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CLIMATE ALERT

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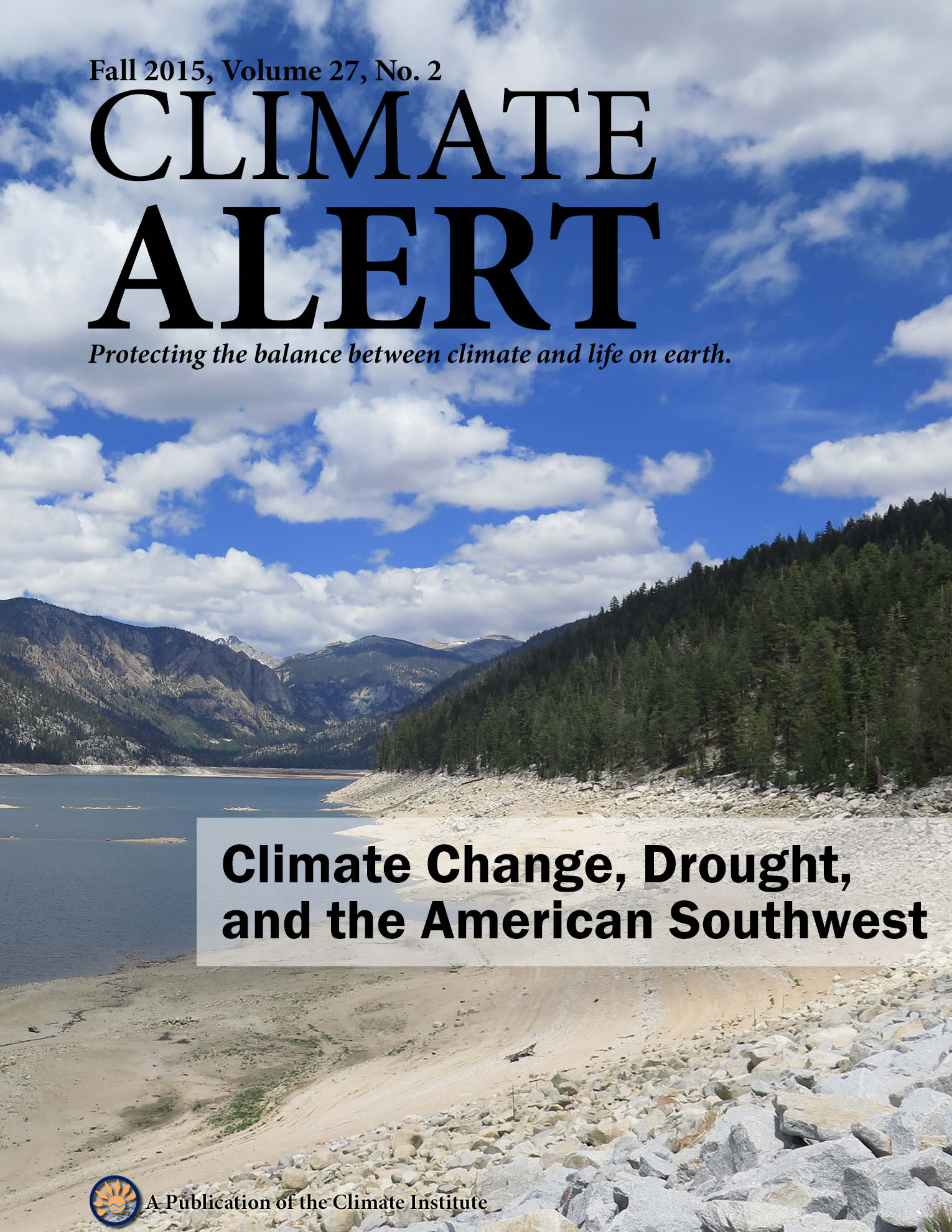

Climate Change, Drought, and the American Southwest

A Publication of the Climate Institute

A publication of the Climate Institute
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Ancestral Pueblo ruins at Wupatki National Monument. In the 13th century, Ancestral Pueblo sites across the Colorado Plateau were abandoned, possibly as a result of severe drought. Photo by Rudy Baum Jr.

Front Cover:
Lake Thomas Edison in the Sierra Nevada.
Photo by Rudy Baum Jr.

Back Cover:
The Rio Grande near Big Bend National Park.
Photo by Rudy Baum Jr.

A Message From the President

An urgent need for imaginative climate adaptations in the U.S.

Although the possibility has been given short shrift in climate protection discussions, the US may be the most vulnerable of all Earth's industrialized nations to climate change. Permafrost thaw and other effects of high-latitude warming are causing several dozen Alaska Native villages to give serious consideration to relocating. Well to the South, about 25 to 35 square miles of coastal wetlands in Louisiana are disappearing into the Gulf of Mexico each year through a combination of sea level rise and other environmental stresses. However, perhaps the most disruptive impact of climate change in the US, and the focus of this issue of *Climate Alert*, will be the change in the frequency and severity of drought in the American Southwest, which for the purpose of our discussion includes much of the agricultural heartland of California. Many of the same stresses will affect northern Mexico, and the effects on agricultural production in California could affect global food markets.

Changes in surface water availability, soil moisture, and snowmelt in the American Southwest are likely to have consequences for agriculture and human settlement in one of America's most rapidly growing regions, and may also increase the risk of forest fires and mudslides when occasional heavy rains wreak havoc on communities where protracted drought has stripped away vegetative cover that could absorb rainfall. These stresses present challenges that will demand imaginative adaptation responses drawing both on the ingenuity and frontier spirit that have made the American West a seedbed of human innovation, as well as successful examples from abroad such as drip irrigation, which has made the Negev Desert in Israel bloom.

Climate Alert Editor-in-Chief Rudy Baum, Jr. provides a compelling overview article, "Effects of 21st century climate change on drought risk in the American Southwest." Reviewing both the paleoclimatic record and the most current climate models, he points out that well before European settlement this region experienced a number of megadroughts that wreaked havoc on indigenous civilizations, and that future climate change-driven droughts may surpass these historical megadroughts in severity. He also points out that uncertainty around the effects of global warming on the El Nino-Southern Oscillation cycle makes precise forecasting future Southwestern aridity difficult.

Brian Fowler, a Climate Institute Graduate Research Fellow, provides an interesting perspective in the "The vanishing jewel of the Colorado," that highlights ecological changes already underway in Utah's Glen Canyon Reservoir, also known as Lake Powell. Already the reservoir is showing great losses of water volume, which could presage conflicts among competing interests, including the natural environment, agriculture, and growing but water-starved communities. Hannah Stroud, a Climate Institute Arctic Research Intern from University of California San Diego, in her article, "California's state of emergency," describes some of the tradeoffs already underway in America's most populous state, involving residential and commercial water use and agriculture.

Two articles highlight imaginative strategies for water resource consumption. One, drip irrigation, with a proven track record in Israel and elsewhere; and another much more in the experimental phase, a microbubbles or bright-bubbles strategy that seeks to reduce evaporation from reservoirs, lakes, or ponds by generating an underwater cloud of bubbles to increase the water's reflectivity. In his article "More crop per drop: realizing drip irrigation's promise in the Navajo Nation," Climate Institute Graduate Research Fellow, Daniel Bornstein, Dartmouth, 2014, now a PhD candidate at University of Wisconsin, discusses the potential of drip irrigation to make Navajo lands in the American Southwest bloom. He describes some preliminary collaboration between Israel's Arava Institute for Environmental Studies and Navajo leaders to see whether drip irrigation can be adapted for use within the Navajo Nation. The Tribal Sustainability Partnership Initiative of the Climate Institute's educational arm, the Center for Environmental Leadership Training (CELT), seeks to promote this effort. In the article, "To cool reservoirs, brighten their waters," Russell Seitz, a Fellow of the Harvard Physics Department and Climate Institute Senior Research Fellow, provides a glimpse of the microbubble strategy that seeks to conserve water by reducing evaporation. Dr. Seitz and two colleagues have a much more comprehensive discussion of this strategy that they hope soon to have published in a leading science journal. The current issue of *Climate Alert* seeks to stimulate within the Climate Institute community a concerted effort to identify and even design water resource strategies that will provide continued availability of a vital resource, even in the face of a worsening climate. ▪

John Topping, *Climate Institute President*

News

Remembering Louis Brown

Louis Brown, a senior fellow at the Climate Institute and former Senior Staff Associate at the National Science Foundation's Directorate for Geosciences, a position that he held for 20 years before his retirement, has passed away.

Mr. Brown was a tireless advocate for international scientific cooperation, working with numerous international scientific organizations, including Inter-American Institute for Global Change Research (IAI), for which he served as the Chair of the Standing Committee on Rules and Procedures. He was also the first Secretary of the International Group of Funding Agencies for Global Change Research (IGFA), and was helped establish the Belmont Forum, which later became IGFA's Council of Principals. Throughout his career, Mr. Brown worked closely with the Intergovernmental Oceanographic Commission (IOC), and in 2011, he was awarded one of the IOC's 50th Anniversary Medals for his contributions to the IOC.

Mr. Brown joined the Climate Institute as a Senior Fellow for International Scientific Cooperation in 2011. During that time, he was a member of a team that presented an interim report to the International Council for Science on how to promote cooperation in global change research in North America. In 2014, Mr. Brown participated in the Conference of the Parties of the IAI, a major focus of which was to improve the dialogue between global change research and public policy in the Americas.

We at the Climate Institute will remember Louis Brown as a scientific diplomat who was skilled at forging relationships between international scientific organizations, especially in regards to climate change. He always knew which goals were attainable in a given context, and how best to achieve them. ▪

Brightening reservoirs to conserve water

Russell Seitz
Fellow of the Physics Department, Harvard University
Senior Research Fellow, Climate Institute

There's more to drought than lack of rain. Deep water is literally as dark as asphalt, and like asphalt it soaks up solar heat. The absorbed solar energy drives rapid evaporation in hot, dry regions like the American West. This loss can be mitigated by making the water brighter so it absorbs less solar heat. By reducing evaporation, more water could be made available for agriculture, industry, and residential consumption. To be practical, however, such an approach must cost less than the value of the water that it conserves.

Fortunately, recent research has revealed an approach that appears to be inexpensive enough to be useful. Just as the microscopic water droplets in a cloud reflect sunlight, an under-water cloud of micron-sized bubbles (known as a hydrosol) can be injected into a body of water, thus brightening it and reducing evaporation by reflecting a greater proportion of solar radiation. The smaller the bubbles, the greater their collective surface area and the brighter the water will appear. Sustained over time, such brightening could cool the water by several degrees centigrade and cut evaporative losses by 20-30%.

The brightening works by continuously adding microbubbles; how long they last depends on water quality. In distilled water, very small bubbles may last only minutes, but the trace amounts of natural surfactants like algin present in lakes and reservoirs can extend microbubble lifetimes long enough to distribute them, and their cooling effect, over significant areas of water.

Microbubbles LLC, a start-up involving the author and former Climate Institute chairman William A. Nitze, is developing new technology to keep reservoirs cool by increasing their reflectivity in consistent and predictable ways. Besides reducing evaporation from reservoirs, aqueducts and irrigation canals, hydrosol cooling can save fuel and cut CO2 emissions by improving the efficiency of power plant cooling ponds.

As already water-scarce regions become even drier as a result of climate change, the microbubble approach to water conservation could potentially play an important role in making communities more resilient in the face of current and future changes in water availability. ▪

The Lake Shasta reservoir in California is currently at 33% capacity, just 56% of its average historical level.
Photo by Don Barrett / CC BY-NC-ND / Cropped from original

The Climate Institute's Nasir Khattak attends the ribbon-cutting ceremony for the Earth Science Gallery at the Children's City museum in Dubai. The Earth Science Gallery was developed in partnership with the Climate Institute.
Photo by Maritza Vargas

Earth Science Gallery debuts in Dubai

In June, the Children's City museum in Dubai opened its Earth Sciences Gallery. Designed in partnership with the Climate Institute, the Earth Science Gallery teaches children about the earth's history and climate.

The Earth Science Gallery was the brainchild of Climate Institute's chief operating officer, Nasir Khattak. When the Children's City was looking for a new exhibit, Mr. Khattak, drawing on the example set by the Climate Institute Mexico y America Latina, suggested Science on a Sphere, which displays planetary datasets on a globe. The Children's City's Science on a Sphere is now the first of its kind in the Middle East and North Africa, and the only one to display data in both English and Arabic. Other exhibits added to the gallery include the Time Wall, which charts the universe's history from the big bang to the present.

Climate Institute staff helped to designed and lay out the exhibits, and installed the Science on a Sphere display. Once the gallery was completed, they created educational guides for the museum staff, translated videos and presentations into Arabic, and trained the museum's education team in earth sciences, climate change, and environmental science. ▪

Book Review: The Water Knife

by Paolo Bacigalup

Reviewed by Rudy M. Baum Sr.

Dystopias have long been a focus of serious science fiction, stories treating both the near and distant future. From "1984" by Aldous Huxley and "Blade Runner," which was based on Philip K. Dick's "Do Androids Dream of Electric Sheep?" to Frank Herbert's epic "Dune," writers have imagined bleak futures for humanity.

The genesis of such dystopias is sometimes explicit—nuclear Armageddon, for example—or, in some instances, left to our imaginations. Recently, however, climate change has become the driver for the fictional collapse of civilization in a number of novels.

This is very much true of the "The Water Knife" by Paolo Bacigalupi, a dystopian tale set in the near future in the desert southwest of the U.S., where prolonged and severe drought has drastically altered the social fabric.

In the novel, Texas has become uninhabitable, and Texans are considered social vermin in Arizona, Nevada, and California. A law—the State Sovereignty Act—allows states to prevent citizens from other states from moving in, and it is enforced by armed state militias. Water rights are more important than life itself. States like California and Nevada fortunate enough to have secured "senior" water rights are quick to employ deadly force to maintain those rights.

Entering into this bleak landscape is Angel, the "water knife" of the novel's title who is one of the Southern Nevada Water Authority's heavies, very much not a nice guy; Lucy, a journalist documenting the disintegration of Phoenix as it is starved for water by California and Nevada; and Maria, a Texas migrant trying desperately to create a new life for herself.

The plot, such as it is, revolves around the desperate efforts by Angel and Lucy, who eventually team up together, to track down an almost mystical document containing water rights dating back to a nineteenth century treaty between the federal government and a long-vanished Indian tribe. Possession of the document leads to a variety of double crosses and leaves a trail of bodies in its wake. As is often the case in such tales, the plot of "The Water Knife" is less important than the bleak landscape Bacigalupi creates.

"The Water Knife" isn't really science fiction. It's a thriller set in the near future in which climate change—specifically a prolonged megadrought in the American Southwest—has laid to waste the legal and social norms we take for granted in today's world.

It is a hyperviolent novel, filled with despicable characters for whom cruelty is simply business as usual. It depicts a world in which the country Mexico has disappeared and been replaced by the "cartel states." It envisions a United States comprised of states at war with each other over access to water.

The breakdown of civility and of law and order depicted in "The Water Knife" seems outside the realm of possibility in our civilized world. But cut off the water to a city—cut it off entirely and permanently—and what would happen?

"The Water Knife" is a frightening, bleak meditation on how climate change could turn us into monsters. ▪

Knopf
$29.95

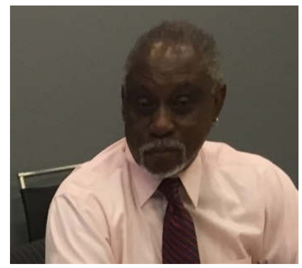
Rudy M. Baum Sr. is a science writer and the retired editor-in-chief of "Chemical & Engineering News."

New members join Climate Institute's Board of Advisors

Philip Johnson, CEO of the clean energy firm Sustainable Solutions Technologies, LLC and a veteran of many community economic development and neighborhood revitalization efforts, has joined the Climate Institute Board of Advisors. Currently, he is helping some CELT fellows and interns to develop low- and zero net-carbon economic plans for biofuels, and for airport and industrial development projects in the southeastern U.S. and Latin America. He has held many positions, serving as executive director of the National Congress for Community Economic Development, the executive director of the National Bar Association, and later leading the Redevelopment Land Agency (RLA) of the District of Columbia.

Tuck Wilson is a 30-year veteran of Portland's transit agency, having served for a time as its Special Counsel. He has specialized in extending light rail and streetcar systems since 1981. Reflecting his ongoing commitment to sustainable practices, he has remained an active supporter of environmental organizations such as the Climate Institute, for which he serves as a member of its Board of Advisors. In May 2015, he wrote an article for the Environmental Centre for Arab Towns describing Portland's light rail experience.

Ethan Forauer served as Program Coordinator of the Climate Institute's educational arm, the Center for Environmental Leadership Training (CELT), from spring of 2014 until his graduation from Clark University in Worcester, Massachusetts in May 2015. Under Ethan's leadership, CELT experienced remarkable growth in membership and activity. In recognition of his success, Ethan, a long-time resident of Hanover, NH, was invited to join the Steering Committee of CELT and the Board of Advisors for the Climate Institute. Ethan' s CELT coordination responsibilities have been assumed jointly by two Dartmouth students, Macy Ferguson , Class of 2016, a North Carolinian of Cherokee ancestry; and Kiana Outen, Class of 2018, and a Floridian. Macy has also become the principal liaison to CELT's Tribal Sustainability Partnership Initiative teams. ▪



Phil Johnson, CEO, Sustainable Solutions Technologies

Ethan Forauer, Past Coordinator, Center for Environmental Leadership Training (CELT)

Impressive achievements for Washington Interns

In the spring and summer of 2015, the Climate Institute drew some remarkably talented interns and fellows to its Washington office from three nations—Korea, Finland, and the US—and a number of colleges and universities. In the spring, **Jeeihn Lee**, a Korean national and member of the Dartmouth College Class of 2017, and **Bryan Robinson**, a resident of Florida and member of Dartmouth's Class of 2016, both helped to develop climate education scripts for use in the new climate theatre in Children's City museum of Dubai. Jeeihn also served as Editor-in-Chief of the Summer 2015 issue of Climate Alert, which explored the potential of methanotrophs—methane-consuming bacteria—to limit Arctic warming due to the release of methane from melting permafrost and the breakdown of methane hydrates. Bryan Robinson worked on improving the format and presentation of the Climate Institute's website, climate.org. **Daniel Bornstein,** Dartmouth Class of 2014, now a PhD candidate at University of Wisconsin, used his agricultural sustainability expertise in two areas—exploring how drip irrigation, used successfully in Israel's Negev Desert, might be adapted for use in the Navajo Nation in the US Southwest; and exploring how degraded land in Latin America and elsewhere might be replenished for financially and ecologically sustainable production of biofuels. **Amanda Farthing,** an engineering major and member of Clemson University's Class of 2018, led the CELT team developing sustainability plans for an airport and research industrial park planned for Alabama. **Minttu Liuhto**, a master's student at University of Copenhagen and a Finnish citizen, researched the implications of climate change for the Sami people. Her research will be available both on climate.org and as an article in the next *Climate Alert*. **Chiamaka Ogwuegbu**, a member of Stanford's class of 2018, worked on both the Climate Institute's effort to develop valuation for black carbon reductions, and on designing sustainability plans for the airport and industrial park being proposed in Alabama. ▪

Clockwise from bottom left: Chiomaka Ogwuebgo, Minttu Liuhto, Sam Sherer (Senior Fellow), John Topping (President), Rudy Baum, and Brian Fowler.

Research

Effects of 21st century climate change on drought risk in the American Southwest

Rudy Baum Jr.
Graduate Research Fellow, Climate Institute

Drought is a common occurrence in the American Southwest.[1,2] Since the beginning of the 20th century, the region has experienced four major multiyear droughts: the Dustbowl (1929-1940), the Southwest/Great Plains drought (1946-1956), a turn-of-the-century drought that lasted from 1999-2005, and the ongoing 2012-2015 drought.[3,4] Other, shorter dry spells occurred during the 20th century as well.[3] During the current drought, many states in the region have seen record or near-record persistent high temperatures, as well as extreme lows in precipitation, streams flows, and soil moisture.[5] California has been hit especially hard. 2012-2015 have been the driest four years in the state's recorded history,[5] and in 2015 the Sierra Nevada snowpack hit a 500-year low.[6] Drought conditions in California in 2014 represented a 200-year event,[7] while the cumulative 2012-2015 drought may be completely unprecedented within the past 10,000 years.[8]

There is a strong consensus that rising global temperatures resulting from anthropogenic CO_2 emissions will increase the frequency, intensity, and duration of droughts across the American Southwest.[9,10,11,12,13] Increased evaporation due to warmer surface temperatures and decreased precipitation will drive significant reductions in soil moisture across the region.[12,13,14] This poses serious environmental and economic risks for the Southwest. Between 1980 and 2003, droughts caused an estimated $190 billion dollars in economic damage across the United States (adjusted for inflation), making it the most costly form of natural disaster over that period.[3] Droughts can decrease the amount of water available for agriculture,[15] reduce power generating capacity,[16] and increase the risk of forest fires.[17,18,19] Between growing demand for water and the predicted increase in drought frequency, the Southwest's water infrastructure may struggle to adapt to a new, drier climate regime.[3]

Climate and paleoclimate of the Southwest

The American Southwest, here defined as the area between 95°W and 125°W and 25°N and 40°N,[9] covers over four million square kilometers. Four of western North America's major watersheds lie within its boundaries: the Colorado River basin, the Rio Grande basin, the Sacramento-San Joaquin watershed, and most of the Great Basin. Annual mean precipitation across much of the region ranges between 10 and 60 centimeters per year,[20] low enough to qualify as arid or semi-arid.[21] Some areas, such as the Sierra Nevada in California and the high peaks of the Colorado Plateau, receive significantly more precipitation, mostly in the form of large quantities of snow.[20] Much of the Southwest's summer water supply comes from the melting of these alpine snowpacks.[6,22]

The combination of low annual precipitation and hot, dry summers makes the Southwest especially drought-prone. 10-15% of the years between 1895 and 1995 saw severe or extreme drought conditions in the region.[1] At most, these modern droughts last about ten years; however, reconstructions of the Southwest's paleoclimate have shown that the region is also susceptible to extraordinary megadroughts that can last for decades or even centuries. A fifty-year drought struck the Southwest, Northern Mexico, and the Rocky Mountains between about AD 1540 and 1590, which contributed to the abandonment of nearly a dozen native pueblos[23] and may have aggravated an outbreak of an unknown, indigenous hemorrhagic virus that killed 7 to 17 million people.[24] Three hundred years before, the Great Drought of AD 1267-1299 was at least partially responsible for the abandonment of Ancestral Pueblo sites throughout the Colorado Plateau.[3,25,26]

Some of the most severe megadroughts to strike the Southwest occurred in California. Between about AD 1250 and 1350, a century-long drought struck the Sierra Nevada region.[27] Another, longer drought in the region has also been identified between AD 900 and 1100,[27] although subsequent research has suggested that this earlier interval may not have been a single, uninterrupted drought, but rather a series of decade-long droughts following one after another.[28] Precipitation was so low during this period that the shorelines of many lakes throughout the Sierra Nevada were tens of meters lower than they are today, which allowed mature pine trees to grow for decades in areas that today are underwater.[27,29] These century-scale droughts caused significant disruptions for native cultures in California and the Great basin, leading to major migrations, site abandonments, and the collapse of long-distance trade routes.[28]

Both the California megadroughts and the Great Drought (which was part of a larger pattern of increased aridity in the

Colorado Plateau) occurred during a period of elevated global temperatures known as the Medieval Climate Anomaly.[3,26,27] In both cases, the droughts were caused by persistent, anomalously cold sea surface temperatures in the eastern Pacific consistent with the La Niña phase of the El Niño-Southern Oscillation (ENSO).[3,23,26,27,30]

Causes of future drought

Although drought is often thought of as the result of a shortfall in precipitation, most studies of drought instead look at deficits in the total moisture content of soils. Drought is therefore most often measured by subtracting moisture demand from soils (evaporation) from moisture supply into soils (precipitation). It should be noted that, throughout this paper, the word "drought" is used to refer to deviations from historical average soil moisture levels. Drought in this case should be understood not as transient weather phenomena, but rather an ongoing process of aridification—a permanent drought, so to speak.

21st century drought in the Southwest will primarily be driven by increased evaporation due to warmer global surface temperatures. Relative humidity will decrease as temperatures rise, which will lead to increased evaporative demand from soils.[9,10,12,13] Enhanced evaporation due to global warming will reduce soil moisture in the Southwest by an average of 3 cm/year.[9] By 2099, soils in the region will be 10-20% drier than they are today, which will increase the risk of drought by at least 20%.[13] One of the characteristic features of climate change is that, for almost all weather phenomena, the risk of extreme events increases more quickly than it does for moderate events.[13,31,32,33] Accordingly, the risk of a severe, multidecade drought occurring in the Southwest between 2050 and 2099 is more than 80% greater than it is today.[34] Soil desiccation will be exacerbated by an increased likelihood of extreme daily high temperatures. Extreme hot days are already five times more likely than they were prior to the Industrial Revolution, and with another 1°C of warming they will become five times again more likely.[33] In some cases, evaporative demand from warmer surface temperatures will exceed available soil moisture—in other words, there will be periods in the coming century during which some soils in the Southwest dry out completely.[12] This excessive drying may feed back into even warmer surface temperatures: there is evidence that as soil moisture content reaches zero, the loss of cooling heat fluxes due to evaporation will cause additional warming.[31]

Changes in precipitation will also play a role in determining the future severity of drought conditions in the Southwest, although not as great as that of evaporation.[12,13,14] As the planet warms, the downward arms of the Hadley Cells will expand poleward. Hadley Cells are a form of atmospheric circulation where air rises at the equator and descends at about 30° latitude on either side (about the latitude of the U.S.-Mexico border in North America). The downward arms of the Hadley Cells are associated with high atmospheric pressure and arid climates. Hadley cell expansion over the American Southwest is predicted to decrease precipitation there by 3-15% by the end of the 21st century.[13,14] The increased high atmospheric pressure over the region will also reduce cloud formation, which will worsen evaporation by allowing more solar energy to reach earth's surface.[13] The decrease in overall precipitation will be exacerbated by changes in the way precipitation falls: more intense, less frequent precipitation will lead to longer dry spells.[13] Increased winter rains, reduced snow packs, and earlier snow melts will also lead to less moisture being available during summer months, when evaporation is most intense.[34,35]

One major source of uncertainty in predicting future Southwestern droughts is the response of ENSO to rising global temperatures. La Niña (the cool or negative phase of ENSO), which is characterized by cool sea surface temperatures in the eastern equatorial Pacific Ocean, is strongly associated with drought conditions across the American Southwest.[3,9,26,36] Indeed, the megadroughts of the 11th-13th centuries are thought to have been caused by unusually persistent La Niña-like conditions.[3,23,30] However, it is unclear how ENSO will react to a warming climate.[11,37] Climate models are split over whether ENSO will become more intense,[37,38] or remain relatively unchanged.[37,39] There is also the possibility that ENSO will evolve non-linearly over the course of the 21st century, initially becoming more intense before returning to normal variability after 2040.[40] The uncertainty surrounding ENSO's response to global warming thus makes it difficult to predict the precise details of future climate regimes in the Southwest.

Predicted effects

As global temperatures continue to rise, perhaps by as much as 2-4°C by 2100,[11] the Southwest will become increasingly dry. Average surface temperatures in the region have already risen by at least 1°C since the beginning of the 20th century.[2] At present, record hot days are occurring at twice the rate of record cold days.[41] By the end of the 21st century, much of the region will experience at least moderate drying.[12] This will lead to significant changes in regional climate types and plant communities, with many temperate climate zones in the region transitioning to semi-aridity.[14]

Changes in precipitation and evaporation will have significant impacts on snow pack levels, water availability, stream flow levels, and soil moisture. Warmer temperatures mean that more winter precipitation will fall as rain instead of snow.[14] Earlier snowmelts have already been observed across the southwest, and in some basins rainwater has come to replace snowmelt as the dominant water source.[35] Given that snowpack serves as a particularly important reservoir during the Southwest's hot, dry summer months—snow melt accounts for between 30% and 75% of the region's stream flows, depending on the basin[6,22,42]—a decrease in total snowpack has serious economic consequences. Further, warmer temperatures will result in earlier snow melts, which in turn will lead to earlier peak stream flows, as well as more extreme low flows later in the year.[2,42,43] By the end of the 21st century, stream flows in the Sierra Nevada are predicted to drop at least 25% below their historical averages;[2] essentially every stream in the Colorado River basin will have below-normal summer flows, with many previously perennial streams developing intermittent flows;[43] and the Rio Grande's upper basin will see total stream flow reductions of over 400 million m^3/year.[42]

The economic and environmental impacts of increased Southwestern drought are substantial. The Colorado River is a major source of drinking water for 40 million people,[44] while the Sierra Nevada snowpack, which accounts for 30% of California's water supply, is a crucial reservoir not just for the state's 38 million residents, but its lucrative agricultural industry as well.[6] The 2012-2015 drought has cost California's economy $2.74 billion (with $1.84 billion in losses coming from the agricultural industry alone) and 21,000 jobs.[15] As surface water supplies decrease, groundwater is being increasingly relied on to make up the difference. Faced with a surface-water deficit of 10.7 km^3, California will extract 7.4 km^3 of groundwater in 2015 alone.[15] In the Colorado River basin, groundwater is currently being depleted at a rate of 5.6 km^3/year.[45] (Note that, as California draws some water from the Colorado River, there will be some overlap between these numbers.) Reduced stream flows also have implications for power generation in the Southwest. By the mid-21st century, hydropower capacity along the Colorado River and in California could drop by 2-5%.[16]

On the environmental side, extended droughts may increase tree mortality, and, as a consequence, fuel loading in forests.[19,46] This can lead to increased forest fire frequency and intensity, which can damage human health and property,[17,18] as well as alter the ecological composition of burn areas.[19,47] Research suggests that forest fires in the region are already becoming more common. Since 1986, the frequency of large-scale forest fires in the western United States has increased by a factor of four, and the total area burned has increased by a factor of six.[48] Drought also imperils the viability of regional stream ecologies. As a result of increased surface temperatures and low stream flows, warmer annual mean temperatures are predicted in many streams across the Southwest.[2,43] This could prove especially damaging for coldwater fish species such as trout. Total suitable habitat for all trout species found in the American West could decline by 47% by the end of the 21st century.[49]

Conclusion

Drought is a regular feature of the American Southwest's climate regime, as can be seen in both the modern record, and through reconstructions of the region's paleoclimate.[1,3,26,27] Over the course of the 21st century, the Southwest will experience significant increases in drought frequency and overall aridity as a result of anthropogenic global warming.[9,10,12,13,14] Warmer surface temperatures will increase evaporative demand, leading to reduced soil moisture content.[9,12,13] Decreased precipitation across the region will also contribute to the increase in drought frequency.[12,13] The effects of increasing regional aridity are expected to include changes in plant communities,[14] reduced snowpacks and earlier snow melt,[22,35] lower stream flows,[2,42,43] warmer stream temperatures,[43] increased groundwater extraction,[15,45] reduced hydropower generating capacity,[16] increased tree mortality,[19,46] and increased wildfire risk.[17,18,19]

In short, in the future the American Southwest will be hotter and drier than it is today. Drought conditions, as defined relative to 20th century averages, will become the norm—a permanent drought, in essence. There will still be wet years, as well as some truly exceptional dry years, but that natural variability will fluctuate around a mean climate state that, overall, will be much drier than the previous century's.[9]

Human adaptation to a drier Southwest will be a challenging proposition. As populations throughout the Southwest continue to grow,[50] so too will the demand placed on the region's diminishing water resources. The Southwest is a marginal landscape, characterized by rugged terrain, low precipitation, and high summer temperatures,[20] and civilization in the region has often balanced on a hydrological knife edge. Within the past 1,000 years, several severe, multidecade droughts have struck the region, causing societal collapse, mass migrations,[3,25,26,28] and in extreme cases perhaps even widespread human mortality.[24] Future droughts in the region will be as or more severe than the megadroughts of the past.[8,9] Due to its wealth, the United States has substantial capacity for climate change adaptation,[51] but the scale of the challenges facing the Southwest in the coming century should not be underestimated. In the past, native civilizations in the region experienced major societal reorganizations or even collapsed in the face of severe, long-term aridificatoin—civilizations that, although less technologically advanced than the modern United States, were nevertheless very well adapted to life in the water-scarce Southwest.[3,25,26,28] The possibility that climate change will fundamentally alter the economy and social structure of the Southwest cannot be ignored. ▪

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The vanishing jewel of the Colorado

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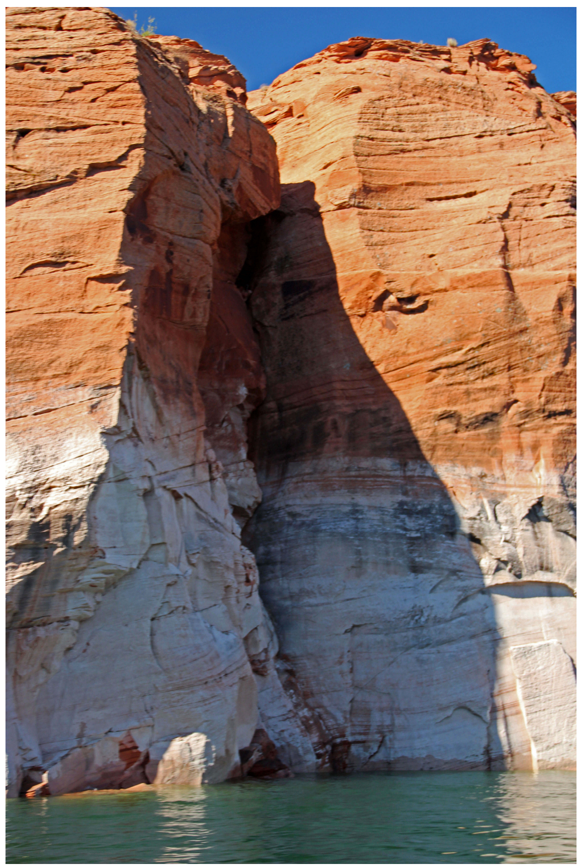
Every year, millions of tourists from across the country visit the famed Colorado River for its many recreational opportunities, including motor-boating, fishing, and rafting. One of the most popular destinations is Glen Canyon Reservoir, otherwise known as Lake Powell. Surrounded by beautiful red rock cliffs and breathtaking geologic formations, the reservoir's unnaturally emerald-green waters stretch from the Utah-Arizona border all the way to the bridge at Hite Crossing over a hundred miles to the northeast. For its many aesthetic charms and laid-back atmosphere, visitors affectionately refer to Lake Powell as the Jewel of the Colorado River. But alarmingly, this jewel could disappear over the coming decades as a result of the regional effects of climate change and the Southwest's increasing demand for water.

Lake Powell's walls can talk; the sandstone cliffs and the reservoir's fifty -nine year history of changing water levels tell the story of the arid west's disappearing water resources. Over the last two decades, visitors have observed that the reservoir's water level has dropped sharply. A white line, made up of exposed calcium carbonate deposits, runs along the walls of Glen Canyon Reservoir. This line, known locally as the "bathtub ring," marks how far Lake Powell's water levels have fallen over the years.


Lake Powell's bathtub ring. Photo by crocus08 / CC BY-NC

Historical data support the conclusions made by casual observations of the bathtub ring. As of April 2015, Lake Powell was at only 45% capacity.[1] This low water volume is part of a seventeen year trend. Evidence compiled by EcoWest shows that, since 1998, water levels have been significantly below the historical average; since 2011, the reservoir's surface has fallen over 50 feet.[2]

Unfortunately for the 40 million people who depend on the Colorado River as their primary water source, this trend of decreasing water availability will likely continue for several decades, if not indefinitely. Climate projections for the already dry Southwest predict a drop in precipitation, as well as an almost certain increase in evaporation caused by higher temperatures.[3] If these projections are accurate, the water level in Lake Powell could eventually reach dead pool, a level so low that water cannot escape the reservoir by natural gravity alone. Dead pool would not only mark the end of Glen Canyon Dam's electric power generation, it would also expose a layer of toxic sediments that have been accumulating below the water since the dam was completed. The Colorado River's red sediment contains trace amounts of heavy metals. When the Bureau of Reclamation built Glen Canyon dam, that sediment began to build up behind its concrete wall. If the dam's managers continue to release water downstream at current levels, the jewel of the Colorado could be transformed into a stagnant pool loaded with decades of accumulated heavy metals.

Although it was inevitable that Lake Powell would one day fill with sediment, the Bureau of Reclamation expected the process to take hundreds of years. However, given projected changes to the region's climate regime, the toxic layer of chemicals could surface in decades rather than centuries.

Currently, Page, Arizona, population 8,000, is the only city that takes water directly out of Lake Powell. The rest of the water is channeled through hydropower turbines and released downstream. That situation could change in the coming years as other desert cities try to stick a new straw into the lake. One such proposal calls for the construction of a 139 mile pipeline to transport water across the state of Utah, at a projected cost of $1 billion.[4] Such projects are politically ambitious and extraordinarily expensive, but as water supplies dwindle, and nearby cities like St. George, Utah, continue to grow, Glen Canyon Reservoir will look like an ever-more attractive resource to the region's water-strapped municipalities. There is no guarantee that the pipeline will be built, but if it were the likelihood of Lake Powell reaching dead pool would only increase as the Southwest's changing climate continues to take its toll on water levels.

Beyond the local problems that dead pool would cause, the falling water levels have chilling implications for the rest of the southwestern region and everyone else who depends on the Colorado River. Much like the Down Jones Industrial Average compiles information from many economic sectors to create a simplified indicator of how the entire economy is performing, Lake Powell indicates how the entire Colorado River basin is performing in terms of water supply.[2] The reservoir's level depends on the amount of precipitation, both rain and snow, that falls in the upper basin states of Wyoming, Utah, and Colorado. All of the Colorado's upper basin tributaries, whose water levels are difficult to measure, combine to make a complex river system that eventually coalesces into Glen Canyon reservoir. Water released from Glen Canyon Dam runs downstream to the lower basin (Arizona, Nevada, and southern California) which receives far less precipitation. If less precipitation falls in the upper basin, then Lake Powell's level will drop, meaning that less water will be available for use in the lower basin. The low water levels that have been recorded for Glen Canyon Reservoir over the last decade indicate a combination of low precipitation in the Rocky Mountains and high rates of evaporation on the reservoir and on the Colorado.

Population growth in the American Southwest has been underpinned by the assumption that there would always be plenty of water for everyone. The 40 million people who rely on the Colorado River for drinking water will have to challenge their old assumptions as a new climate regime significantly decreases water availability. The dream of endless development and population growth will soon come to an end as the region wakes up to its new, water-scarce reality. Glen Canyon's bathtub ring is irrefutable evidence of how precarious the water situation in the arid southwest will be over the coming decades. If Southwesterners want to maintain their livelihood in the great American desert, they will have to change their mindset from one of expansion to conservation. ■

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California's state of emergency

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California is in a state of emergency. As the state grapples with its fourth year of drought, the total amount of water stored in its twelve major reservoirs stands at only at forty-two percent of the historical average.[1] In 2015, the Sierra Nevada snowpack, a major supply of water, reached 0% before the end of May, the earliest it has ever thawed. In fact, the April 2015 Sierra Nevada snowpack was the lowest in the last five hundred years.[2] As California is the world's eighth largest economy and the producer of about half of the fruit, nuts, and vegetables consumed in the US, the effects of a drought this large will be felt beyond the state's borders.[3]

80% of California's water use is agricultural. In 2014, farmers faced a shortfall of 6.6 million acre-feet of water (an acre foot is an acre of water a foot deep) from surface water sources.[4] To make up for this loss, an additional 5 million acre-feet of water was pumped from aquifers, which increased groundwater's contribution to total statewide irrigation from 31% to 53%.[5] Even with the increased usage of groundwater, the drought is estimated to have cost the state's agricultural industry $1.5 billion in 2014.[5]

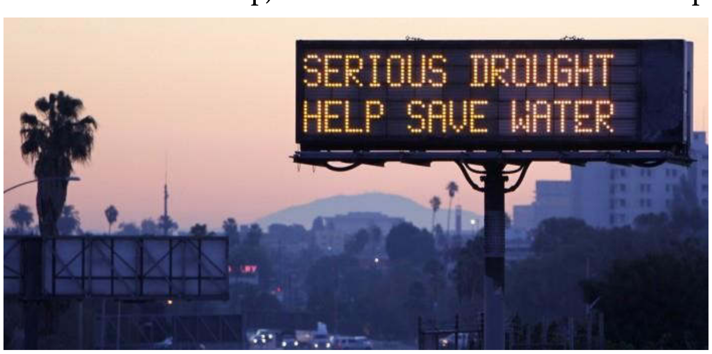

Photo by USDA

Pumping water from aquifers is not sustainable, and it raises legal questions as to who owns the water. Water is being pumped out of the ground faster than it is being replenished, and it is only a matter of time before the groundwater is tapped out as well. Depleting groundwater sources can cause detrimental environmental effects including ground subsidence, which can further damage the farms that lie above.[6] Recent research from NASA has shown that some areas of the Central Valley are sinking as rapidly as two inches a month.[7]

The duration and severity of the current drought also highlights both regulatory and sustainability issues in the agricultural system. The planting of perennial crops, which need constant irrigation, has increased in the last decade. Since the drought, many orchards and fields, particularly in the Central Valley, have been left fallow as many farmers face harsh water restrictions. Meanwhile, some farmers in the Sacramento Valley, whose water rights predate 1914 and are thus less strictly regulated,[8] flooded their fields to grow rice for export. Better regulations are needed to ensure that California's agriculture industry uses water more responsibly.

The remaining 20% of California's water is consumed by households and non-agricultural businesses, with about half of this being used in landscaping.[9] Most of California's residential water use is concentrated in the state's two most densely populated areas, the San Francisco Bay area and the South Coast. While water use per person varies substantially from region to region, people in all areas need to continue to conserve water. Some areas in the Central Valley have been without running water for months. In Tulare County, about 5,433 people don't have water for basic functions such as showering and flushing the toilet.[10] For some of these communities, this has been the case for over a year. They rely on various charitable organizations to provide relief in the form of portable toilets and showers, and packages of bottled water.

In the past year, with a "state of emergency" status in place, there has been some progress in California's drought policy. In April, Governor Jerry Brown issued a mandate calling for a 25% reduction in water usage in cities and towns, compared to their usage in 2013. Since July, urban water consumption has dropped 31%.[11] In June, farmers whose water rights predate the 1914 Water Commission Act were faced with the first cuts to their water usage since 1977.[12] These restrictions have led to more fallow fields, and a large increase in the use of ground water for irrigation. While policies that focus on conserving groundwater resources are in the works, they will not take effect immediately.

The dry summer, with its record heat and countless wildfires, has made the drought the focus of news in California. Communities and individuals have learned to make every drop count. But more needs to be done. While this summer's efforts are commendable, they were also long overdue. This is the first year of widespread public water conservation efforts, but the fourth year of drought. Despite increased precipitation in the fall of 2014 compared to 2013, there is still a long way to go before the state's reservoirs can recover. Even if El Niño is as strong as predicted, one year of above average rainfall will not fully replenish the state's reservoirs and aquifers. It will take years of good rain to fully recover from the drought, and, as a result, it is imperative that Californians continue to conserve water.

A study from Columbia University's Earth Institute measured global warming's influence on the drought, declaring that it increased the severity of the drought by as much as 25%.[13] Numerous other studies warn that droughts will become more frequent as we continue to emit greenhouse gasses and the effects of global warming become more pronounced. This problem will not go away, and its effects will extend far beyond California's borders. Conservation in all areas is the most reliable method to ensure all Californians have water in the future.

In the dry, dusty Central Valley, signs line the interstate that read, "Congress created the Dust Bowl." In reality, it was own our unsustainable system of irrigated crops and cosmetic landscaping. As we enter a world racked by higher temperatures, unpredictable precipitation, and an increase in extreme weather events, a "new normal" needs to be considered as we plan our food system. New technologies, such as hydroponics and drip irrigation, will need to be adopted in order to make every drop of water count. The state of emergency in California is not just a call for the state to fix its water policy; it is also a warning. California cannot afford to assume that this is an isolated incident, or that its water resources will revert back to normal conditions with a few good years. It is time to invest in new technologies and formulate new policies to make California's water infrastructure more adaptable in the face of a new and changing climate. ▪

Wildfires in Yosemite National Park. Photo by NASA

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More crop per drop: realizing drip irrigation's promise in the Navajo Nation

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In the 1970s, U.S. Secretary of Agriculture Earl Butz famously called on farmers to grow crops "from fencerow to fencerow." Intent on feeding the world with American grains, he was embracing a water-intensive model of agricultural production that is no longer viable. In recent years, numerous water crises have upended that complacency about the water supply in global agriculture. A drought in Australia was a key contributor to the 2008 world food crisis, which set off riots in over 30 countries and highlighted the dependence of developing nations on food imports. Today, the ongoing drought in California has removed millions of acres of farmland from production, a jarring transformation from the bountiful harvests of previous years.

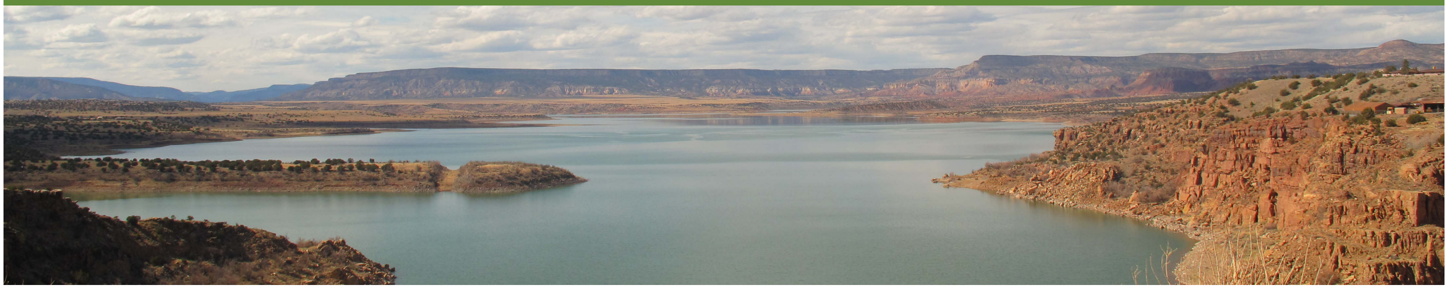
Climate change will bring with it more extreme weather patterns and increased aridification. Farmers worldwide need efficient irrigation methods to cope with these changes. At the same time, as the world's population reaches 9 billion by midcentury, and emerging economies demand more resources to fuel their economic growth, competing demand for scarce water resources is inevitable. One promising solution to these related issues of drought, agriculture, and sustainability is drip irrigation. For communities in arid regions, such as the Navajo in the American Southwest, drip irrigation could make agriculture more productive and thus improve their rural economy.

Navajo leaders, in fact, are already aware of this potential. Since the 1980s, they have been working with researchers from Israel, which has emerged as a global leader in drip irrigation technology, to improve agricultural productivity in the Navajo Nation. In 1985 David Mazigh, an agronomist best known for his groundbreaking work on pistachio production in Israel, travelled to Arizona to introduce drip irrigation to the Navajo.[1] More recently, in December 2012, Navajo Nation president Ben Shelly visited Israel to learn about agricultural innovations that could be adopted back home.[2]

Since the mid-1960s, Israel has used scientific ingenuity to transform the Negev desert into an agricultural machine. Led by the pioneering efforts of World Food Prize-winning scientist Daniel Hillel, the desert, once thought to be uninhabitable, now hosts over 250 agricultural settlements.[3] The Arava region in particular accounts for 65% of the country's vegetable exports.[4]

At the core of this breakthrough have been advances in drip irrigation, in which water is applied directly to plant roots via a system of tubes and emitters (or "drippers"). Water is applied slowly at low volumes so that the soil maintains an optimal balance of air and water. This makes it unnecessary to shower large quantities of

Water is a scarce resource in the Navajo Nation. Photo by Quinn Dombrowski / CC BY-SA / Cropped from original



Navajo Lake reservoir in northern New Mexico, near the Navajo Nation. Photo by Rudy Baum Jr.

water onto the soil, a significant fraction of which runs off or evaporates without being taken up by plants—a wasted resource that Israel, with its limited water resources, can ill-afford. The outcome is a huge reduction in the amount of water required per unit of agricultural land.

Drip irrigation is considered more efficient than other irrigation methods. According to researchers at MIT, it has a 90% field application efficiency (a measure of the amount of water stored in the root zone relative to that applied to the field),[5] allowing it to deliver "more crop per drop," a tagline that has come to encapsulate the drip technique's bold promise in arid regions. And because the water is contained in tubes, it is less susceptible to runoff or evaporation.

Despite its benefits, drip irrigation has been implemented on less than 4% of the global land area under agricultural cultivation.[5] This low implementation rate may be due to drip irrigation's high cost: drip irrigation systems cost about $500-1200 per acre, not including annual upkeep costs.[6]

Ben Gurion University's Arava Institute for Environmental Studies is well-positioned to make major progress in implementing drip irrigation across the Navajo Nation. The most lasting contribution Arava Institute could make in the American Southwest is to train the Navajo's next generation of agricultural specialists. The Navajo would benefit from greater collaboration with Israel, furthering the progress made decades ago by Israeli agronomists and more recently by Ben Shelly's visit. Students from tribal colleges would have the opportunity to interact with experts and learn the farming strategies most transferable from the Negev to the arid Southwest. The Center for Environmental Leadership Training (CELT), part of the Washington-based Climate Institute, plans to lead the charge to make such a partnership happen. Recently, CELT helped provide organizational support for a conference of the Indigenous Peoples' Climate Change Working Group. The conference, held at Dartmouth College in Hanover, NH, focused on helping native tribes adopt clean energy initiatives and improve their ability to adapt to the effects of climate change. Agricultural innovations require significant attention to human and institutional capacity, and CELT strives to be a leader in that area.

The University of Arizona has also done some studies and outreach on drip irrigation in the Navajo Nation, including the installation of drip irrigation systems in some areas. One of the key findings of their research was the need to be attentive to the salinity level of the water, which could be detrimental to crop growth.[7] In hot, arid regions, salinization is a frequent byproduct of irrigation. As the water evaporates, it leaves behind any salts that it contained. In more humid areas, the salts would be carried away by rain, but in the desert they often become concentrated in the soil. Indeed, one of the research projects at Arava Institute focuses on development of salt-tolerant crop varieties—an approach that is no doubt applicable to the attempts of Navajo farmers to overcome high salinity levels.

It is time to transform rural development in the Navajo Nation by drawing on innovations from arid regions that have developed water-efficient approaches to achieve agricultural sustainability and a thriving rural sector. There is hardly a more opportune moment to boost the Israel-Navajo connection as a strategy to improve water efficiency in agriculture. Political and scientific leaders now need to marshal the resources to apply drip irrigation and introduce the method to farmers.

The Green Revolution led to tremendous breakthroughs in agricultural production in the 20th century, but we are now starting to see the limits of those solutions. They were less applicable to communities, like the Navajo, plagued by water scarcity. Working toward sustainable solutions for people and the planet demands a new focus on how we equip farmers with the tools to thrive in a dramatically altered world. If this transformation succeeds among the Navajo, it could set the stage for collaborative science-policy partnerships on a wider scale. ■

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The Climate Institute

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Founded in 1986, the Climate Institute was the first non-profit organization established primarily to address climate change issues. Working with an extensive network of experts, the Institute has served as a bridge between the scientific community and policy-makers and has become a respected facilitator of dialogue to move the world toward more effective cooperation on climate change responses.

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