson, T.L., Pang, H.C., Li, Y.Y., 2009. The potential contribution of subsurface drip irrigation to water-saving agriculture in the western USA. Agric. Sci. China 8 (7), 850–854.

US EPA, 2014. Climate changeindicators in the United States. A Closer Look: Temperature and Drought in the Southwest. . https://www.epa.gov/climate-indicators/southwest (date accessed 06/17/2020).

US EPA, 2017. Climate Impacts in the Southwest. https://19january2017snapshot.epa.gov/climate-impacts/climate-impacts-southwest_.html.

USDA, 2012. National Agricultural Statistics Service. USDA agriculture censushttps://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Farm_and_Ranch_Irrigation/index.php and 2017 (accessed on 06/17/2020).

USDA, 2019. National Agricultural Statistics Service. Farms and Land in Farms 2018 Summary. ISSN: 1995-2004.

USGCRP, Garfin, G., Franco, G., Blanco, H., Comrie, A., Gonzalez, P., Piechota, T., Smyth, R., Waskom, R., 2014. Ch. 20: Southwest. Climate Change Impacts in the United States: The Third National Climate Assessment. In: Melillo, J.M., Richmond, Terese (TC), Yohe, G.W. (Eds.), US Global Change Research Program, pp. 462–486.

Ward, F.A., Pulido-Velazquez, M., 2008. Water conservation in irrigation can increase water use. Proc. Natl. Acad. Sci. 105 (47), 18215–18220. https://doi.org/10.1073/pnas.0805554105.

Yadav, P.K., Sharma, F.C., Thao, T., Goorahoo, D., 2020. Soil Moisture Sensor-Based Irrigation Scheduling to Optimize Water Use Efficiency in Vegetables. http://www.irrigation.org/IA/FileUploads/IA/Resources/TechnicalPapers/2018/Soil_Moisture_Sensor-based_Irrigation_YADAV.pdf.