"My fascination with meteorology and climate sciences began during my childhood, during which I had the wonderful opportunity to observe how different crops grow in different microclimates. This early fascination was further encouraged by one of my high school geography teachers, who stimulated my enthusiasm for the intricate Earth systems. During my undergraduate studies, I delved deeper into the complexities of climate, weather, and cities."

— **Wenfeng Zhan, Nanjing University, and Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application**

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Wenfeng Zhan in front of a historic monument for Private University of Nanking, one of the predecessors of Nanjing University.

"When I realized the magnitude of the challenge that climate change is imposing on our way of living, I could not think of anything else that would be a better use of my time. Then, I stumbled upon the field of micrometeorology, and sonic anemometers, infrared gas analyzers, and turbulence theory, which all enchanted me. For mysterious reasons, working with sensors, installing flux towers, and studying turbulence are fascinating and fun endeavors for me. Now, I try to put my knowledge and experience to the service of issues that I consider very relevant to our society, which is very fulfilling."

— **Nicolas Bambach, University of California, Davis**

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Nico Bambach and his husband, Chad, after a hike around the Iao Valley State Park on the island of Maui in Hawaii.

Connecting Satellites and Farms to Support Sustainable Food Production

The Tree-Crop Remote Sensing of Evapotranspiration Experiment (T-REX)

Key messages from "The Tree-Crop Remote Sensing of Evapotranspiration Experiment (T-REX): A Science-Based Path for Sustainable Water Management and Climate Resilience," by **Nicolas Bambach** (University of California, Davis), **Kyle Knipper, Andrew J. McElrone, Mallika Nocco, Alfonso Torres-Rua, William Kustas, Martha Anderson, Sebastian Castro, Erica Edwards, Moises Duran-Gomez, Andrew Gal, Peter Tolentino, Ian Wright, Matthew Roby, Feng Gao, Joseph Alfieri, John Prueger, Lawrence Hipps**, and **Sebastian Saa**. Published online in *BAMS*, January 2024. For the full, citable article, see **https://doi.org/10.1175/BAMS-D-22-0118.1**.

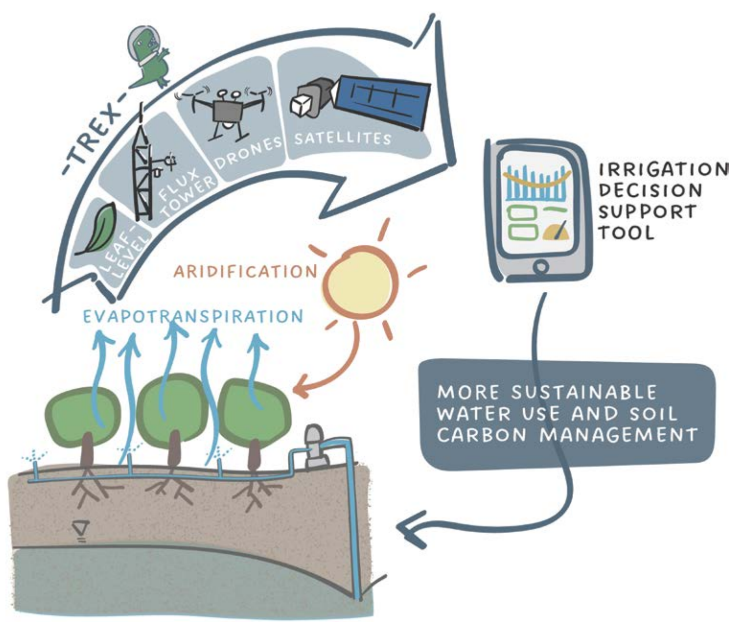

Illustration of the components, interactions, and outcomes of the T-REX project. [Artwork created by Bonnie McGill]

In the history of humanity, many civilizations have collapsed because they could not produce food sustainably. A poignant example is the ancestral native Rapa Nui Society, where population growth, land and resource exploitation, and climate trends transformed a once paradisiacal society into a survival tribe facing severe droughts and food scarcity. We fear that our contemporary global society is on a similar path. We are grappling with climate change and the consequences of decades of turning fertile soils into dust. We have overused groundwater to the extent that the ground collapses beneath us. To produce food, we often contaminate our rivers, deteriorate surrounding ecosystems, encroach on forests, and more. The research question that inspired the Tree-Crop Remote Sensing of Evapotranspiration Experiment (T-REX) is simple: Can we develop a path toward sustainable food production in California? While our study does not provide a defin - tive answer, it outlines a comprehensive research strategy that leverages cutting-edge technologies and an interdisciplinary approach to address this challenge.

California generates about 11% of the U.S. agricultural value, contributing more than $50 billion annually to the state's economy. Not only is California's agriculture economically significant, but it also ranks as the world's fifth-largest supplier of food and other agricultural products. More than half of all fruits and vegetables grown in the United States are produced in California, making a thriving agricultural sector in the Golden State crucial for Americans to maintain a healthy and affordable diet. Unfortunately, California's Mediterranean climate is characterized by large interannual variability in precipitation, known as the boom-and-bust cycle of the state's water supply. Recent years have vividly demonstrated how this pattern is being exacerbated by climate change, with residents experiencing cycles of wet, flood-risk years and extreme droughts and fires within the span of half a decade.

Agriculture in California relies heavily on a complex water system that stores and distributes surface water as needed. When that is insufficient, groundwater reserves are tapped. About 40% of the water used on California's farms and in its cities is drawn from underground aquifers, a percentage that rises during dry years. A major environmental cost of California's agriculture is the depletion of these aquifers, with agricultural irrigation accounting for nearly 70% of groundwater withdrawals. In some areas of the state's Central Valley, the land collapse is as much as 11.5 feet due to excessive groundwater pumping, particularly during drought periods. In response to this crisis, the state enacted the Sustainable Groundwater Management Act (SGMA) in 2014 to curb groundwater overexploitation. Ultimately, reducing water

Micrometeorological ux tower in an almond orchard in Woodland, California; T-REX site in the Sacramento region.

use is imperative, and both farmers and residents must adapt to continue producing sufficient food to meet the growing demand for healthy ingredients, fruits, and vegetables.

The notion that "growers should not bear the cost of sustainability" highlights the tension between sustainable practices and economic viability. Producing sustainable food is costly and difficult to scale with current technologies. Sustainable practices,

Uncrewed aerial systems ight in an almond orchard in Vacaville, California; T-REX site in the Sacramento region.

such as those recommended under the umbrella of regenerative agriculture, are perceived by growers as potentially diminishing their already slim profits. Our focus is on the almond industry as a flagship case of farmers pushing themselves to adapt to survive in a challenging context. With more than 7,600 growers—90% of whom farm less than 100 acres—facing soaring costs up to nearly $4,000 per acre, the economic viability is tenuous. Considering average yields are about 2,200 pounds per acre and recent price fluctuations around $1.85 per pound, many growers find the business marginally profitable and are increasingly seeking innovative solutions. For example, pioneer growers in regenerative agriculture have developed a holistic management framework that not only conserves soil and water but also enhances biodiversity and has the potential to mitigate climate change. Their approach, which emphasizes natural over synthetic inputs, has reduced operational costs and improved market prices, inspiring other growers to adopt regenerative practices.

The T-REX project aims to develop tools that support agriculture management and facilitate the adoption of sustainable practices. We combine different data sources across various temporal and spatial scales, including leaf physiological measurements, micrometeorological monitoring (surface energy, water vapor, and CO_2 fluxes), uncrewed aerial systems for near-ground thermal and spectral remote sensing, and satellite thermal and spectral imagery. Using state-of-the-art modeling techniques, we have developed a framework that provides near-real-time crop water use estimates with reasonable accuracy (~13% bias when comparing satellite-derived evapotranspiration to irrigation records and winter precipitation). Our goal is to collaboratively develop irrigation decision support tools with growers and stakeholders, optimizing water delivery precisely where and when needed. Additionally, we use our crop sensing infrastructure to develop novel techniques for crop stress detection to help farmers manage water stress effectively to achieve specific production qualities and uniformity. While challenging, we are also working toward developing a framework to monitor soil carbon accrual and other soil health parameters using satellite remote sensing information. Our vision is to create products equivalent to actual evapotranspiration mapping and vegetational indices (e.g., OpenET) that enable growers (and anyone) to monitor the effect of their management practices on soil health.

We believe that accessible and reliable information on crops, water, weather, and soil is critical for achieving sustainable agricultural management. Our efforts are focused on employing a science-based, holistic approach that puts cutting-edge technology, such as satellite imagery, into the hands of growers. However, we recognize the challenges of farming in a changing climate and amid deteriorating natural resources, including water and soil—a task that requires courage and deserves greater appreciation.

METADATA

BAMS: What would you like readers to learn from this article?

Nicolas Bambach (University of California, Davis): *The scientific community has recently created a powerful tool that has the potential to help farmers use water more efficiently. The OpenET platform (https://etdata.org) can be used to further develop precision irrigation management tools. We focus on the almond industry, and our results have shown that using biophysical models in conjunction with satellite imagery and weather data can lead to accurate evapotranspiration (ET) estimates. Our goal is to improve the accuracy of ET models' estimates for woody perennial crops and create new accessible and reliable data products, such as ET forecasts, crop water stress monitoring, weather parameters critical for farming, and carbon sequestration.*

BAMS: How did you become interested in the topic of this article?

NB: *The triad of farming, water issues, and climate change is a topic that I feel somewhat morally obligated to study. Throughout my adult life, I keep finding myself between the academic community and farming communities in regions with scarce water resources (Chile and California). In academic forums, it has become almost "cliché" to hear phrases such as: "Growers need to adapt by using less water"; "New crops with more water use efficiency need to be developed"; and "Agriculture is the largest water user, and they need to adapt." On the other hand, I hear growers saying: "irrigation costs money, I try to do my best" or "I fear my well might go dry any minute." Thus, I feel there is a disconnection between these communities.*

Moreover, I think it is not very helpful to provide general recommendations for solutions to the climate crisis, while not understanding the innumerable challenges farmers face to put food on our tables. I am not sure that our society has a grasp of how challenging it is to produce healthy food sustainably and at a cost that guarantees access to everyone. I think we do not value enough the work of farmers and how hard they try to optimize their operations to produce food sustainably. I hope to use the scientific method to investigate and improve technological tools to ease farming and promote sustainable practices.

BAMS: What surprised you the most about the work you document in this article?

NB: *I am honestly surprised by the level of accuracy achieved by biophysical models driven by satellite remote sensing data. These tools have huge potential, and as scientists, we need to keep digging to find ways to use this information to support our communities. Based on our results, I feel confident that if we can put this ET data in the hands of growers, they can use that to inform their irrigation decisions. In my opinion, the data provided by OpenET provides more accurate and reliable information than most commercial products available in this space.*

BAMS: What was the biggest challenge you encountered while doing this work?

NB: *Our research findings become relevant if we translate them into actions. Growers and farm advisers who use ET data to make irrigation decisions are used to the concept of crop evapotranspiration (ET_c). That is obtained by combining reference evapotranspiration (ET_0) with empirically derived parameters (crop coefficients). ET_c is different from actual evapotranspiration (ET_a), which is somewhat confusing for ET users. Helping ET users interpret this information and communicating the value of OpenET compared to their traditional approach has been challenging.*